Distribution Network Visibility

LCN Fund Tier 1 Close Down Report

UK Power Networks

PPA Energy

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ukpowernetworks.co.uk/innovation

1. Foreword

The transition to a smarter grid and low carbon technologies (LCTs), especially the increase in domestic micro generation and the electrification of transport and heating, has intensified the need to improve visibility of the distribution network at 11kV and below. This improved visibility is expected to enable Distribution Network Operators (DNOs) to make smarter decisions in the areas of network planning, asset management, new connections and network operations. It will also enable DNOs to better manage the new challenges that this transition will bring. These include:

- Embedding Low Carbon Technologies at lower voltage levels.
- Changing load profiles from historic pattern assumptions.
- A potential increase in voltage and harmonic issues.

Most DNOs have limited monitoring at lower voltage levels. UK Power Networks' London network is different. It has an extensive and widespread monitoring capability, with Remote Terminal Units (RTUs) deployed in approximately 60% of the distribution substations. These RTUs, primarily used to remotely control the high voltage network, had a range of unused features ready to be fully exploited.

The Distribution Network Visibility LCNF Tier 1 project successfully harnessed the monitoring capabilities of these RTUs, enabling the collection of large volumes of relevant network data. The project developed a set of algorithms and visualisation tools (the DNV application) to manipulate, update, and where necessary cleanse this data to automatically detect network performance issues and produce useful information such as available capacity.

This Close-down Report details the Distribution Network Visibility project commitments (section 3), before describing the project activities and specific areas investigated (section 4). The outcomes of the project including the various benefits realised are described (section 5), and compared with the original aims and objectives (section 6). Details are provided of areas where the project differed from the original plan in terms of approach (section 7) and cost (section 8). The lessons learnt during project are presented (section 9). Finally, the report describes the planned implementation within UK Power Networks (section 10), and what would be necessary for successful implementation by other DNOs (section 11). A number of appendices have been included to provide supplementary information.

Contents

2. Executive Summary

2.1. Project Scope

The main aim of the project was to demonstrate the benefits of the smart collection, utilisation and visualisation of distribution network data. To achieve this, the following areas were addressed:

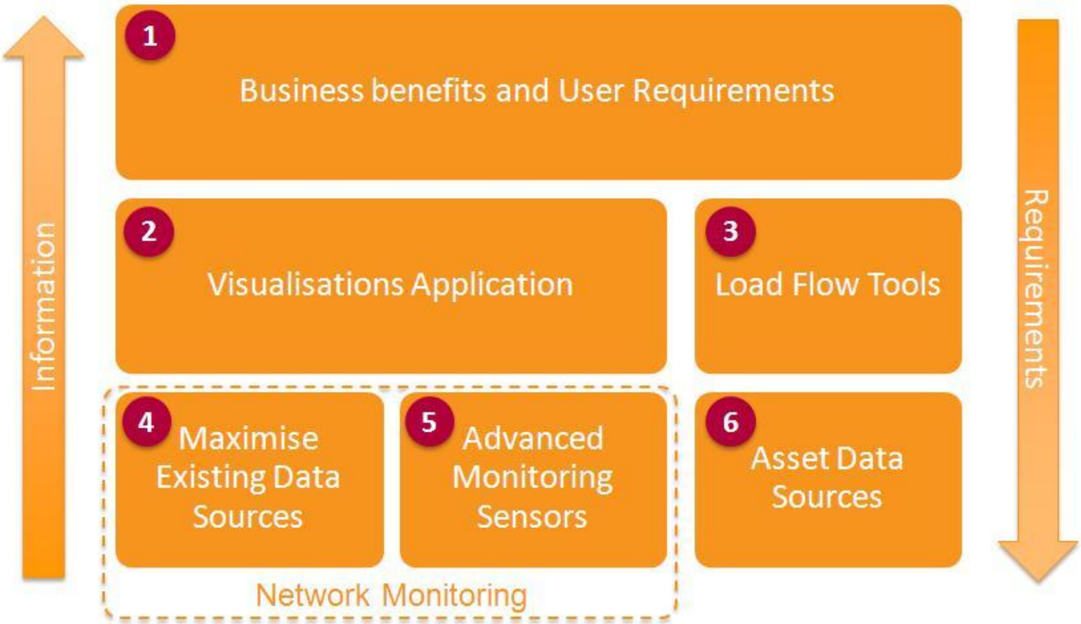


Figure 1: Areas addressed as part of the project

1. **Identify business benefits and user requirements**: Identifying the business units that would benefit from visualisation and analysis of the data, and defining the functionalities they would require to deliver these benefits.
2. **Development of a visualisation application**: Developing an application that implements the functionalities defined to make them available to the users.
3. **Trial load flow tools:** Trialling commercially available load flow tools that can use both the network and asset data to visualise dynamic load flows on distribution networks.
4. **Maximise existing data sources:** Confirming what data was already available and exploring a number of unused features, such as extra data measurements and additional data captured in response to events, available from existing monitoring devices.
5. **Trial advanced monitoring sensors:** Trialling the use of advanced monitoring sensors, including novel optical-based sensors, to monitor areas that lack monitoring and supplement existing monitoring.
6. **Identify and integrate other data sources:** Identifying other data sources that could be used in conjunction with network monitoring data to ensure the visualisation tools developed and trialled provide valuable information to users.

Although the project included areas related to monitoring of the network, a major focus was on processing the data into useful information that can be presented to users in the most appropriate way, and support them in delivering tangible benefits.

2.2. Activities

Employing a phased approach, the project addressed the areas described on Figure 1 by carrying out the following main activities, some of which spanned multiple project delivery phases:

- **Definition of business benefits and user requirements:** Through engagement with various business units within UK Power Networks, a list of benefits that could be enabled by better visualisation of the distribution network was compiled and categorised. In the process of defining this list, areas where only minimal benefit could be achieved were identified, ensuring work focused on the most important areas. As part of this discussion with stakeholders, an initial assessment of what users would require to deliver the benefits was made. Both the benefits and requirements were refined during the iterative process of developing and trialling the visualisation tools.

- **Assessment of data requirements and data collection:** This involved analysing the data that would be needed to support the requirements of the functionalities. To ensure this data was available the following work was undertaken:

  - **Exploiting existing network data sources:** The existing power monitoring devices installed on the London network had further measurements and advanced functionalities that were not being used. Work was done to upgrade the communications module to allow the extra data to be retrieved. A trial was also carried out to investigate the advanced features available on the devices such as the capture of detailed waveform data.
  - **Advanced monitoring sensors:** Novel optical sensors were trialled to increase monitoring on networks where it was lacking and to increase the detail of the monitoring where it was already present. Limitations in their application with HV steel wire armoured cables were found, so other sensors were trialled to assess their applicability in a wide range of scenarios.
  - **Integrating asset data:** Combining network monitoring data with other data relating to the asset being monitored often greatly increases its value. When working with large volumes of data, it was important to ensure this data was automatically allocated and processed.
  - **Upgrading the data historian infrastructure:** To allow the integration of multiple data sources and support the development of the visualisation application, UK Power Networks' network data storage system was upgraded.

- **Implementation of visualisation and power flow tools:** To combine the data sources described above and process them to fulfil the user requirements, a visualisation application was developed. It enables the integration of multiple data sources, and makes it available to users through an easy to use and visual interface.

  To generate network load flow visualisations using the network data, third party tools were trialled. This involved configuring them to reflect the network and requirements of users, and assessing them for their suitability.

2.3. Outcomes of the project and key learning

Outcomes

- **Visualisation application:** A production web-based application was successfully developed to implement a suite of visualisations and analysis tools for network data. This application has now been adopted business as usual by UK Power Networks as part of our corporate IT landscape and is being used by various business units.
- **An IT White Paper has been written** to assist other DNOs, particularly their IT departments, in replicating the results of the project.
- **Remote Terminal Unit (RTU) upgrade:** 9,885 Secondary RTUs on the London network were upgraded to allow retrieval of a further 11 analogue network measurements in addition to the existing four previously available.
- **Load Flow Tools:** Two commercially available load flow tools (GE DPF and CGI DPlan) were trialled, and recommendations made on what further work is required between DNOs and suppliers of these tools to ensure they deliver maximum benefits.
- **Data Integration:** Data from six separate databases has been integrated into the visualisation application to ensure users are provided with useful information to support business decisions and deliver benefits.
- **Advanced RTUs features:** These were only partly assessed due to concerns principally relating to compromising the operational SCADA or communication systems, which resulted in only 27 independent RTUs being upgraded and a limited number of network events captured.

Learning

- **Benefits:** Areas where benefits are expected to be delivered through network data analysis and visibility have been identified, and functionalities required to deliver them developed. Examples include:
    - **Deferring and avoiding network reinforcement:** Relying on assumptions when analysing load allocation on networks necessarily involves the use of safety margins to account for unknown and unexpected loading conditions. Having accurate information regarding the loading of assets allows them to be utilised more efficiently, while at the same time ensuring they are not unknowingly overloaded.
    - **Reducing frequency and duration of customer interruptions:** Having greater visibility of network conditions allows DNOs to identify areas of the network that may be experiencing abnormal loading. Failures could be prevented, avoiding customer interruptions. It will also mean that when interruptions do occur, responses can be faster, better targeted and remedial action can be more effective.
    - **Avoiding and limiting damage to assets:** Detailed network loading analysis can ensure that assets are being utilised within safe limits in terms of load, duty and other parameters such as harmonics, ensuring they are not being subjected to damage. Simulation of planned operations using historic data will also help to avoid damage related to these operations and the conditions the network experience as a result of these operations.

- **Improved customer service:** In addition to reducing interruptions, DNOs are able to take proactive approaches to voltage issues and be able to provide customers with better information regarding outages. More accurate and timely connection proposals can also be made.

- **Advanced monitoring:** Efficient ways to monitor distribution networks have been explored through trials of a variety of network monitoring sensors (from LV to 33kV) along with analysis of the data requirements of the tools used to enable benefits. It was established that the optical sensors were a suitable solution to monitor sites with no RTUs, although there are limitations in their application with HV steel wire armoured cables.
- **Data Quality:** Data quality was identified as a significant issue and a study into data anomalies, their source, and how to correct them has been carried out and implemented. It was found that this is essential due to the fact that tools such as the application developed allow users to access much larger volumes of data than they can practically review manually.
- **Load profiling:** It has been shown that by applying load profiles to substations and the load profile of new loads, a more efficient use of assets than traditional maximum demand methods can be achieved.

2.4. Conclusions and future work

Great Britain's transition to a Low Carbon Economy is expected to lead to an increase in loads on electricity networks due to transport electrification, heat pumps and cooling demand. This project has shown that visibility of network data and the combination with other data sources can help facilitate this increase. This will be done by ensuring efficient and safe utilisation of assets, avoiding the need for unnecessary expensive network reinforcement.

It has also been shown that this same visibility can help DNOs tackle the challenges they are already facing such as operating an efficient network, reducing customer interruptions, increasing asset lifetimes and improving customer service.

As the project has progressed, areas that are of interest and could be explored further have been identified:

- **Dynamic ratings of assets:** The concept of dynamically rating a distribution transformer has been proven. There is an opportunity to finalise this work and possibly extend it to other asset categories, in particular underground cables which have a high thermal inertia to take advantage of.
- **Load flow tools:** There is still work to be done to ensure the available load flow tools deliver the requirements of DNOs at a cost that is affordable. Other useful functionalities have also been identified for development such as predicting future load flows based on historic data for similar time of day, network conditions, running arrangements, etc.
- **Integration of further data sources:** Although the tool already sources data from a wide variety of business systems, there is scope to extend this to many more in particular non load related data. This would allow further functionalities to be developed and synergies between different types of data to be exploited.

3. Project overview

This close down report is designed to allow readers to compare the outputs to our original project commitments. The original project registration information is shown below (updated only for the change to the company name).

Project Title	Distribution Network Visibility
Project Background	It is widely acknowledged that greater visibility of power flow on the distribution network will be required in order to manage the more complex load profiles and greater levels of distributed generation expected in future. UK Power Networks (formerly EDF Energy Networks) has Remote Terminal Units (RTUs) in all its primary substations and, in LPN, around 45% of its secondary substations (approximately 7500 sites). These units not only provide telecontrol, but also have the capability to measure a significant number of analogues. These analogues include the current and voltage on each LV phase, power factor, voltage and harmonic distortion. Currently, the full set of analogues is available for control engineers to interrogate 'on the spot' when making operational decisions, but only a limited 'core' set is stored in our central database or 'historian'. The Intelligent Distribution Network Monitoring IFI project has concluded that a novel utilisation of existing systems can facilitate the transition to a low carbon energy sector and lead to more effective planning, better investment decisions, asset management and operational decisions.
Scope and objectives	The main objective of the project will be to demonstrate the business benefits of the smart collection, utilisation and visualisation of existing data (i.e. analogues available from RTUs). The project will establish optimum levels of distribution network monitoring and frequency of sampling for specific scenarios and applications. It will also trial various optical sensors that could potentially be used to provide detailed monitoring of sites with no RTUs. Some concrete examples of where the data is potentially of use to the DNO include: • Identification of localised load growth and changes in load patterns, in order to determine a wide range of options early on. • Understanding where Distributed Generation (DG) is masking load, which can have an impact on planning, outage calculations and restoration actions after an outage. • Understanding whether traditional assumptions about the duty of assets (e.g. tap changers, transformers, etc.) are accurate. The project will operate in a phased manner within the overall funding requested below:

	• The first phase of the project will prioritise areas of interest to stakeholders, develop initial mock ups and validate assumptions. • The second phase will concentrate on the collection of additional analogues into the historian, validation of the accuracy of sensor readings and implementation of standalone solutions (with relatively few touch-points on our live systems). We are likely to be able to report at the first LCNF annual conference which tools we are planning to take forward into the second phase of the project. • The third phase of the project will develop and integrate some of the tools demonstrated as part of the second phase into operational systems, and will therefore require more resources. The rationale for the original specification of the RTUs installed at secondary substations in LPN was in part based on the operational benefits (Quality of Supply, fault recovery) of such a densely loaded underground network. We recognise that this project will therefore deliver both benefits in terms of transitioning to a Low Carbon future, but also operational benefits in the existing operating environment. We propose that the Low Carbon Networks Fund funds the first phase of the project which will include the detailed investigation into the use (via ""use cases"") of the data and upgrade of relevant systems. The funding for the second and third phase of the project will be split between the Innovation Funding Incentive (1/3 of the cost) and the Low Carbon Networks Fund (2/3 of the cost). This split has been carried by assessing the use cases (19 in total), and identifying the proportion which are strongly contributing to the transition to a low carbon future. This will continue to be reviewed throughout the project and the proportion of the project cost allocated to the LCNF may be reviewed (there will be no increase in the LCNF project expenditure).
Success criteria	The project will have succeeded if UK Power Networks and its partners are able to: • Validate the RTU analogue readings which are not currently being stored. • Evaluate the suitability of optical sensors for sites which are not equipped with RTUs. • Store the data in the historian in a way that is scalable to a larger roll-out; • Work with stakeholders to identify particular applications for which the data will be of high value. • Prioritise amongst these and develop business applications for high priority opportunities. • Work with stakeholders to identify particular applications where the data will add little extra value, and report these as lessons learned. • Recommend a future monitoring strategy based on the results.

4. Details of the work carried out

4.1. Background

In UK Power Networks, all the data from primary substations' (33/11kV, 132/11kV and other variants) Remote Terminal Units (RTUs) is displayed in real time on the Control system diagram.

The Secondary substation (11kV/415V) RTUs (Figure 2) installed in the London (LPN) area, for remote control and automation of HV and LV switchgear, were specified in 1995 to collect a range of data points greater than those collected from the RTUs on other distribution network operator's networks, including those on the Eastern (EPN) and South-Eastern (SPN) networks.

Figure 2: Secondary RTU (Left / Centre) / Current Clamps and Voltage Fuses (Right)

Part of the rationale for this was the high load density and almost entirely underground nature of the LPN network, where network events have the potential to affect large numbers of customers and network interventions can be more difficult than on semi-urban or rural systems. The intention was that the data collected would progressively allow the development of a range of asset management and operational strategies, allowing improvements in quality of supply and reductions in operating costs as a result of the ability of being better able to diagnose network problems.

It was subsequently found that the communications and IT architecture did not have the capability to allow routine polling (i.e. collection) of large volumes of parameters, and the number of analogue data points collected was reduced to four, although the RTUs could still be interrogated individually (Figure 3) from the control system.

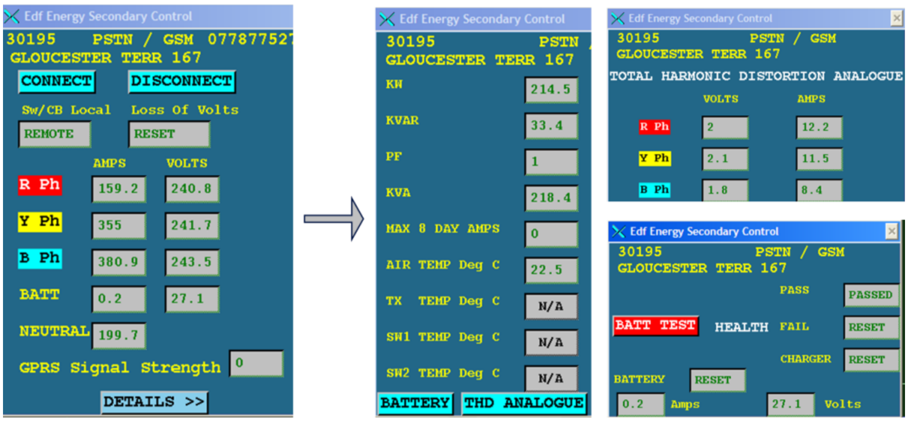


Figure 3: View of instantaneous data available to control engineers at the beginning of the project (Secondary RTUs).

The "Intelligent Distribution Network Monitoring" project carried out under the Innovation Funding Incentive (IFI) scheme in 2008/2009 concluded that the existing RTUs should be considered as an integral part of a wider 'smart network' philosophy, and that the current emphasis on smart networks to support a low carbon future provided a new and important driver to develop more intelligent tools to improve the management and operation of the distribution network. The project concluded that:

- The current level of monitoring in the LPN area is appropriate.
- Communications should be upgraded to GPRS to enable more data to be collected from secondary substations.
- Improvements to the IT infrastructure should be carried out to allow the data to be analysed, manipulated and presented. This would enable a number of tangible benefits to be delivered.

4.2. Overview

The project was divided into three main tasks. Each of these was subdivided into several activities and the details of the work carried out can be found in the relevant sections below.

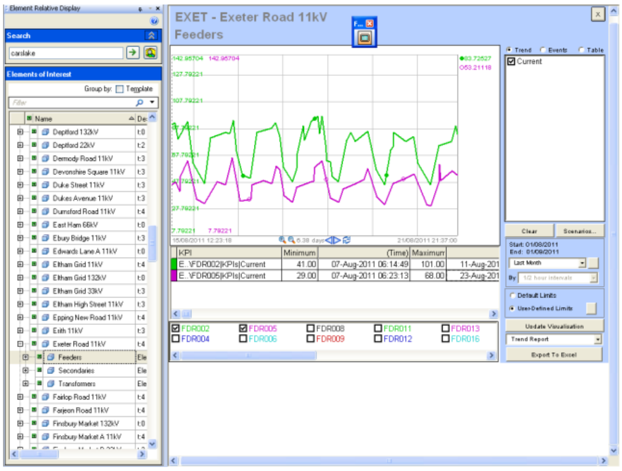
- Definition of business benefits and user requirements (section 4.3)
  - Business benefits (section 4.3.1)
  - User requirements (section 4.3.2)
- Assessment of data requirements and data collection (section 4.4)
  - Data requirements and collection considerations (section 4.4.1)
  - Validation of existing RTUs (section 4.4.2)
  - RTU advanced features (section 4.4.3)
  - Advanced monitoring sensors (section 4.4.4)
  - Integration of external databases and data (section 4.4.5)
  - Upgrading the data historian infrastructure (section 4.4.6)
- Implementation of visualisation and power flow tools (section 4.5)
  - Power flow visualisations (section 4.5.1)
  - Visualisation application (section 4.5.2)

The work outlined above was undertaken in three consecutive phases. A full project review was carried out following each phase to allow the learning to inform the work to be carried out in the next phase.

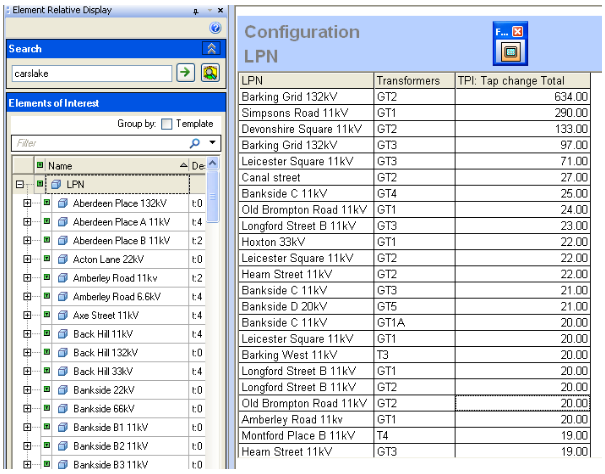
Scoping Phase

The main objective of this phase was to define in more detail the business and user requirements that would achieve the objectives of the project.

This involved confirming what data was already available and the development of a proof of concept tool to help demonstrate and explore the possibilities of analysing and visualising it (Figure 4).



Easy access and comparison of feeder loads to enable load transfers



League table of tap changer operations (Number of tap change operations / Daily average)

Figure 4: Proof of concept tool

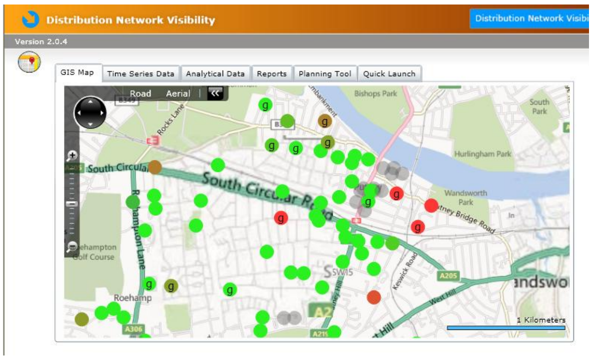
Following workshops with key business units including Asset Management, Connections and Network Control, a series of benefits sheets (see summarised version in Appendix F) were developed describing the potential business benefits and the expected improvements to existing policies and processes. The benefit sheets were also used to document the proposed delivery and review processes, which allowed potential solutions to be mocked up. After a technical review, each benefit sheet was signed off by the relevant business unit, and a functional specification of the solution for the next phase of the project was developed.

In addition, preparatory work was carried out to facilitate future activities of the project. This included upgrading the data historian infrastructure to support the needs of the solution to be developed, and validating the technical specification of the RTUs and pilot installations of the proposed advanced monitoring sensors necessary to achieve some of the potential solutions at LV and HV and on overhead lines at both 11kV and 33kV.

Standalone Phase

The main activities undertaken during this phase of the project were:

- The development of a more advanced and more flexible web based visualisation and analysis tool (DNV Application, standalone phase release / Figure 2): At this stage, the application used extracts from other databases such as the asset register and the distributed generation database but was not integrated into UK Power Networks' existing data systems, with the exception of the network measurement data held in the data historian. This allowed refinement of the business benefits previously identified, and led to the finalisation of the architecture required to deliver the fully integrated solution. Work was also started on the development of data quality algorithms.



GIS Map Tab: Showing an overview of secondary substations utilisation

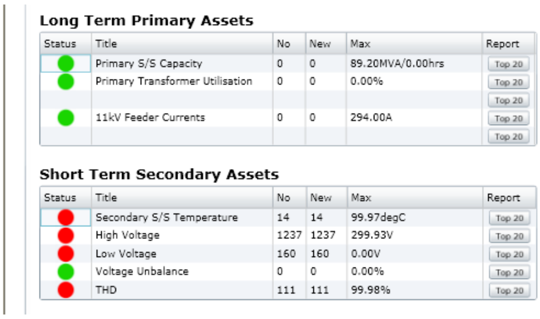
Analytical Tab: Bar Chart Data comparing the number of tap change operations of four primary Transformers

Figure 5: DNV Application / Standalone phase release

- RTU upgrade: It was identified that there was significant latent functionality available in the existing population of secondary substation RTUs installed across the LPN network. To access these extra data sources required the following work to be undertaken:
    - Manually upgrade 500 RTUs to recover a further 11 analogue measurement values.
    - Develop software to systematically upgrade the remaining 9,385 RTUs remotely without compromising the remote control functionalities critical to day-to-day operations.
- Commission a trial of 10 independent RTUs to enable additional functionalities such as exception alarms, detailed event waveform data and harmonics data. The functionality in the advanced RTUs was designed to provide information necessary for the analysis of various transient conditions and complex network arrangements. These independent RTUs were installed in representative substations to capture a wide range of conditions.
- Advanced monitoring sensors trial: hardware was installed and commissioned at eight additional substations in LPN to monitor both radial and meshed HV systems.
- A review of the GE Distribution Power Flow tool with measured data was undertaken.

Integrated Phase

This phase integrated all identified data sources and developed several of the advanced functionalities (See DNV Application / Integrated phase release / Figure 3). A series of case studies (See Appendix F) were produced to demonstrate how the analysis and visualisation functionalities developed will lead to benefits for customers.



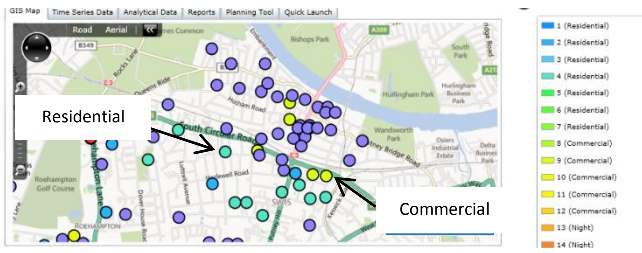
Long Term Primary Assets

Status	Title	No	New	Max	Report
	Primary S/S Capacity	0	0	89.20MVA/0.00hrs	Top 20
	Primary Transformer Utilisation	0	0	0.00%	Top 20
					Top 20
	11kV Feeder Currents	0	0	294.00A	Top 20
					Top 20

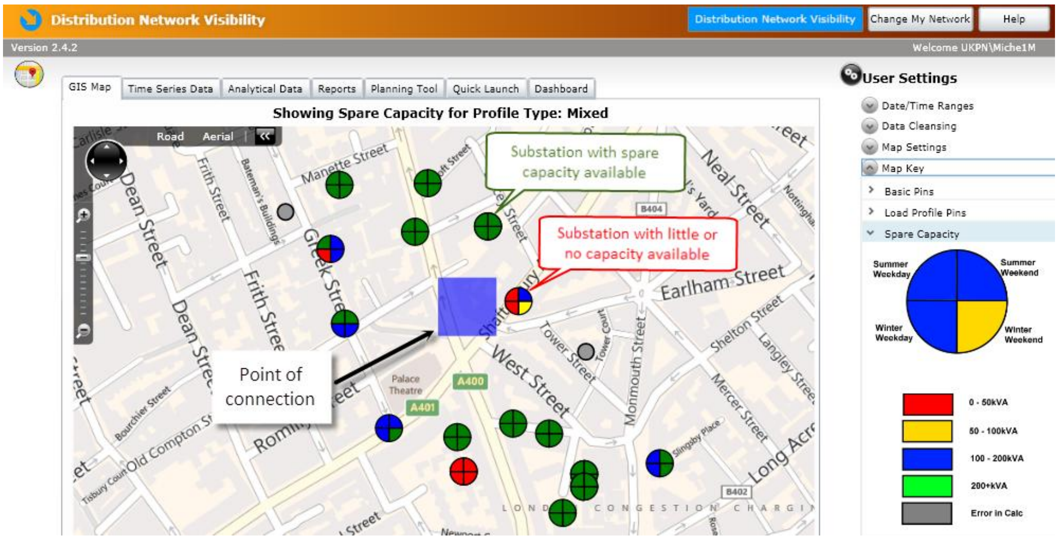
Short Term Secondary Assets

Status	Title	No	New	Max	Report
	Secondary S/S Temperature	14	14	99.97degC	Top 20
	High Voltage	1237	1237	299.93V	Top 20
	Low Voltage	160	160	0.00V	Top 20
	Voltage Unbalance	0	0	0.00%	Top 20
	THD	111	111	99.98%	Top 20

Dashboard Tab: Provides an overview of Network Issues



GIS Map Tab (Automated Load profiling): Enables the detection and management of more complex "Low carbon loads"



GIS Map Tab (Connections Tool): Facilitates the connection of additional load

Figure 6: DNV Application/Integrated phase release: Example of advanced functionalities

This phase also saw the 9,385 remaining RTUs in the LPN area remotely upgraded to recover and record all the selected additional analogue measurements available.

Finally, the trial of advanced RTUs was extended (17 additional independent RTUs) to provide a wider dataset and this was also augmented with advanced monitoring sensors to demonstrate the benefits of advanced monitoring and visualisation of both interconnected LV networks in central London and small section rural HV networks in Sussex (SPN). The interconnected LV network in central London was also modelled using CGI DPlan software.

Following a review, the GE DPF tool was not investigated further in this phase and the study of the benefits to control engineers of real-time load flow values concentrated on another tool, DPlan, provided by CGI. This is discussed in Section 5.5.

4.3. Definition of Business Benefits and User Requirements

4.3.1 Business Benefits

When the project commenced, the four analogue values from secondary RTUs saved in the OsiSoft PI database or 'historian' were available to UK Power Networks' business units via a spreadsheet interface. It was necessary to identify areas where visualisation and analysis of the existing, and combination with other available data would help improve business processes and achieve a number of business benefits.

Business users in the Network Control, Connections and Asset Management (including load-related planning) areas were identified to inform the project in understanding the current business processes, and review the network visibility concepts. This process resulted in the identification, detailed definition and rationalisation of the business benefits:

Category	Business Unit	Benefits
1. Real time Loading, Voltage Profiles and Events	Control	1.1 Real time network power flow
		1.2 Prevention of LV interconnected network cascade following HV faults
2. LV Faults and Events	Control	2.1 Detection of faults and events on the LV networks
3. Network Performance and Utilisation	Asset Management	3.1 Voltage investigation
		3.2 Identification of areas with poor power factor
		3.3 Identification of LV out of balance and harmonics
4. Load Growth and Profiles	Connections & Asset Management	4.1 Information to support new customer load connection and general network reinforcement
		4.2 Load analysis and growth profiling to improve planning process
5. Transformers Duty and Defects	Asset Management	5.1 Improved management of secondary substation ventilation
		5.2 Reduction in operational risk of failure of primary transformer tap changer

Table 1: Business Benefits

The Network Control benefits were associated with real time data and its translation into real-time load flow information, whereas the Connections and Asset Management benefits were associated with the use of historic data. The Control Engineers were clear that their preferred visualisation solution was one which sat within their present control system environment. This is one area which, whilst identified as a benefit, has been shown by the project not to be economic for full integration at this stage, due to further development of power flow tools being required.

A benefits sheet was produced for each area and captured information such as the scope, user functionality to be delivered, data to be used, overview of existing and modified business processes, detail the business and low carbon benefits, etc. As the project progressed these benefits sheets were reviewed to track progress and identify issues. Appendix F contains practical examples of not only screen-shots from the tool, but also the kind of follow-up investigations that result from issues which are flagged by the tool.

A number of specific areas where visualisation and analysis of the data was identified as adding limited extra value to the business were identified:

Area	Existing business process	Comment
Primary substation firm capacity point loads and transformer loads	A spreadsheet linked to PI is currently used by Infrastructure planning.	The development of visualisations or analysis tools would not lead to any tangible improvement in efficiency.
Oil temperature of some oil switches	Sensors are linked to an alarm threshold for Control.	There is no benefit in repeating this process.
Cable fluid pressure	Transducers generate alarms into SCADA system. Trend analysis and failure prediction for fluid filled cables is already undertaken.	The development of visualisations or analysis tools would not lead to any tangible improvement in efficiency.
RTU battery health	A periodic review of battery health is currently undertaken.	The development of visualisations or analysis tools would not lead to any tangible improvement in efficiency.
Use of notifications within PI to send automatic e-mails	Control have existing SCADA alarms. Other users, who do not require visibility of data in real time, access the cleansed data through the dashboard.	There is no benefit in repeating the SCADA alarm process. Other non-cleansed data could be misleading to users.
Accessing historic data in PI	The Infrastructure and Distribution Planning Engineers used a spreadsheet based method to access the PI time series data for use in power system analysis studies.	The techniques and methods used in the DNV application have largely superseded this method of data collation.

Table 2: Areas identified as offering limited potential for achieving benefits

These processes were agreed to be out of scope, and not brought into the suite of tools. They are being maintained separately.

4.3.2 User requirements

A straw man concept was used to develop and demonstrate visualisation ideas and techniques within the project consortium. This identified the key elements of the visualisations and functionalities which the users are now using, and which can be seen in Appendix D. Examples of elements which were agreed on at this stage are:

- Daily overview dashboard
- Time series line charts

- Chart suitable for plotting power factor
- Load profiling types
- Spare and transfer capacity
- Connections tool
- GIS colour map pins
- Reports – above and below user limits
- Tabular data exportable to excel, visual data exportable to file

4.4. Data requirements and collection considerations

4.4.1 Data requirements

Historically, analogue data associated with primary substations has been collected by SCADA in real time and displayed on the control system diagram. The data was averaged over a half hourly period and this average value stored in PI. Real time analogue data from secondary substations could also be displayed by request, while a limited set of half hourly averaged analogue data was collected daily from the secondary substation RTUs and stored in PI. These limitations, resulting from the bandwidth of the communications and IT architecture available when the secondary substation RTUs where commissioned in the 1990s, are no longer restrictions and therefore these were reviewed to assess our current data requirements. The appropriateness of calculating and storing half hourly averages was also reassessed and the need for data quality better understood.

The user requirements as determined by the benefits sheets identified that the following needed to be considered when assessing data requirements.

Data averaging intervals

Although the secondary substation voltage and current data varies instantaneously with demand, historic half hourly average data is of value to the Planning and Asset Management Engineers when considering system planning and asset performance, since all of our plant has an amount of thermal inertia meaning that it does not react instantaneously. Where the direction of real or reactive power flows alternate in direction at a monitoring point the half hourly average figures do not provide adequate information for detailed understanding of power flow, and half hourly maximum and minimum figures in addition to average values would be the best solution. These figures could be reported back from the RTU on an individual case basis.

From the Network Control Engineer's perspective, if system events and faults are to be observed and managed, continuous sampling at a minimum of one second intervals is required to allow automation algorithms to make intelligent decisions about the level of variance of the data. For example, whilst step changes associated with switching of large generators (>200 kVA) downstream of secondary substations were observed using the half hour average figures, it was concluded that increased granularity of data would be required to allow the observation of the changing response of smaller generators.

Use of a disturbance recorder collecting five seconds of data at even higher sampling rates would be required if functions such as distance to fault, visualisation of incipient faults, voltage dips due to HV faults and HV incipient faults are to be enabled.

It was noted that alarm limits can be used to report the duration of events such as overloads or high harmonics. It was considered that they could be used to trigger a period of data collection at a higher sampling rate at a location, or the expansion of reporting, for example, to report on individual harmonics.

Data Quality

The required DNV application would generate reports and undertake calculations using maximum, minimum and average values and hence data quality was identified as a key consideration to ensure that the business decisions are correct and to achieve user confidence in the DNV application. Validation of the monitoring equipment data is critical but needs to be a once-only activity to give confidence in the new data that is being collected. This is discussed in Section 4.4.2.

As part of the process, algorithms were developed within the DNV application to identify data quality issues such as gaps (zero and non-zero), spikes, drop outs and out of range, by identifying data quality points. These data quality points are detailed in the application and the user can request whether the time series plots, analytical calculations and reports ignore the identified data quality points, thus resulting in average, maximum and minimum figures which are not corrupted by erroneous data. The original measured data remains in the PI database and is never overwritten as it may represent a genuine system event, or it may be desired to allow the data to be reprocessed in the future. Further discussion of specific findings associated with data quality is presented in section 5.

The DNV application has been designed to produce the following daily reports:

- Health report: To identify RTUs with data anomalies (no data, flat lining, data out of range, etc.), as well as RTUs with suspected hardware or sensor problems.
- PI tag report: To identify component points with a high volume of daily data storage. The PI database is designed to optimise storage using data compression algorithms, so any points with a high volume need their PI compression settings checking. Note in some cases, a high count occurs if the load is variable, for example feeders feeding industrial loads.

Analysis of the data identified that many apparent issues are RTU defects rather than genuine network issues and techniques for separating and reporting the different types of defects were developed.

4.4.2 Validation of existing RTUs

The project team worked closely with the UK Power Networks' Real Time Systems (RTS) and Operational Telecoms teams (responsible for the maintenance and deployment of RTUs), as well as Remsdaq, the manufacturers of the secondary substation RTUs, to fully understand constraints associated with the existing data acquisition, storage and communications system.

Secondary Substation RTUs

Real time data could be interrogated by control system operators from secondary substations using the PowerOn control system. At the start of the project, the policy was to retain half hourly average data for four parameters in the enduring historian (red phase voltage, power (kVA), power factor and substation temperature). These were downloaded every night from each RTU to Pi.

The Remsdaq Callisto 1 RTU used in the LPN secondary substations has a wide range of functionality in addition to that used as part of the HV automation system. This includes:

- Power analysis tools – including; power direction, power factor and harmonics.
- Analogue Limit Excursion (ALE) log.

- Fault detection and disturbance recorder.
- Potential for up to 18 additional channels for circuit monitoring (HV and/or LV feeders).

These functionalities are nevertheless common in new RTUs, and the majority, with exception of the disturbance recorder, are part of any new RTU purchases.

The project aimed to explore and utilise this latent functionality, to the extent that it was shown to deliver benefits. Initially ten RTUs were set up to report to an independent system and as the project progressed, a further seventeen were added. Event and individual harmonic data was collected from these RTUs and a variety of configuration settings were explored to produce an optimal configuration.

Secondary Substation RTUs: Validation of additional analogues

Only a few of the additional functions had been used since original testing and commissioning in the mid-1990s because of limited communication bandwidth. Although Remsdaq still supports the Callisto 1 RTU, it is a now legacy product (two generations from the current commercial offering) and validating the RTU functionality was problematic due to:

- The lack of software capable of reading and interpreting the normal, advanced and fault data direct from the RTU.
- Outdated documentation.

Very few Remsdaq engineers were familiar with these functions and operations.Initial validation of the RTU analogue readings was undertaken at Southampton University in their HV laboratory.

The Southampton tests validated the Callisto1 and NX (the latest model of Remsdaq RTU) “out of the box” settings, as these would be used in the field. Post-test calibration tests revealed small inconsistencies in the results between the standard 100A current clamps used with the Calisto 1 RTU and the split core multi-ratio CTs used with the Calisto NX. These were traced to small defects on the CT mating surfaces of the split cores CTs. With these errors corrected the variations between the readings of the fault systems were generally consistent within +/- 2% with no pronounced trends.

Field validation of the RTU data at specific locations has been on-going during the project as additional monitoring devices have been installed. Power direction is provided by the sign of the real three phase power and was confirmed to be working during the three phase tests at Southampton.

At several stages during the advanced monitoring sensors trial, comparisons were made between RTU readings and optical sensors readings, either by direct replication of monitoring or by validation of both sets of measurements by calculation. It was found that the RTU half hourly average values compared favourably with the optical sensor measurements (which were averages calculated over a ten minute period).

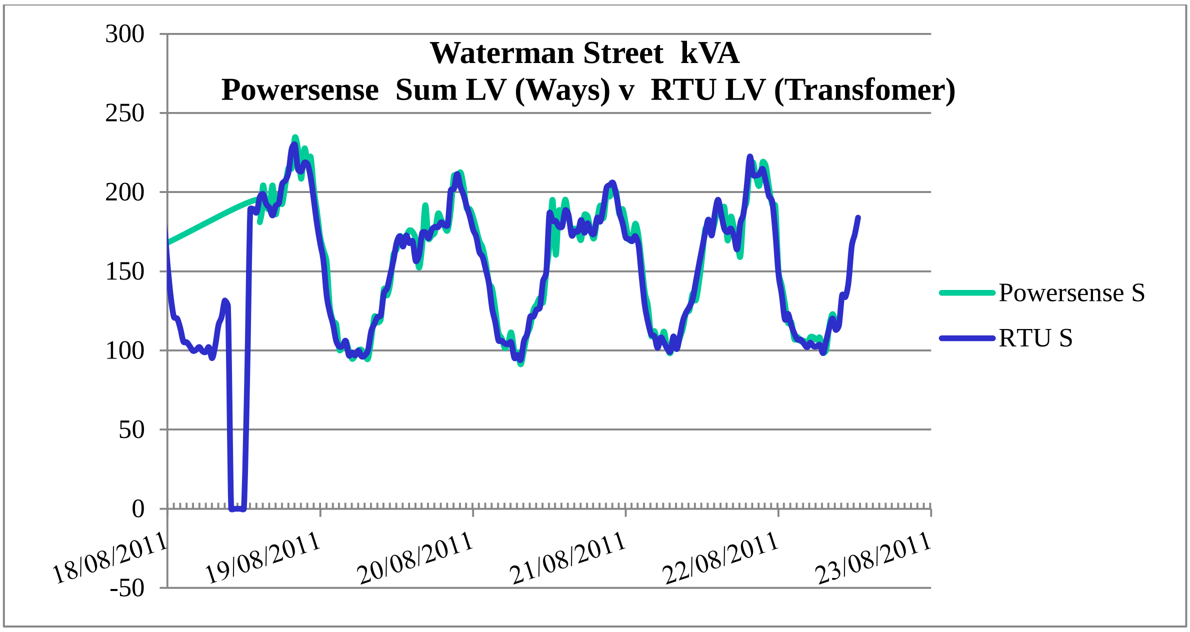


Figure 7: 98% correlation between Powersense/ Optical sensor (10 mins) and RTU (30 mins) data

RTU upgrade

A RTU Protocol Convertor was developed to allow the remote reconfiguration of the secondary RTUs, and the following additional analogues to be saved into PI:

- Yellow and blue phase voltage
- Red, yellow, blue and neutral phase current
- Real and reactive power
- Red, yellow and blue phase total harmonic voltage distortion

The upgrade was carried out in two stages:

1) 500 RTUs individual Callisto 1 RTUs were updated individually by UK Power Networks in the standalone phase of the project late 2012.
2) Following the development of automated software by Remsdaq, the remaining 9,385 secondary RTUs were upgraded as a batch in 2013 during the final phase of the project.

During the upgrade process, it was discovered that a number of RTUs (approximately 700) use RPI protocol associated with fixed line communications. This restricted them to sending back eight analogue values. These RTUs were generally located in basements or substations enclosed in buildings where it was not possible to obtain a GPRS signal, but a full analogue set could be obtained by upgrading them with DNP3 protocol convertors.

Primary Substation RTUs

The analogue data from Primary Substations is recovered and displayed on the control diagram in real time, but in many cases the data is limited:

- Current values are normally obtained from a single secondary CT installed on the centre phase of existing measurement CT wiring at Circuit Breaker positions. A single phase current value is therefore available from all the transformer incomers, each out-going secondary feeder and any bus-sections or bus-couplers.

- A single phase voltage output is obtained from a voltage transducer on the VT associated with each transformer incomers.
- Power is derived from a simple current x voltage calculation within the PowerOn/ENMAC control system, but phase angles or power factor cannot be calculated and current and voltage unbalance values are unavailable. At some sites a power meter with three phase current and voltage inputs has been installed and these can provide real time phase and neutral currents, all phase voltages, power factor, power (MVA, MW and MVAr) and harmonic content. Where these are displayed, only a single phase current and voltage is presented, with only the half hourly average of these values stored in PI.

It was decided that there was value in the visualisation of the available data, but there would be limited additional value created by recovering more data from the Primary substation sites. As such, no validation activities were required.

4.4.3 Advanced RTU features

RTU Analogue Limit Excursions (ALE)

The ALE functionality enables the reporting of current or voltage excursions and has facilities to report power factor and harmonic excursions from set limits. Limits can be specified which, when exceeded, will produce a record summarising the start time, duration above or below the limit and the maximum and average amplitude of the value over this duration.

RTU harmonic data

The RTU has the ability to monitor and report the 1st to 15th order harmonics. In order to assess whether a substation has abnormal harmonic voltages and/or currents that require further investigation, a review of the total harmonic distortion (THD) of all substations provides a quick overall insight. If the reported THD exceeded a threshold, the individual harmonic retrieval procedure would be triggered. A harmonic trial has been undertaken using the independent RTUs to demonstrate that harmonic data can be successfully extracted and visualised from the RTUs. This is shown in Appendix F.

RTU fault disturbance recorder

The fault disturbance recorder contains two buffers each capable of storing 50 cycles of data from up to 12 channels, although in practice only seven are currently used. The disturbance recorder will activate if one of the channels it has been configured to monitor exceeds the current limit and drops below the voltage limit. Once activated, it will record all the channels it has been configured to monitor into an empty buffer, if one is available. Disturbance data will not be stored if both buffers are full.

Alarms can also be sent, which themselves provide valuable information on the geographical location, the history and rate of change. When used in conjunction with the fault database, it may be a means of validating that incipient behaviour has been remedied by maintenance.

A trial undertaken using the independent RTUs demonstrated the RTU capability to record a 50 cycle window of phase voltage, phase current and neutral current waveforms within an internal buffer, notify control system operators of the capture and store waveforms until manually erased (via remote control) or automatically erased after four days. The remote download of fault disturbance recorder data has been proven with the capture and analysis of more than 80 live network events.

The new protocol convertor software has been designed to allow recovery of the disturbance data to a central database, clear the buffer and re-arm the RTU.

At this stage, the fault disturbance functionality is remaining in a ‘sandpit’ comprising of a network of 27 independent RTUs, and has not yet been strongly correlated to unreported fault events on the LV network, or to incipient faults at either HV or LV. A transfer into business-as-usual is therefore not justified.

4.4.4 Advanced monitoring sensors

In areas of the secondary LPN network not covered by RTUs and in the majority of the SPN and EPN secondary networks (apart from the primary substations), there is very little visibility of power flow. The project undertook trial installations of Powersense optical current sensors with the aim of developing and validating a toolbox of applications. These cover the majority of the HV and LV equipment found in the LPN area, and to demonstrate 33 and 11kV OHL line applications in SPN which would be applicable to networks in SPN and EPN.

A summary of the individual installations and learning can be found in Appendix B. As part of this work, a technique known as the ‘Sequence Component Transform’ method was further developed. It allows monitoring of HV current and voltage at a substation using only HV current sensors LV voltage measurements, avoiding the need to measure HV voltage. Details of the method are available to other DNOs on request.

4.4.5 Integration of external databases and data

The PI database in use by UK Power Networks at the start of the project did not allow for links to other databases or for asset hierarchy information to be stored. Asset hierarchy is the way in which a transformer is marked as being associated with a substation, and a measurement is associated with that transformer and in turn with that substation. During the first phase the Asset Framework (AF) was added to PI which allows for such links and hierarchy.

Data was obtained from a number of sources and stored in the most appropriate location in the DNV system:

- The main source for dynamic system data (e.g. asset hierarchy) was from the operational control systems (PowerOn Fusion). This data was stored in PI.
  It is possible to obtain real-time information from other sources. For example, weather data was obtained from text files and stored in PI.
- The main source of fixed asset information (e.g. transformer rating) was the asset database (Ellipse). This data was stored in AF.
- Information was also obtained from other disparate databases. For example, G59 and G83 generation capacity and location information was obtained from spreadsheets, and connection referrals data was obtained from the Planning referrals database. These were both stored in AF.

In order to keep the data saved in AF up-to-date and relevant, automatic routines retrieving and refreshing the latest configuration from a number of source databases on a regular basis were implemented.

4.5. Tools

4.5.1 Power Flow Tools

Real GE DPF Trial

UK Power Networks currently use the GE PowerOn/ENMAC systems to control the EHV and HV systems of all three networks. GE have a Distribution Power Flow (DPF) application which can sit within the PowerOn environment, and produces a real time power flow that can be used to plan switching and determine fault levels.

The Carslake Primary substation network was chosen for a trial of the DPF application as impedance data was readily available and additional monitoring equipment was to be installed as part of the project. The trial was set up on a standalone PowerOn system using the historical time-series half hour data from PI and 10 minute readings from the optical sensors.

The accuracy of the load flow produced by the DPF application was depended on the number of monitored secondary substations and the accuracy of the load profile data for the non-monitored substations. The conclusion from the trial was that if the DPF application was to be used by the Control Engineers it would be necessary to use real time data from the RTUs.

DPlan trial

The CGI DPlan DPF package was evaluated for use on the pilot network, and both HV and LV network data models were built by CGI. This trial was carried out as the DPlan package offered features that were not available in the DPF tool without further development.

The CGI DPlan software is predominantly a planning tool focused on LV distribution networks which can combine the geographic based data such as metering point data together with measured data. At present DPlan has no capability of real-time unbalanced power flow at 11kV, however this might be achievable in future so it can be suitable for planning and with further development real time operations feeding into control systems.

The basis of the model is the MPAN metered data collected every half hour from large customers and longer intervals from smaller customers such as residential households. The model was set up to use RTU primary feeder and secondary substation data and Powersense monitored data. However, the DPlan load allocation algorithms required development by CGI to undertake a load allocation for a meshed LV network. There was also no phase information available with the metering data and it was assumed that the model is a three phase balance system (real time substation measurements reveal this is not an accurate assumption). It therefore did not allow the benefits of the LV unbalanced power flow to be realised.

4.5.2 Distribution Network Visibility (DNV) application

Proof of concept

This application was developed during the scoping phase of the project. Its aim was to use OSIsoft Process Book to make the data more readily available to users. Development initially progressed well but it soon became apparent that the environment had a number of shortcomings when applied to the project requirements:

- The VBA language and development environment lacked many features of modern environments and that made development difficult.

- The Process book VBA environment used a COM framework whereas the most recent AF libraries use the .NET framework. A COM to .NET wrapper had to be developed resulting in performance issues.
- The visualisation applications and components available to Process Book were outdated and did not meet the user expectations.
- Serious data quality issues such as spikes, gaps, flat-lines and bad data were also identified with the PI data. A mechanism was later developed to analyse these issues and provide options for viewing a cleansed version of the data.

Review of options

The solution was to develop a web-based application, able to display time series data collected from primary and secondary substation RTUs (stored in UK Power Networks' PI Historian), and associate it with data from various databases. The application was also required to perform analytical transformations and present the data in various formats such as trends, bar charts, table or geographically, as requested by the user.

A range of visualisation applications were evaluated, the summary of which is given in Appendix C.

Chosen Solution Architecture

The Distribution Network Visibility (DNV) architecture consisted of the back-end data sources, PI historian data archive and a MS SQL server running both the PI AF and DNV databases. The front end application, visualisation display, was run as an intranet web application hosted through Microsoft's IIS.

Figure 8 below illustrates the system architecture for the DNV system.

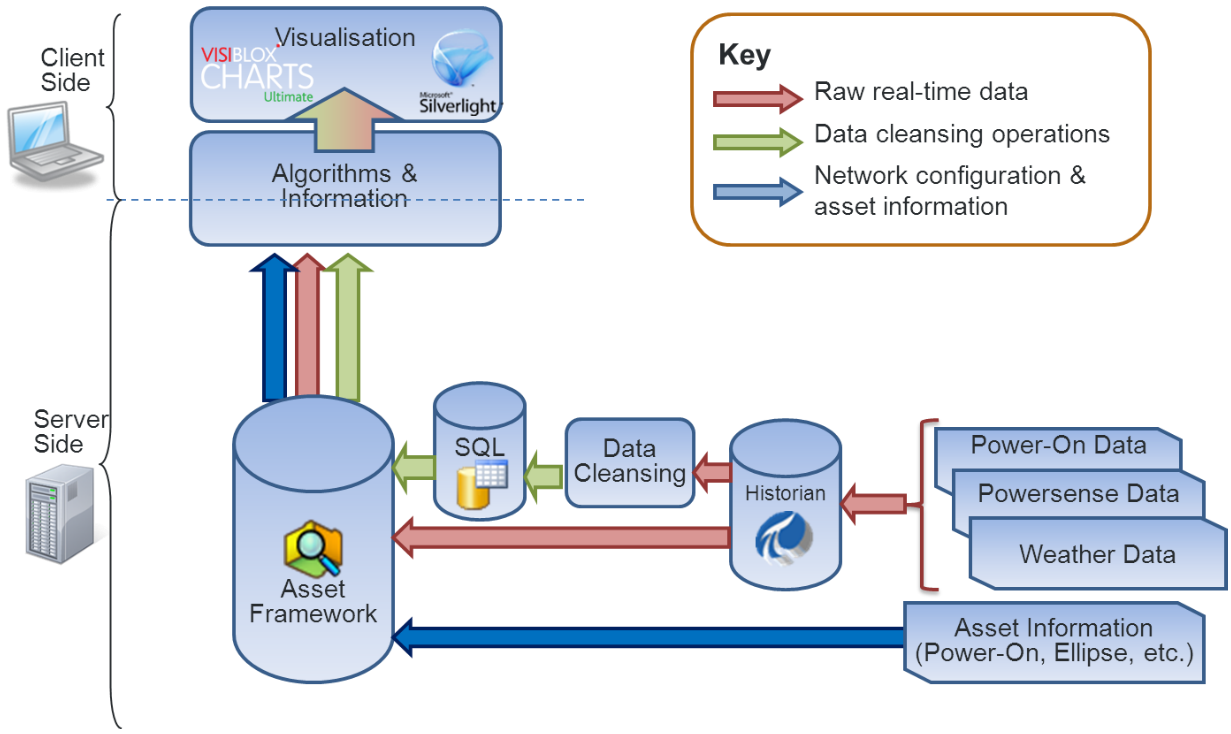


Figure 8: Solution Architecture

The application was implemented using the Microsoft's Silverlight platform, and the coding languages C# and JavaScript were used to create the forms and controls in the DNV application. The application was developed using the MS Visual Studio 2010 environment with some integrated third party components to achieve the required visualised output.

A third party component, Visiblox, was identified. It met the requirements to produce the application visualisation graphics and came with some additional functionalities that offered richer GUI controls to pan, zoom, and drill into the generated graphics. To meet a further requirement of generating a GIS with the application the third party component, and an integrated component with Silverlight, was Bing Maps. This mapping component allowed the user to identify key locations and can illustrate graphically their status and details, as well as standard maps application operation such as panning and zooming into the map.

Physical Architecture

The front end application was delivered to UK Power Networks through IIS, and hosted on a webserver. The IIS server was configured to run the application using .NET framework 4.

Figure 9 below illustrates an overview of the hardware components and their relationship within the system.

The main components of the architecture implemented are:

- An Application Server (ForPIAppD1) running the AF and SQL Server, and hosting the application's AF and SQL databases.
- A Production Web Server (ForPIWebP1) hosting the Silverlight application and serving it to client PCs.
- A Production PI Server (ForPIHistP1) hosting the network data.
- UKPN Data repository used for integrating external data sources (see section 5).
- PowerOn/Weather data.

A Development PI Server (not shown in figure above) was also used as part of the development, and used a PI-to-PI interface to take live PI data from the production server.

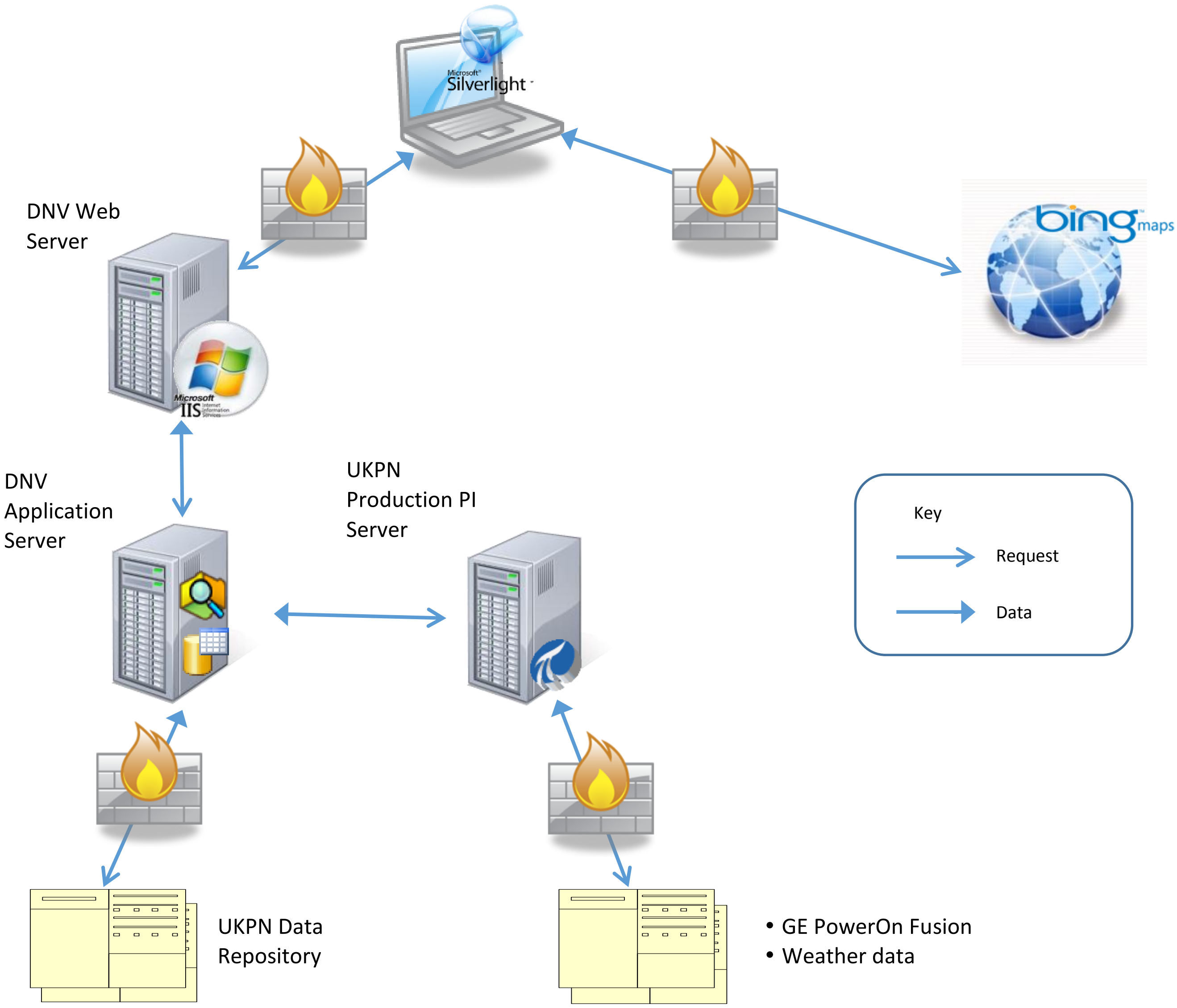
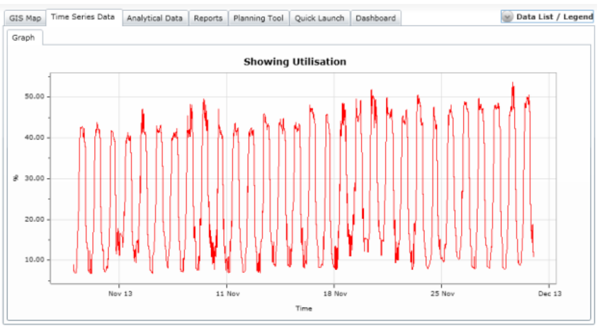


Figure 9: Physical Architecture

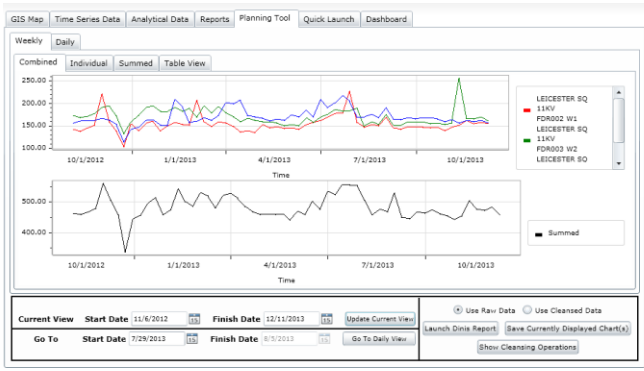
DNV application – User Interface

The DNV application provided a combination of visualisations ranging from an overview dashboard, GIS based pins, reports, time series charts to analytical charts, full details of which are given in Appendix D.

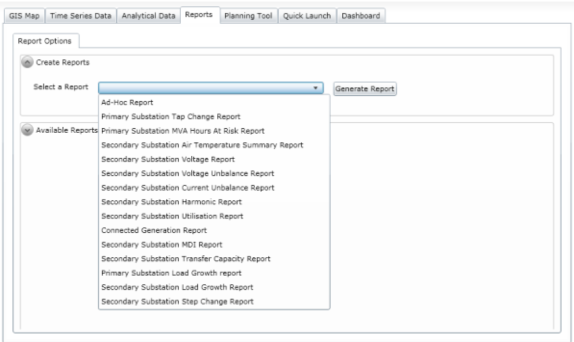
In addition to the GIS map, dashboard and analytical tabs shown on Figures 5 and 6, the following tabs have been developed:



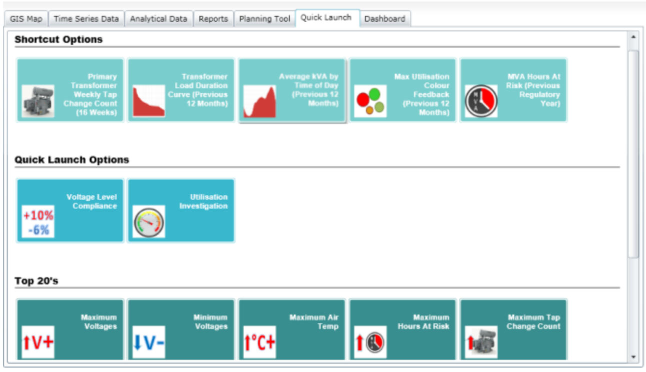
Time Series Data Tab: Enables any time series data to be displayed



Planning Tool Tab: Enables a group of feeders to be assessed for maximum demand and an input file for the load flow tool to be produced



Reports Tab: Enables large volumes of data to be analysed and key information such as Maximum demand, Load growth to be extracted



Shortcut Tab: Enables quick access to key functionalities

Figure 10: User Interfaces developed for displaying various visualisation functionalities.

Advanced algorithms developed

Some features within the DNV application required more detailed analysis of the data before being visualised. For this the following advanced algorithms were developed:

- **Secondary substation load profiling**

Visualisation of secondary substation load profiles was an important factor in managing load growth, and to provide early identification of changes in load profiles due to change in demand such as penetration of electric vehicles and heat pumps. Knowledge of secondary substation load profiles is expected to provide the connections and planning engineers with information in respect of spare capacity for different demand profiles.

The work undertaken to classify the secondary substation load profiles is detailed in section 5.4.

- **Spare capacity and new connections**

Determining the available spare capacity at each secondary substation was undertaken with the application by not only taking account of maximum demand but also the load profile. For example, a transformer with an existing residential load profile has more capacity available for a “commercial” load than for a “residential” load.

The spare capacity was determined on a four period approach: winter weekday, winter weekend, summer weekday and summer weekend. For a given transformer, at a given location, the spare capacity varies over the seasonal year. Similarly, new demand will also respond to seasons. The spare capacity and/or the new demand may be highest in summer (air-conditioning) or in winter (heating). Additional demand which is required to be connected to an existing transformer may add from a seasonal perspective, or may be opposite in terms of the existing maximum demand. Therefore, spare capacity was defined on a seasonal basis. Also, as demands may be different during weekends and during weekdays, they were also considered separately.

The Planning and Connections Engineers can then assess the spare capacity for their individual requirements. Existing referrals were considered in the calculation and the reduction to transformer ratings used in interconnected areas was taken into account.

- **Generation detection**

An algorithm was created to determine step changes in secondary transformer measured power as it can indicate the switching of large demand or generation. The concept of detecting generation and large discreet loads has been proven, but requires further work to make it more robust, before it can be fully implemented.

Planning schematics

The project contracted Sterling Power to understand the challenges and benefits of linking vectorised engineering schematic datasets to the DNV application. The benefits to planning are having one version of a scheme under investigation that can be accessed by all planning and connections engineers irrespective of their location. This reduces delays, avoids duplication of effort and improves accuracy.

A clear workflow exists to take the data from UK Power Networks’ operational system and put into a “non-live” environment for viewing linked to the DNV application, as well as to be made available for the Planning team to undertaking planning and design work in an electronic environment.

5. The Outcomes of the Project

The main objective of the project was to demonstrate the benefits of the smart collection, analysis and visualisation of network data.

A number of areas relating to the collection and visualisation of data were also explored. The findings of the work carried out in these areas are summarised in this section, and more details are available in separate reports. A list of these reports and a brief description of the content can be found in appendix E and are available to other DNOs on request.

The main outcomes of the project are as follows:

- **Business benefits have been defined and case studies carried out.** Please see section 5.1 and Appendix F.
- **Data from six business systems was successfully integrated to produce meaningful information.** Please see section 5.2.
- **The DNV software application was successfully developed**

The DNV software application has become a production tool that is now being used by various business units within UK Power Networks. It successfully integrates data from various sources, and delivers the visualisation and analysis tools necessary to achieve the benefits identified.

Following the completion of the project, the application is being embedded into “business as usual” within UK Power Networks. The application will be owned by the Asset Management business unit, and will be supported by Capula through the IT department, in line with the standard application support process.

The process of developing the application is outlined in section 4.5.2 and details of the functionality implemented in the application can be found in Appendix D.

- **An IT White Paper has been written**

To assist other DNOs in replicating the results of the project, a paper has been produced to explain the process that was followed to determine the most effective way to set up the IT infrastructure required to implement the DNV application.

The IT White Paper will be available on request.

- **A range of optical/advanced monitoring sensors have been evaluated**

Another key element of the project was to explore ways in which alternative sensors could be used to monitor areas of the network with little or no monitoring at secondary substation level, and also enhance the level of monitoring where RTUs are already installed (e.g. data available down to LV Feeder ways, HV directional power flow, etc.), to enable increased functionalities of tools and therefore further benefits.

This involved trialling a variety of sensors, both optical and electromagnetic, to assess how they could be installed on the network in the least invasive way (to minimise disruption to customers), and also assess what additional benefits could be achieved using the extra available data. Details of the trial can be found in section 4.4.4 and the benefits of the monitoring can be found in appendix F in particular the sections on benefits 1.1, 1.2, etc.

The trial generated significant learning regarding the ways in which the network can be monitored efficiently in terms of deployment of monitoring hardware. This is described in more detail in section 5.7 below.

- **The advanced features of secondary RTUs were assessed**

In addition to the analogue measurements that can be obtained from the RTUs installed on the LPN network, a number of features that can be used to identify and investigate network issues were assessed. This was done through the use of 27 independently commissioned RTUs which made the features available for analysis (see section 4.4.3).

Although it is expected that the benefits associated with the advanced functionalities could still be delivered, they were not successfully demonstrated as part of the project. This was due to concerns principally relating to compromising operational SCADA or communication systems, which resulted in only 27 RTUs being upgraded and only a few network events captured. More details of the work carried out can be found in section 5.7 and appendix F (benefit 2.1).

- **9,885 secondary RTUs were successfully upgraded (section 5.6)**

Some areas of significant learning underpin the functionalities and tools that deliver benefits. These areas have been successfully demonstrated and can be tailored for replication by other DNOs. These are listed below and their outcomes detailed in the relevant sections.

- **Data quality.** Please see section 5.3.
- **Load profiling to allow higher utilisation.** Please see section 5.4.
- **Load flow tools and greater accuracy due to measured data.** Please see section 5.5.
- **Monitoring strategy.** Please see section 5.7.
- **Dynamic rating of assets.** Please see section 5.8.

5.1. Benefits to the Business

The table below describes the benefits that were identified at the beginning of the project as being of priority for demonstration. The potential business benefits have also been identified.

A more detailed explanation of each benefit category and the findings of the work done to address each one can be found in Appendix F.

Benefits description	Capability demonstrated	Potential Business Benefits
1.1 Real time network power flow	Greater visibility of Power flow leading to better assessment of utilisation. Identification of highly loaded sections of network.	Avoid network reinforcement. Avoid customer interruptions and asset replacement associated with load related faults and damage.
1.2 Prevention of LV interconnected network cascade following HV faults	Visibility of load flows on the LV interconnected system highlighting potential issues.	Avoid customer interruptions: Information on post-fault running conditions on interconnected networks. Identify fuse failures by detecting unbalance on the LV interconnected network.
2.1 Detection of faults and events on the LV networks	Ability to analyse detailed information relating to events on LV networks. Users alerted to abnormal conditions on LV networks.	Reduce length of customer interruptions and avoid future similar interruptions by analysing fault conditions.
3.1 Voltage investigation	Network-wide reporting of voltages outside of limits.	Improve customer service by proactively solving voltage issue Avoid the need for fitting voltage measuring equipment in response to inquiries.
3.2 Identification of areas with poor power factor	Network-wide power factor report. Mapping of power factor for secondary substations.	Reduction in network losses. Avoid network reinforcement through better utilisation of existing assets.
3.3 Identification of LV out of balance and harmonics	Network-wide voltage unbalance report. Visualisation of extensive harmonic data available from RTUs.	Identification of potentially dangerous network conditions. Increase asset life by identifying and addressing areas with high harmonic distortion.

4.1 Information to support new customer load connection and general network reinforcement	Assessment of nearby substations and spare capacity when assessing connection requests. Network-wide reports showing areas of spare capacity for differing load profile types.	More efficient use of existing network by making connections to most suitable substation. Connection of more load (including future low carbon load) and potentially generation, to existing network avoiding reinforcement. Time savings due to more efficient workflow.
4.2 Load analysis and growth profiling to improve planning process	Load profiling of secondary substations. Network-wide load growth report for secondary substations.	Avoiding network reinforcement through higher utilisation of assets using load profiling. Avoiding overloaded assets by identifying areas of high load growth enabling pre-emptive action.
5.1 Improved management of secondary substation ventilation	Network-wide substation temperature report showing sites where ventilation action is required.	Extend life of assets by limiting exposure to damaging conditions. Avoid situations where RTU batteries life is shortened due to high temperatures.
5.2 Reduction in operational risk of failure of primary transformer tap changer	Tap changer count report identifies changes in tap changer behaviour.	Avoid asset failure by identifying issues early allowing corrective action. Enable transition to duty based maintenance schedules with potential to extend asset life.

Table 3: Summary of capabilities developed and benefits

The business and the low carbon benefits were determined by the project team following discussions with the business units. Through continuous engagement with the business units, new functionalities and additional benefits were identified. Each was assessed on a case by case basis considering the benefits and the cost (both timescales and man effort), as well as ensuring that achieving the original planned functionality would not be adversely affected. As the project progressed, benefits sheets (Appendix F) were reviewed to track progress and identify issues.

5.2. Data integration

Network measurement data often needs to be combined with other sources to have value. For example, load measurements in isolation have little value without knowing the capacity of the asset carrying the load. As well as asset data, various other datasets can be used to give context to network measurements such as location and network hierarchy data.

Data	Source	Value
Secondary Network Measurement Data • 3 x Phase and Neutral Currents • 3 x Phase Voltages • Total kVA • Substation Temperature • Power Factor • Real and Reactive Power • 3 x Phase Total Harmonic Voltage Distortion	PI Data Historian	Visibility of various network parameters as measured at secondary substations
Primary Network Measurement Data • Primary Substation Totals: - Real, Reactive and Apparent Power - Phase Angle • Primary Transformer: - Current - Real, Reactive and Apparent Power - Phase Angle - Tap Change in Progress and Tap Position Indicator signals - Voltage • Busbar Current • HV Feeder currents	PI Data Historian	Visibility of various network parameters as measured on the primary network
Asset Data • Asset location • Asset ratings • Maximum Demand Indicator Readings • Tap Change Counter Readings	Asset register (Ellipse)	Allows assets to be plotted on map Allows loadings to be compared to ratings to derive utilisation Gives readings from inspections to be compared against calculated values
Network Hierarchy Data	Control system (PowerOn / ENMAC)	Gives all asset and network measurement data a structure reflective of the network that it represents
Generation Data	G59 and G83 databases	Can help to give an indication as to the cause of various

		network conditions and events
Connection Referrals	Referrals database	Allows various tools and the users to take account of extra load that has been committed to be connected to the network
Weather Station Data	Met Office	Gives an indication of substation ambient temperature for outdoor sites which is a consideration for some functionalities such as dynamic ratings.

Table 4: Data Sources

It is important that this data is available in such a way that it is easily associated with the network measurements it relates to. A combination of these data sources can then be used to generate information from the data that is useful to the user.

The various calculated and derived information sets are described below:

Information Point	Data Used	Description
Utilisation	• Total kVA • Transformer rating	Utilisation expressed relative to the rating of the transformer is useful when evaluating the loading on the transformer itself.
Load Profiles	• Total kVA	This processes the loading on a transformer over a longer period of time to categorise the characteristic shape of the loading on a daily basis. See section 5.4 for more information.
Planning Tool	• HV Feeder currents • Total kVA • Distribution substation Maximum Demand • Network hierarchy	This tool allows planners to produce a spreadsheet which will automatically populate the existing load flow tool with data regarding HV feeder loads and individual substation loading avoiding a significant manual task.

Spare capacity and New Connections	• Total kVA • Transformer Rating • Location • Referrals kVA	Bringing this data together allows the substations nearest to a point of connection to be assessed for spare capacity. See section 5.1 for more information.
Tap Changers	• Tap change in Progress • Tap Position Indicator • Tap Change Counter	By analysing these signals abnormal tap change frequencies can be identified and a comparison with the count read at the substation can be used to confirm accuracy.
Step Changes	• Total kVA	Detailed analysis of the loading of a transformer can be used to identify step-changes which may indicate the presence and size of connected generation or disturbing loads.
MVA Hours at Risk	• Substation total MVA • Substation Firm Capacity	By comparing substation load to its firm capacity the amount of time a substation is "operating at risk" can be calculated.

Table 5: Combination of Data Sources

These calculated values and other sets of information are then visualised for presentation to the user in the way that best suits both the information being presented, and the way in which the user will use it. These visualisations and functionalities are described above in section 4.5.2 and in detail in appendix D.

In addition to the visualisations, the combination of data sources can be fed into other tools such as those described in section 4.5.1. The data can then be analysed and modelled to predict current and future network load flows. An example of this is given in section 5.5.

5.3. Data quality

It was determined at the time of project conception that data quality issues would have to be addressed. As the work progressed, it became clear that data quality was a bigger issue than first anticipated not only in its prevalence in the existing data but also in identifying and rectifying these anomalies automatically. As the project progressed and as real users started using the application in realistic scenarios, it was confirmed that data quality was extremely important to ensure confidence in the functionalities that use the data.

Different users have a different view on what is a data quality point, or set of genuine data. In certain instances, the data captured and recorded may have a high deviation from normal values but this may be because of an event on the distribution network rather than bad data. For Control engineers operating in real time, the data may represent a system event. However, for Planning engineers, the data may corrupt any statistical analysis they wish to undertake.

5.3.1 Types of data quality

PI data

PI data can contain anomalies in the form of missing data, flat lining data, spikes etc. as illustrated in the figure below, which without correction will adversely affect any analysis such as identifying load profiles or determining statistical maximum, minimum and average values. There are also occasions that a point is created by PI during data anomalies, these points often cause spikes in the trends and should be excluded from any analysis.

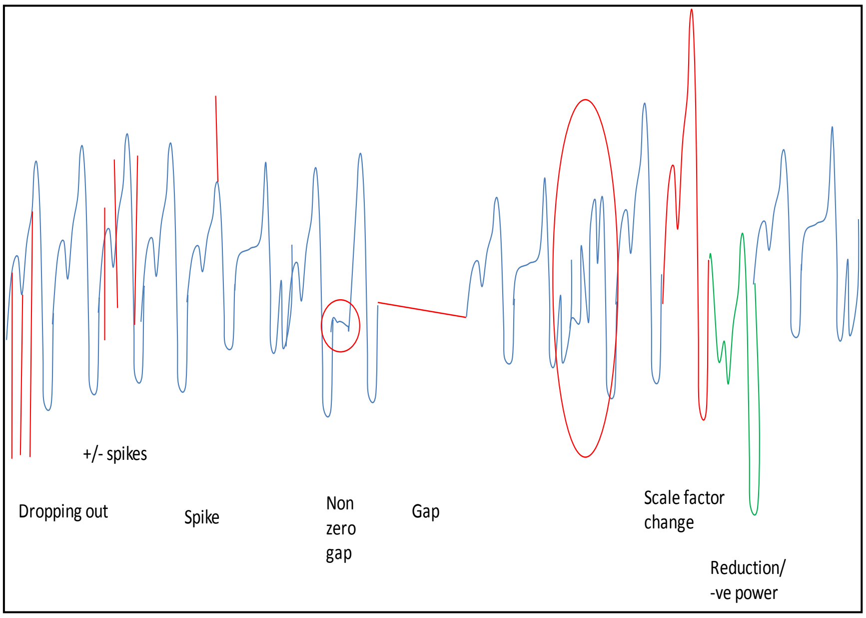


Figure 11: PI Data Anomaly Examples

Half hour averaging

The half hourly average values reported by the RTU can result in anomalies when the data fluctuates between positive and negative during the half hour. For example, the half hourly average power factor at a lightly loaded substation where the reactive power varies across zero i.e. from lagging to leading can be reported by the RTU as a seemingly anomalous value of -0.2 as illustrated in the figure below. For this reason a calculated power factor value (from kW and kVAr) is also plotted and can be used in reporting. It is also noted however that half hour averages are not necessarily the best option for recording data associated with real and reactive power when the values alternate between positive and negative throughout the half hour. Knowledge of the half hourly maximum and minimum values would provide additional useful data.

Figure 12: Illustration of half hourly average power factor data anomaly
(Power factor on left scale, power and currents on right scale
Purple RTU power factor, Green calculated power factor, Orange kW, Black kVar).

Missing data

Where PI data is not available, either because of data quality or because there is no RTU present some values can be estimated from known parameters. For example, the feeder current and measured RTU kVA values can be used together with Maximum Demand Indicator (MDI) readings or transformer ratings to apportion the remaining load across the unknown secondary substations.

Not all the secondary substation data (power, power factor, red phase voltage and substation temperature) was available during 2011 as some of the data points were disabled during the transition of UK Power Networks' LPN control system from Corgis to GE PowerOn.

5.3.2 Dual transformer tails

For the larger (typically>500 kVA) transformers, two parallel cables are used per phase between the transformer and the LV busbar. The RTU CTs are clipped to one of the two cables and the measured value doubled within the RTU. In a small number of instances the parallel cables are not sharing the current equally and erroneous values are reported by the RTU. There may also be an error due to differences in the route of the transformer tail circuits (bends) and differences in phases (circuit spacing). This may result in the total measure current being under or overstated by up to 10%, although errors in the range of + 3% are more common.

At the substation shown below, site current measurements indicated that there were high impedance terminations on two of the cables so that nearly all the current was flowing in only one conductor. Doubling the current on the measured cable results, in this case, in incorrect red and yellow current values. The incorrect current values also result in incorrect RTU calculated neutral current and power readings.

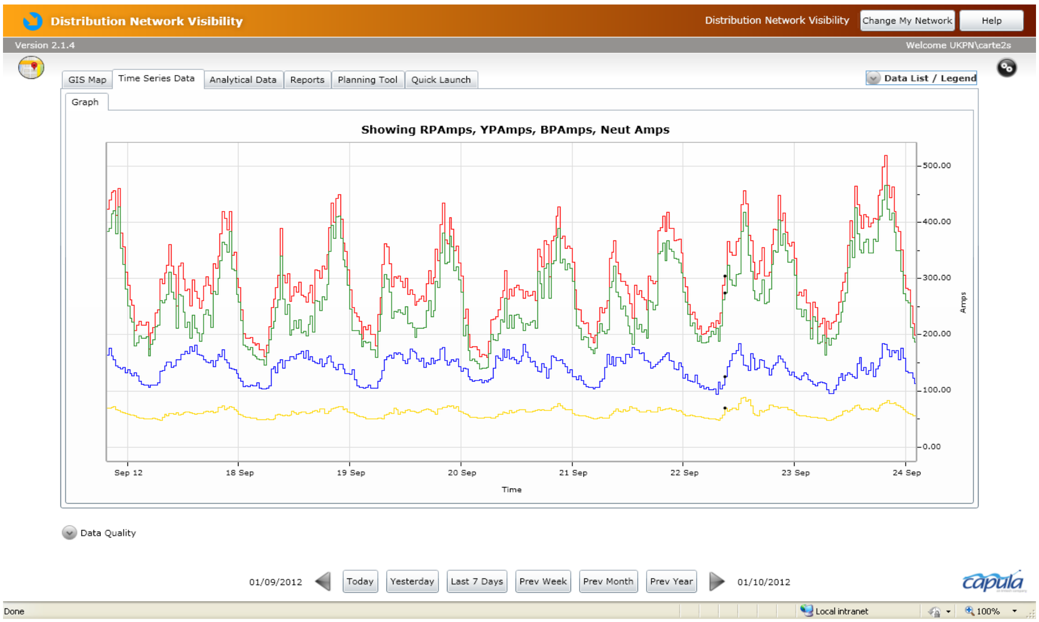


Figure 13: Half hourly average three phase and neutral current for a week showing current unbalance (Red, Yellow, Blue Phase Currents, Neutral Current: Green)

5.3.3 RTU connections

For some RTUs, the calculation of apparent power S did not satisfy the formula $S^2 = P^2 + Q^2$, identifying an error with the physical connection of the RTU CTs or voltage connections such as direction, wiring connection, placement, ratio or dual tail issues.

5.3.4 Greenwich Mean Time (GMT) / British Summer Time (BST)

During the development of load profiles, it was observed that the RTU time clocks remain in GMT whereas the demand adjusts according to BST. As a consequence, an allowance needs to be made for the change between GMT and BST in the load profile algorithms.

5.3.5 Transformer ratings

In a small number of cases, the transformer rating held in the Asset data base was incorrect, probably due to initial data input errors. For example, some incorrect secondary transformers were logged as having 11 kVA ONAN ratings, whilst others had low 100 kVA ONAN ratings logged, which were confirmed to be incorrect.

5.3.6 Extent of data quality

377 RTUs were analysed against the logic criteria $S^2 = P^2 + Q^2$. 95% were found to obey the expected logic within 15 kVA, with 5% identified as probably having installation problems.

Running the DNV application reports throughout the project and visiting sites to check the RTU measurements has identified several sites where there was either a problem with the RTU hardware or the transducers.

Physical issue	Number of substations found to be affected (from sample of 500 upgraded RTUs)
RTU incorrect current reading	2
RTU incorrect voltage reading	7
Transformer tail parallel cable	5

Table 6: Summary of data quality issues found in sample data set

5.3.7 Solutions to data quality issues

The data anomalies were defined as Data Quality Profiles (DQPs) and are detailed in the table below. Algorithms were developed to detect and address the DQPs.

Although the original values in PI must not be altered since they record the actual values reported by the sensors, they can skew some calculations such as maximums and it is necessary to identify and discount them when making calculations. As data anomalies are expected to be infrequent, the option of storing a cleansed version of each tag in the PI historian was not considered an efficient option. Instead, a daily process has been implemented to analyse the latest PI data, and stores a record of each DQP in the DNV application database.

Component Name	Component Description
DQP1	DQP1 Checks for instantaneous dropouts to a specific value (range). 'Non-Zero – Zero—Non-Zero' values, if the current value is zero the previous value and next value is used.
DQP2	DQP2 attempts to identify unusual spikes in relatively smooth data. It does this through finding data points outside a PI tag's specific standard deviation of the daily average value.
DQP3	DQP3 is static (flat lining) data which is not equal to zero. Identified by looking for long periods with no change. Optionally, flat lining can be identified at a specific value. The length of time which defines a flat line is dependent on the tag.
DQP4	DQP4 is an actual gap or hole in the data. Note that this is not a long period between two valid values; it is actually a 'Bad' value (for example 'IO Timeout' as reported by the interface when it is unable to communicate with the data source or 'Bad' as reported by the interface when the value it receives from the data source is not a valid data value.

Component Name	Component Description
DQP5	DQP5 is essentially identical to DQP3 except that DQP5 is specifically designed to look for flat lining at zero values, or around zero depending on the boundary conditions set on the tag.
DQP6	DQP6 identifies any values which fall outside of the specified ranges.

Table 7: Data Quality Profiles

Data from PI is retrieved by the DNV application through AF attributes that use the PI-Point data reference. To enable the retrieval of cleansed data, a new custom data reference has been implemented which retrieves the raw un-cleansed data from the original AF attribute and the associated cleansing operations from the application database. The cleansing operations are then applied to the raw data to produce a cleansed data-set which is presented to the user. Note that the database of cleansing operations is expected to grow at a significantly smaller rate than the data itself, as such, this approach is scalable over the long-term.

A RTU health report is produced daily and details the number of hours each RTU experienced different data anomalies in the previous day, allowing UK Power Networks to prioritise RTU maintenance. The $S^2 = P^2 + Q^2$ check is included in this report.

5.4. Load profiling

Overview

The ability to automatically classify substation demand into different profile types provides opportunities to better utilise the existing equipment capacity, and provide early identification of changes in load growth and demand patterns as the distribution system migrates to a low carbon distribution network. As customers begin to alter consumption behaviour by moving from gas to electric heating and heat pumps, EV charging points or small-scale distributed generation, it is expected that geo-spatial clusters of such loads will begin to form and may lead to extreme loading conditions. Visualisation of such clusters will warn of the changes assisting the Network Planner to manage this change more effectively.

Rather than using the traditional method of assessing spare capacity based on the maximum demand of a substation and applying 80% diversity of new demand, load profiles can be used to assess transformer spare capacity which may allow connection of additional load. Visualisation of secondary substation load profiles type also provides the distribution planner with visibility of opportunities for power transfers between adjacent secondary substations. New low carbon profiles such as those associated with electric vehicles can be considered.

Load profile determination

Load profiles at each secondary transformer have been determined on a daily basis. As expected, substation load profiles vary seasonally and between weekends and weekdays. Some substations have highly variable profiles, whilst others are more stable.

Broadly, there are five kinds of existing load profile:

- **Residential**: rising from a minimal value through the night to a peak between 6am and 9am before dipping to a mid-level through the day, rising from mid-afternoon to a high level during the evening, and finally dropping again through the night.
- **Commercial**: A sustained peak value through the working day from around 8am through to around 6pm, and a sustained base load value outside of these hours.
- **Mix**: A profile which has both commercial and residential characteristics.
- **Night**: A high load during the night.
- **Industrial**: A flat load profile.

Transformers with very low utilisation do not classify well and any transformer with a maximum load (over previous 12 months) less than 25% of the transformer capacity is used as a cut off below which the load profile is not classified.

The ½ hour average Apparent Power (kVA) of the secondary substations with RTUs for 2010 and 2011 were analysed to establish a library of load profiles. The kVA data is normalised to allow for a focus on the shape of the usage pattern to enable comparison of the consumption habits from two households or commercial areas of different sizes.

The load profiles of flat loads, which are typically industrial, are excluded from the clustering, but included at a later stage in the visualisation.

Clustering method:

The K-means method was used to determine a set of daily load profiles. The K-means method uses Euclidean distance calculated for centre c = ($c_1; c_2; \ldots; c_n$) and point p = ($p_1; p_2; \ldots; p_n$) as

$$distance = \sqrt{\sum_i (c_i - p_i)^2}$$

Each data point is assigned to one of the cluster centre locations by selecting the centre that is nearest to that data point. Once all the data points are assigned, each collection of points is considered, the new centre of the allocated points is calculated and the centre for that cluster is reassigned. The points are then reallocated to their new nearest centre and the algorithm continues as before until no changes are made to the allocations of points for an iteration. The K-means algorithm returns the n centres of the clusters (called centroids), and the classification of each point in the cluster it belongs to.

The method is highly dependent on the initial random allocation of cluster centres. The k-means algorithm can be run multiple times to reduce this effect.

Optimisation

The optimal number of clusters depends on the shapes and the number of the points on which the algorithm is applied. A good clustering scheme will create clusters where the members of a particular cluster are closely grouped, but where the different clusters are well separated. The method used to determine the optimal number of clusters uses a measure assessing the quality of the clusters generated known as the Mean Index Adequacy (MIA)

$$MIA = \sqrt{\frac{1}{K}\sum_{k=1}^{K} d^2(r^{(k)}, C^{(k)})}$$

Where K is the number of clusters defined, $r^{(k)}$is one of the load profiles assigned to cluster number k, and $C^{(k)}$is the centroid of the cluster k.

The MIA assesses how the different points of the clusters are regrouped around their centroids. A low value of MIA indicates more compact clusters. Using this measure the optimum number of clusters was determined to be between 10 and 15. The resulting 15 load profiles are shown in figure 14. A range of automatically generated profiles from residential, commercial and loads with high night demand can be seen. For simplicity, an integer number known as "Load Type" is allocated to each load profile which is stored in the application database as a Load Profile Library. Each actual secondary substation daily load profile is then analysed by the application and matched against the set of common load profiles in the library. The profiles can be visualised on a geographical map or obtained in a report. In this way, changes in usage patterns over time can be easily spotted.

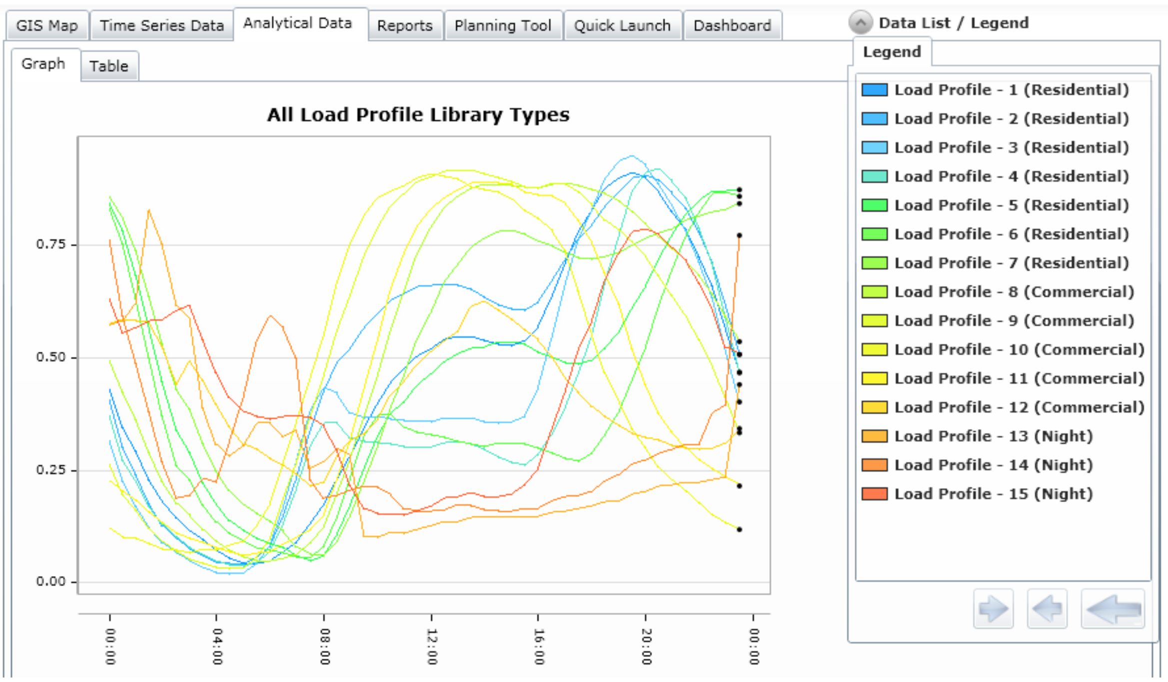


Figure 14: The Load Profile Library

The DNV application can plot the load profiles on the GIS map together with the size of the pin representing a second parameter such as utilisation (Figure 15).

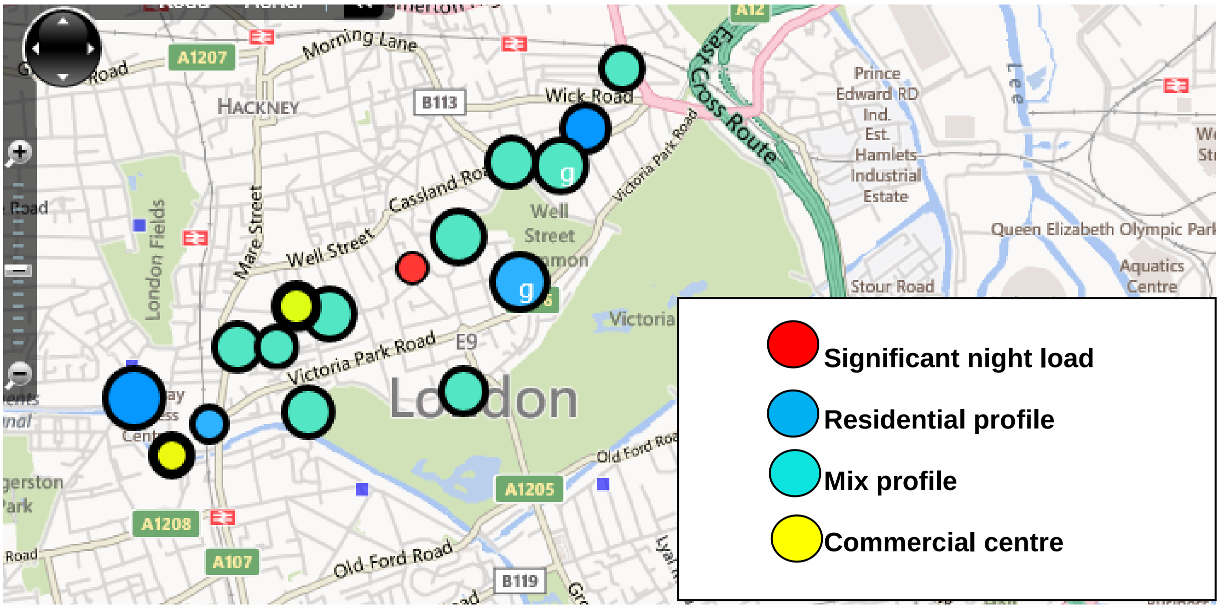


Figure 15: Load Profile GIS visualisation

Due to the variability of the load profiles the visualisation application was developed to provide an indication of the variability of the profile over time as a colour band at the edge of the pin.

A time slider can be used to view the variation of the profile over time, or the mode profile can be plotted. A time series chart showing the variation of profile over time can be obtained as well as a report detailing the correlation of each load profile so emerging profiles can be seen.

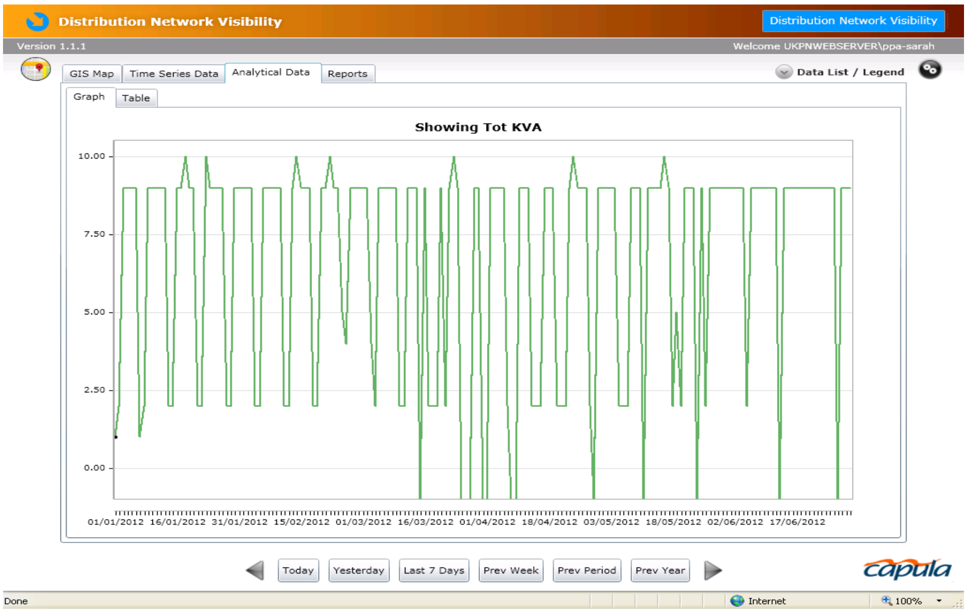


Figure 16: Graphical view of change in load profile:
Types 9 & 10 commercial (weekdays); type 2 residential (weekends)

Spare capacity to residential, commercial and mixed loads is calculated by the DNV application for each transformer. In order to meet a new load connection, such as a residential development, the application adds the new load profile to the existing transformer maximum demand profile and compares the resulting profile with the transformer utilisation. This is considered on a seasonal basis so air conditioning and heating load can be assessed. Transfer capacity for each substation to adjacent substations is also determined. Benefits 4.1 and 4.2 in appendix F detail this further.

5.5. Load flow tools

Traditionally, load flow analysis has been undertaken by System Planners using the maximum and minimum system load conditions to check circuit loading and voltage profiles. In LPN, the Primary substation feeder currents and the RTU measurements were used to allocate loads either at secondary substations or by distributing the loads throughout the LV system. Half hourly metered customer data could be used to refine the model in some cases. At 11 kV the study would traditionally be undertaken using a single phase representation of a three phase system.

If power flow tools are to be used in real time to make operational decisions, the variation of demand over time must be represented for all three phases.

GE Distribution Power Flow (DPF)

Some load flow tools allow for 24 hour load profile data which may be set by day of week and season. This is the basis of the DPF which expects the load profile data to be set up for each secondary substation whilst DPlan uses customer profiles. DPF allows for 3 phase 11 kV network modelling and uses the existing PowerOn topology. Circuit and transformer impedances can be imported from DINIS.

The main concern with the methodology of the DPF tool is the dependency of the tool on generalised load profile data. As the UK migrates to low carbon distribution networks, it is expected that significant changes will occur to the load due to new generation, load types and controls, e.g. distributed generation, demand side management, electric space heating, electric vehicles and energy storage, all of which will create load profiles on circuits that are very different from the present day domestic/commercial profiles. It is evident from the work undertaken by the DNV project that daily and weekly load profiles can be very different in adjacent substations and can and do change very rapidly.

The LPN system has measured load data at a significant number of secondary substations which means actual data can be used at these locations, requiring load profiles to be used at the remaining substations. A trial was set up on a standalone PowerOn system using the historical time-series half hour data from PI and 10 minute Powersense readings. The DPF load allocation algorithm used the measured primary feeder current, other HV monitoring devices installed on the Carslake Road feeders, RTU secondary substation data and where RTU data was not available, the secondary substation load profiles to determine the power flow in the 11 kV circuits.

The accuracy of the load flow produced by the DPF application was dependent on the number of monitored secondary substations and the accuracy of the load profile data for the non-monitored substations. The conclusion from the trial was that if the DPF application was to be used by the Control Engineers it would be necessary to use real time data from the RTUs. However issues that require addressing before a full roll out to the LPN system is considered are:

- Development of a load forecaster for the secondary substations with RTU data, in order to undertake a proposed switching operation study. This would allow the Control Engineers to plan outages with confidence. The load forecaster should allow for substituting of data following an RTU or communications failure, and enable feeder loads to be used to determine load profiles for non-monitored substations.

- The tool currently does not allow negative loads. It is likely that power will flow from the LV system to the HV system in future as embedded generation increases and this can already occurs under some fault conditions on the interconnected LV networks.
- The tool currently does not allow for meshed networks. Some of the 11 kV LPN networks are run in a meshed operation, particularly in the LV interconnected areas.
- Consideration should be given to the use of the measured secondary voltage in the power flow analysis, and the inclusion and use of iron losses in the losses calculation.

CGI DPlan

The present version of CGI DPlan software is predominantly a planning tool focused on LV distribution networks which can combine the geographic based data such as metering point data together with measured data. At present, DPlan has no capability for real-time unbalanced power flow at 11 kV.

The CGI DPlan Distribution Power Flow package was evaluated for both HV and LV Network models and data was obtained from the RTUs and Powersense sensors. DPlan requires quarter-of-an-hour data intervals so adjustments or averages were used to import Powersense and RTU data into the model.

The model used the MPAN metered data collected every half hour from large customers and longer intervals from smaller customers such as residential households. Comparison between metered data and real time measurements showed significant mismatch between results that is attributed to the use of standard load profiles, errors in the connection of services to the correct part of the network, and of the complexity to set up and manage the necessary LV network and input data.

HV connectivity and impedance of the model was obtained from DINIS. As there is no phase information available with metering data, it is assumed that the model is a 3 phase balanced system which it is evident from real time substation measurements, is not an accurate assumption and does not allow the benefits of the LV unbalanced power flow to be realised. If the loads were allocated on a per-phase basis at LV, DPlan would determine a three phase LV power flow.

MPAN load data was available for the large customers (HH=Half Hourly) on a half hourly basis and was used to allocate load to each applicable MPAN. All small customers (NHH =Non Half Hourly) were allocated a profile class in the electricity market. The profile classes have a profile for each day. These profiles together with the annual consumption were used to allocate load to each customer. The topology of the HV network was created from an extract from DINIS to identify the network components and impedances.

In order to demonstrate meshed load flow in DPlan it was necessary to create a work-around solution. This is due to the complexity of allocating load in a meshed LV network such that a match was achieved between the measured RTU data, advanced monitoring sensor data and the model. In order to match the power flow results produced by DPlan with the measured values from the Primary Feeder, Powersense and RTU values, a slack MPAN was allocated to the LV side of each secondary substation transformer. It was assumed that each Slack MPAN only affected the flows at the substation at which it was connected. Several iterations of the model were undertaken to achieve the best possible match. The difference at peak demand in power flow using customer metered data and data adjusted for measurement, ranges from 28% below reality to 38% above reality.

The key findings of the DPlan trial are:

- In order to get the LV DPlan model right, a significant amount of time and effort is required to ensure correct allocation of the load on the LV feeders.
- Three phase metering data is not reported by phase, and the power factor if reported is unused. Consequently, at present, a balanced three phase unity power factor loading model is used even though the model is capable of LV unbalanced studies.
- If DPlan is to be used for meshed LV analysis, a load allocation technique is required within the tool to match both phase unbalance and power factor to measured real time data. It is understood that this is something CGI are addressing.
- Discrepancies in the order of 30 - 40% can exist between the load flow resulting from the measured from RTUs/Powersense data, and the load flow using the MPAN metering data.
- PI data validation is needed before it is used in a real time load flow, i.e. the data validation must be real time.
- Following HV outages applied to the model, it was observed that the load changed reasonably. Further studies to confirm it matches with real time measurement during actual switching are recommended as part of any future network modelling validation.
- The usability, reporting and visualisation features of the tool will need detailed consideration once the basic operations have been verified.
- Systems to automatically and routinely check and report the status of the network model and its ability to converge to credible results are also recommended.

Summary

At this time, it is not economic to deploy a load-flow tool for use in the control room. Of the two approaches, however, the use of real-time substation data based on the capabilities of the secondary substation RTUs seems more fruitful.

5.6. RTU Upgrade

As stated in section 4, the existing secondary RTUs in LPN were only communicating 4 out of a total of 15 possible analogue measurements. To facilitate an initial assessment of the advantages of making all 15 measurements available, a sample of ~500 RTUs were upgraded to make all the analogues available.

This trial sample of measurements was available for use in the DNV application, and other tools trialled to determine the additional benefits that could be realised from the availability of the extra data. This was used to successfully justify to the relevant parties within UK Power Networks that the remaining ~9000 RTUs should be upgraded.

The original four available measurements were:

- Total kVA for Transformer
- Red Phase Voltage
- Power Factor
- Substation Ambient Temperature

The additional measurements and associated benefits are explained below:

Analogue Measurements	Benefits
3 x Phase Currents and Neutral Current	**Validation of RTU data:** Having access to three-phase current measurements highlighted a significant difference in the currents at several sites. Upon investigation, it was found that there were high impedance connections on one set of parallel cables between the transformer and the LV board. This meant that the current was not being shared equally between the sets of cables. Due to the fact that the current is only measured in one set of cables and doubled to derive total current, which in turn is used to calculate the kVA, hence this can lead to very inaccurate results being reported. The total kVA RTU values are used extensively by various teams within the business and it is important to verify its accuracy. **Improved quality of Supply:** In interconnected areas it is common for supplies not to be interrupted following a fuse failure. Visibility of the three phase currents is expected to help identify areas where a fuse has blown and needs to be replaced. It could also lead to the identification of open-circuit faults that do not cause immediate loss of supply until another fault occurs on the interconnected network. **Reduction of Losses:** Imbalance in the currents between phases mean cables cannot be used to their full potential and can lead to unnecessary overheating. Identification of areas with consistent abnormal loading throughout the year will highlight the need for consideration of balancing the load on the transformers and reducing the neutral current which will reduce system losses. **Maximise the utilisation of assets:** Loads are expected to increase dramatically towards the end of the ED1 period due to the uptake of Low Carbon Technologies. Making best use of existing assets will help ensure costs are kept efficient and will help to avoid any problems arising from cables being more heavily utilised.
3 x Phase Voltages	**Voltages outside of statutory limits:** The increase in connection of single phase generation is expected to result in increased voltage imbalance and voltage rises. Through its dashboard functionality, the DNV application is able to detect these issues automatically and having access to all three phase voltages ensures all voltage issues can be detected irrespective of which phase they occur on. The ability to detect and fix these issues early is expected to reduce the number of customer inquiries due to voltage issues. **Metal theft detection:** Abnormal voltages were identified at a

	particular site using the DNV application and prompted a site investigation. It was found that the earth bonding had been stolen and the site left unsecured. This potentially dangerous situation was identified and rectified by having access to all three phase currents and use of the DNV application. Please see appendix F for more information.
Real and Reactive Power	**Validation of RTU data**: Having access to S, P and Q readings has highlighted some sites where $S^2 \neq P^2 + Q^2$ indicating that there is an error with the physical connection of the RTU CTs or voltage connections. This can be addressed and ensure correct data is provided by the RTUs for use by the teams within the business. **Improved visibility of generation**: Visibility of P and Q provides information about direction of real and reactive power flow and information about embedded generation. Algorithms have been developed which determine step changes in P (typically > 50 kW) and which identify switching of load and generation.
Total Harmonic Distortion (THD) for each Phase	**Low Carbon Technologies:** With the increase of small scale embedded generation and electronically controlled loads such as electric vehicles and heat pumps, harmonics on the LV network could increase. Identifying and reacting to cases of high harmonic distortion could help to reduce damage to assets and increase their operational life.

Table 8: Additional Analogues and associated benefits

5.7. Monitoring Considerations

The sensor trials undertaken in this project have tested a variety of non-invasive solutions that can in most cases be installed without customer outages. These sensors enable visibility of accurate complex power measurement of HV circuits and transformers using a sparse system of measurements. It has been shown that knowledge of network and transformer voltages and power flow can be achieved with limited monitoring on both the HV and LV system combined with use of a star/delta sequence component transform (SCT).There are a range of suitable monitoring devices available and to reach an optimal solution the configuration should take into account financial factors including capital, installation and maintenance costs as well as the technical performance of the network and not just the individual site.

5.7.1 Urban networks

For urban networks with existing RTUs each feeder can be divided into measurement zones, where the boundary of each zone has an HV sensor or open point.

The optimal measurement of a given network is defined by the following rule:

> *Within each zone, if n is the total number of substations, the number of substations requiring HV or LV measurement should be n-1.*

LV measurement can be from the HV ring circuits, from transformer tails, from transformer temperature or from each of the outgoing LV feeders depending on the access available and the LV granularity required.

LV power flow was considered for an LV interconnected area using substation monitoring devices only. This highlighted that in order to achieve an accurate picture of LV power flow monitoring devices are also needed at key locations through the LV system. As this is being trialled in other projects, it is not considered further here.

5.7.2 Rural networks

The following suggested guidance has been determined from the pilot system for the placement of monitoring equipment:

- Nominal HV balanced feeder current and substation busbar voltage.
- HV phase current and voltage at each root of each main branch with more than 4 equivalent 3 phase transformers from the main feeders.
- HV voltages and currents at key normal open points of the main branches.
- HV voltages at near extremes of the main branches and minor branches with more than 4 equivalent 3 phase transformers (normally by LV SCT).
- No more than 9 equivalent 3 phase transformers between monitoring points.
- Transformer temperature monitoring can be used to determine profiles of larger transformers and provides fast low cost load estimation to fill monitoring zone gaps.
- Additional monitoring of heavily loaded transformers or HV supplies may also be warranted.

5.7.3 Monitoring Hardware Solutions

This section describes appropriate hardware solutions identified for typical network situations.

Three core HV cables

Powersense optical phase sensors have been successfully used within HV end boxes and externally on PICAS, plain lead and lead sheathed joints, but is not suited for steel wire or tape armoured cables. Cutting back armours is a viable approach for some HV PILSWA/S cable sites but this approach is not suited where cable boxes are close to the ground where there is no space for armours to be removed and re-terminated in situ.

In-situ alignment and calibration can be undertaken using LV measurements, the transformer nameplate data and the SCT together with an HV switching sequence.

Where removal of the cable armours is not a practical solution this points to the use of a Multi-core Cable Ring sensors on 3 (or 4) core armoured cables and to contactless voltage scavenging sensors on transformer tails for fast simple live installations and commissioning with inherent directional power flow monitoring.

Single Core HV cables

Conventional split core CTs have been successful used on Triplex HV cable where the cores can be separated sufficiently to allow a set of three CTs to be fitted externally. Powersense optical phase sensors have been successfully used externally on HV Triplex cables in situations where the cores are tightly packed together and cannot be separated.

HV Overhead lines

The unique proposition of the Powersense optical OHL Combi sensors is that they can be installed onto live 11kV and 33 kV systems to provide not only current but real and reactive power, direction, phase voltage and directional fault passage indication.

HV OHL Line and Phase Voltage Monitoring: The separate development of a star delta sequence component transform means the that the line and phase voltages of HV OHL can be directly calculated in real time from LV current and voltage measurement from pole mounted transformers and fixed transformer data. This approach allows the use of Powersense OHL optical current sensors to measure real and reactive power, direction, phase and line voltage and directional fault passage indication. This eliminates the need for, and asset risks presented by, high voltage resistance dividing sensors hung from lines as the connections to the Powersense sensors are fibre optic cables only.

Secondary Substations

Straightforward transformer tail or LV way monitoring with CTs or Rogowski coils are not considered in detail here as there are now many solutions on the market. However LV/HV monitoring and for problematic installations there are alternative technologies with low installation resource approaches:

- **LV Boards and Cabinets**: Difficulties and time considerations associated with installation of LV Board current and voltage sensors point to the advantage of using wire-free contactless V & I scavenging sensors for fast simple live installation.
- **Top entry LV Boards** and some small dimension cabinets using 4/c armoured LV cables present specific challenges for sensor installation and point to the advantage of Multi core Cable Ring sensors located away from the LV Board and contactless voltage scavenging sensors on transformer tails for fast simple live installations with inherent directional power flow monitoring.
- **Package/Unit substations** can present specific difficulties in monitoring transformer LV currents and a variety of options have been successfully demonstrated including HV ring circuit subtraction which combined within iterative Sequence Component Transforms have been used to obtain a full set of HV and LV phase voltage current and directional power measurement.
- **Pole Mounted Transformers** LV 3 phase Voltage and current monitoring can be used with the SCT to determine HV volts at or near the end of a spur line or near a normal open point.
- **Distribution transformers temperature monitoring.** The loading profiles of transformers of all types can be quickly and easily monitored using wireless magnetic temperature sensors combined with ambient weather, s/s type and transformer size to produce transformer load utilisation profiles.

5.7.4 Efficient Monitoring Deployment

Combinations of HV or LV monitoring devices can be used to provide virtual monitoring in substations where there is no transformer monitoring and to provide full three phase LV time series voltage, unbalanced currents and directional power measurements.

Virtual measurements in a substation with no hardware monitoring can be calculated by dividing the system into a series of measurement zones. In a complex urban area the aim is to achieve 100%

coverage of the HV circuits and transformers with the optimal configuration of a minimal number of new devices installed resulting in real or "virtual" measurements for all nodes. For rural networks it is unlikely to be cost effective to achieve such comprehensive coverage and monitoring zones can be created in which the power flow in circuits and small groups of transformers can be determined.

Careful selection of networks, simple design rules and value engineering all have their place in reducing the costs of installation and ownership, but for the time being the overall costs per circuit mean that that application of HV circuit and transformer monitoring is likely to be gradual and based on specific network and load or generation growth needs rather than an extensive independent roll-out.

Options to reduce costs and to increase benefits can include incorporating relevant monitoring aspects with remote control and automation scheme upgrades and to explore addition functionality such as automated fault and incipient fault detection and location.

5.7.5 Communications

All the distribution monitoring undertaken as part of this project has used wireless systems. M2M multi-network SIM cards that automatically select the best available signal plus careful positioning of aerial and in some cases use of wireless repeaters have meant that reliable communications from sites as diverse as deep inside steel framed buildings in Central London though rural forested countryside in East Sussex to the Brighton Lanes have all been successfully achieved. Remote monitoring and visibility of signal strength and alarming of low signal level and missing data is recommended.

5.7.6 Frequency of Sampling and Averaging Periods

The monitoring systems used in DNV have generally been used in fixed 10 or 30 minute reporting periods which has proved adequate for most studies to-date. The following provisional assessment of the desirable capabilities and uses of variable sampling are provided but should be adapted in the light of deployment of systems that are capable of both autonomously and on request changing minimum and maximum reporting rates. However in order to commission and validate monitoring of complex measurement and zones it is desirable to be able to select the use of synchronized monitoring times. For DNV we have successfully used 10 and 30 min values for the current pilot implementations to analyse measurements which are all tagged with synchronized timestamps and experienced difficulties when it has been necessary to used interpolated data.

Most modern monitoring systems do not use fixed sample reporting periods but rather report values only when they change significantly in order to conserve storage and communication resources, with a dead-band mechanism often being used. This approach ensures that the system records a reasonable estimate of real-time values with a blocking time used to set the minimum update period and a maximum age used to set the maximum update period.

Measurements should capable of being stored locally at the monitoring frequency and retrieved at a requested sample rate at a later date on request.

System Events

If system events, faults and fluctuations are to be observed and managed, continuous sampling at 1 second intervals or better using a local system to make intelligent decisions about the level of variance of the data and the selection of the storage period is required. During the real time management of faults and restoration sequences and to enable prioritisation of actions to avoid cascades, these readings would be sent at a sample rate of 1, 5 or 10 minutes. Ideally this sample rate and the period of time for which this rate was used would be remotely specifiable.

Use of a disturbance recorder collecting 5 seconds of data at high resolution of 4 kHz or above with settable trigger thresholds and pre and post trigger point criteria for three phase voltages and currents as well as calculated values such as out of balance/neutral, I2t, Real and Reactive power, power factor and sequence components would provide information to assist fault management in interconnected areas, information about LV faults including distance to fault, visualisation of incipient faults, voltage dips due to HV faults and HV and LV incipient faults.

Alarms

Alarm limits can be used to report the amplitudes and duration of events such as lows or highs, sags, swells overloads, high harmonics etc. as well as of calculated quantities. They could be used to trigger more intense levels of reporting frequency at a location or the expansion of reporting for example to report on individual harmonics.

Generation and Disturbing Loads

For the detection and analysis of fluctuations from intermittent generation and disturbing loads causing flicker, the ability to select periods at 1 second sampling would be valuable. For the detection and estimation of capacity of the operation of distributed generation and switching of larger point loads then sampling minimum periods of 5 or 10 minutes may be appropriate. The application of these techniques to intermittent generation such as PV and wind is under separate development but is likely to need smaller sampling periods.

Network Planning

Although the secondary substation voltage and current data varies instantaneously with demand, historic half hourly average data is of value when considering system planning and asset performance as this matches cable, transformer and switchgear thermal demand timescales. For overhead lines a 5 or 10 minute reporting period would be appropriate once currents have exceeded specified thresholds. These sampling rates could be varied with a dynamic rating system.

Where the direction of real or reactive power flows alternate at a monitoring point absolute maximum and minimum figures are required to aid understanding of the power flow as well as average values (10 min or 30 min).

Functional Requirements	Monitoring requirements
Observation and management of system events, faults and fluctuations	Continuous sampling at 1 second intervals or better. Data to control tool at 1 min, 5 min or 10 min as remotely specified. Local system to make intelligent decisions regarding variance of the data and storage period. Disturbance recorder 5 seconds of data, resolution > 4 kHz, settable trigger threshold

	and pre and post trigger point criteria Use of alarm limits
Detection and management of flicker	1 second sampling
System planning and asset management	30 minute averages (absolute max and min where power flow changes direction)
Detection and analysis of distributed generation	5 to 10 minutes or less for smaller generation
Overhead lines	5 to 10 minutes once current exceeded threshold

Table 9: Monitoring requirements to achieve the functionalities.

5.8. Dynamic rating of assets

It was identified in the progress of the project that the data available was sufficient to assess the possibility of dynamically rating assets based on recent historic loading and environmental conditions. Although dynamic ratings are possible for many types of asset, it was decided to perform a proof of concept study on distribution transformers due to the fact that the independent RTU setup (described in section 4.4.3) allowed for a temperature sensor to be fitted to the transformer to develop and validate a dynamic rating algorithm.

The first step in the study was to build a model that predicts the temperature of the housing of the transformer, based on readings from the RTUs and other external data sources such as weather data. Figure 15 below shows the correlation between the measured temperature and the temperature predicted by the model.

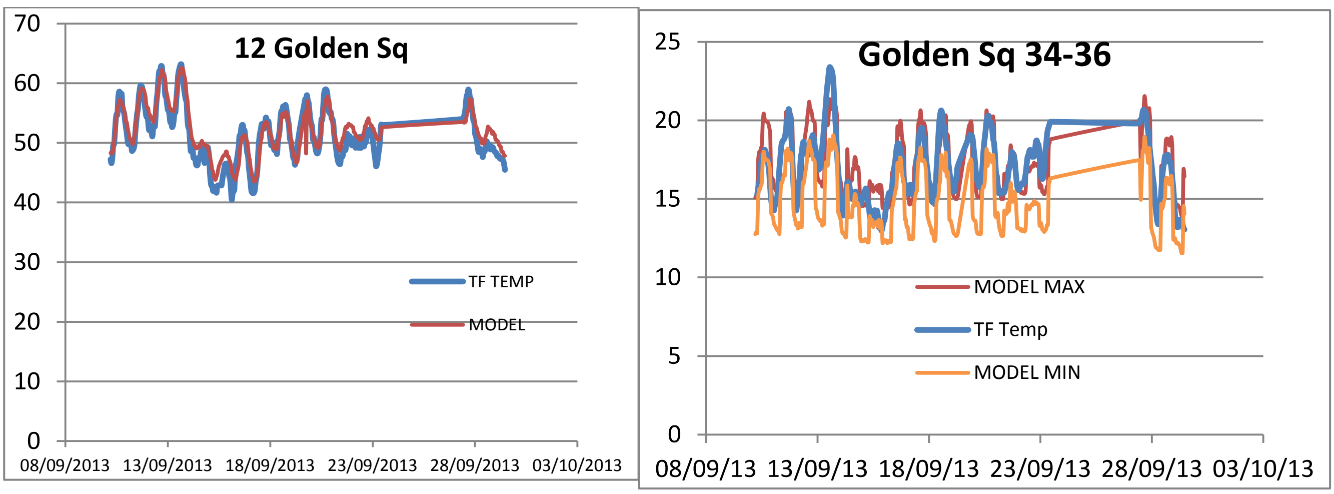


Figure 15: Comparison of transformer housing temperature predicted by model and measured transformer housing temperature of two substations, (y-axis is the temperature, in ˚C).

The next stage is to calculate the transformer hot spot temperature, as this is the key indicator of the rate of loss of life of the transformer. Finally, a dynamic rating can be assigned to a transformer based on the current utilisation, and the amount of time the higher rating will be utilised.

This dynamic rating also depends on the rate of loss of life that can be accepted. An example of the results of this dynamic rating is shown on Figure 16. This considers an acceptable loss of life, which is the maximum relative deviation between the cumulated loss of life and the normal loss of life, e, as 5%.

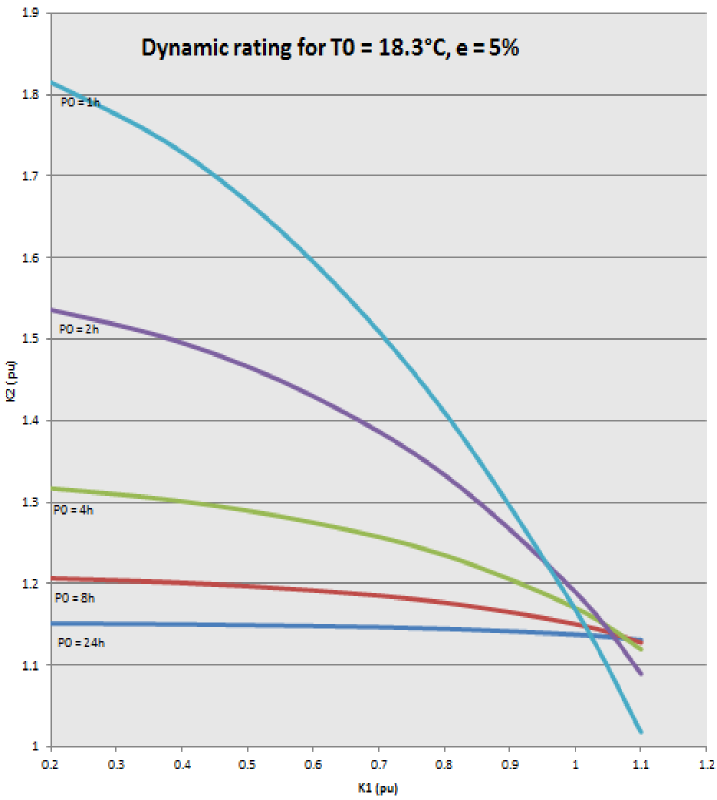


Figure 16: Allowed operating time for transformer where K1 is the initial load factor and K2 is the new load factor.

This work is described in much more detail in a report published by PPA Energy (see appendix E). This study has proved the concept of dynamically rating distribution transformers, and made initial steps to validate the method. Further work is required to validate the process with a wider range of situations and a larger sample, as well as to integrate the solution into existing systems so that it can deliver benefits.

6. Performance compared with project aims, objectives and success criteria

The performance against the original aims and objectives is summarised below:

Project Aims and Objectives	Did the Project meet this objective?	Comments
The main objective of the project will be to demonstrate the business benefits of the smart collection, utilisation and visualisation of existing data (i.e. analogues available from RTUs). Three concrete examples of where the data is potentially of use to the DNO are listed below.	✓	A set of business requirements were developed in consultation with the relevant business unit within UK Power Networks. These benefits were then demonstrated by developing a visualisation tool and using load flow tools.
1) Identification of localised load growth and changes in load patterns, in order to determine a wide range of options early on.	✓	An algorithm was developed and implemented in the DNV application to categorise the load profile on secondary substations. The application also allows users to see how a substation's profile is changing over time (see section 5.4). A feature has also been implemented to identify long-term load growth patterns at secondary substations. These functions make use of the historical data available which often goes back 5 years or more. Examples of both of these features are included in Appendix F, benefit 4.2.
2) Understanding where Distributed Generation (DG) is masking load, which can have an impact on planning, outage calculations and restoration actions after an outage.	✓	Data from connected generation records is integrated in the DNV application and associated with the assets it is connected to. This allows the presence of generation to be identified and the potentially hidden demand can be added to various graphs generated by the tool. A practical example of this is given in Appendix F, benefit 4.1. Initial work was also done to identify embedded generation from automatically analysing step-changes in network monitoring data waveforms and recommendations made for how this could be improved and implemented.
3) Understanding whether traditional assumptions about the duty of assets (e.g. tap changers, transformers, etc.) are accurate.	✓	Load profiling and growth analysis techniques for transformers were developed as described above (see section 5.4). A feature was also implemented which calculates and displays a transformer's

		average daily load profile based on a year of historical data. This gives a much clearer insight into the duty of assets than traditional assumptions. A case study making use of this feature can be found in appendix F, benefit 4.1. Features were developed in the DNV application to analyse frequency of tap changes allowing identification of changes in behaviour (see Appendix F, benefit 5.2).
The project will establish optimum levels of distribution network monitoring and frequency of sampling for specific scenarios and applications.	✓	The data requirements for each functionality that delivers benefits has been determined, including what data needs to be measured, at what frequency and what supporting data is needed (e.g. asset rating). This can be found in section 5.7.
It will also trial various optical sensors that could potentially be used to provide detailed monitoring of sites with no RTUs.	✓	Optical sensors were trialled and their limitations have been identified and documented in appendix B. Following this, alternative sensors have been assessed for their suitability to complement the capabilities of optical sensors to provide detailed monitoring.
The first phase of the project will prioritise areas of interest to stakeholders, develop initial mock ups and validate assumptions.	✓	This initial work was carried out and a proof of concept tool was developed. It was important in identifying, in detail, areas of the business that could benefit from visualisation of network data, and also what the possibilities and limitations of the data were.
The second phase will concentrate on the collection of additional analogues into the historian, validation of the accuracy of sensor readings and implementation of standalone solutions (with relatively few touch-points on our live systems). We are likely to be able to report at the first LCNF annual conference which tools we are planning to take forward into the second phase of the project.	✓	500 RTUs were initially upgraded to collect an additional 11 analogues. The number of upgraded RTUs was increased to 9,885 by the end of the project. Additional data sources that could add value when combined with network data were identified and a first version of the DNV application was released.
The third phase of the project will develop and integrate some of the tools demonstrated as part of the	✓	Building on the work done in the previous phases, the various data sources were integrated into a single solution which has

second phase into operational systems, and will therefore require more resources.		now been adopted into UK Power Networks as a business as usual application and is being used by multiple business units.

Table 10: Performance against objectives

The performance against the original success criteria is summarised below:

Success Criteria	Did the Project meet this Success Criteria?	Comments
Validate the RTU analogue readings which are not currently stored	✓	The RTUs and their CTs were validated at Southampton University HV laboratory and the National Renewable Energy Centre. The monitoring trials have compared RTU readings with other data sets and correlation achieved. The ability of the DNV application to produce system-wide reports means that some transducer errors have been identified and an RTU health and PI data report run each night alerts the business to RTU issues. Data quality algorithms have been used to give the users the opportunity to undertake analysis with improved data quality.
Evaluate the suitability of optical sensors for sites which are not equipped with RTUs	✓	Powersense optical sensors have been trialled with the LPN and SPN networks on cables and overhead lines. Where necessary, other sensors have also been trialled resulting in a selection of sensors to meet different requirements and for different installation challenges. The results can be found in appendix B.
Store the data in the historian in a way that is scalable to a larger roll-out	✓	The PI historian was upgraded and is able to store the additional analogue data from all LPN RTUs.
Work with stakeholders to identify particular applications for which the data will be of high value	✓	Benefits cases were developed following engagement with the Control, Connections and Asset Management business units.
Prioritise amongst these and develop business applications for high priority opportunities	✓	The DNV application has been developed and is in use by the business to meet a variety of benefits associated with the historical use of

		data in respect to Connections and Asset Management. Details of the application's features are in appendix D.
Work with stakeholders to identify particular applications where the data will add little extra value, and report these as lessons learned	✓	These areas were identified as part of the same process carried out to identify areas of high value. Some examples include: when the SCADA system is set to alert Control engineers to ensure prompt action is taken, or where a spreadsheet had previously been developed to use PI data. The DNV application did not replicate processes.
Recommend a future monitoring strategy based on the results	✓	A variety of sensors have been trialled with the LPN and SPN networks resulting in a number of monitoring considerations for urban and rural areas. These findings are detailed in section 5.7 and are also informed by the data requirements that were identified to enable the features of the tools to be developed and demonstrated.

Table 11: Performance against success criteria.

7. Required modifications to the planned approach during the Project

7.1. RTU advanced features

The original intention was to explore and utilise the advanced features of the RTUs on a large sample of live RTUs. However, due to concerns in respect of the potential for compromising operational SCADA or communication systems, and in diverting UK Power Networks' SCADA systems resources from other projects, an offline trial was carried out. Initially 10 RTUs were set up to operate and report to an independent system, followed by a further 17 units. Events and individual harmonic data were collected during these field trials and the optimisation of a wide variety of configuration settings was explored.

Whilst we were aware at the start of the project that UK Power Networks had not utilised these latent features, as we worked with the manufacturer it became clear that few if any of their clients had used this feature in this particular generation of RTUs. As a result, the project had to expend more time and effort than was originally anticipated accessing the advanced features and learning how they could be used. In practice it was easier and quicker to operate on and make changes to the small scale and independent system than would have been possible though larger scale trials using production systems. This flexibility allowed the applications of the features to be explored more easily although at the same time limited the ability to demonstrate them on a network-wide scale and, although identified, the benefits of this were not demonstrated.

Unfortunately only a limited number of network events were captured and that the ambition of recognising incipient faults and categorising fault events was not achieved. However, a better understanding of the capabilities and limitations of the advanced features was developed which contributed to the learning of the project.

UK Power Networks currently specifies these advanced features as an option in its RTU specification used to tender for new devices. This allows us to continue to purchase the features where it is justified and of little additional cost. At this time we would be unlikely to integrate the feature into all RTUs, or necessarily enable the feature to report back automatically onto the SCADA network.

7.2. Real time power flow tools

Following discussions with the Network Control team, it was concluded that the introduction of another tool in the control environment would not be acceptable. During the project, the LPN control system migrated to GE PowerOn which has a power flow add on module, DPF (Distribution Power Flow). A trial of DPF was undertaken with GE on a four ring 11 kV feeder using data from the 11kV feeders, secondary RTUs and Powersense devices. This trial identified areas that were preventing the tool delivering the anticipated benefits. Recommendations were made in respect of additions that would improve the DPF tool to enable realisation of the identified benefits, however it has not been possible to progress this further due to time constraints and current development costs being prohibitive.

To further explore the potential benefits of load flow analysis a trial was also undertaken using DPlan which is a load flow package being considered by the Distribution Planning team. The DPlan tool implements some of the features which were identified as needing development in DPF which allowed the analysis to be taken further. This trial involved both the 11kV and LV systems for a meshed network. The trial identified modifications to the tool which would be necessary to use the tool in real time. However, as DPlan could not undertake a three-phase 11kV load flow, a custom built demonstration tool was used to demonstrate the benefits of the monitoring and the requirements for advanced load flow and visualisation tools.

The fact that a power flow tool could not be implemented in the current control system environment limited the opportunity to test the functionality offered by such tools in a genuine control-room environment. Consequently the benefits of these tools were not demonstrated in an operational context and this has been reflected in the expected benefits as described in section 8. The project evaluated two commercially available load flow tools and the improvements that can be achieved over traditional methods have been identified and documented in section 5.5. Despite the reduction in expected benefits, these findings support the project success criterion of identifying particular applications where data will add little extra value. In this case the cost and difficulties of integrating this use of data limit the value of such an application at this time.

7.3. Powersense measurements

The Powersense optical sensors were found to be suitable for use inside cable end boxes and externally on a range of unarmoured cables but unsatisfactory to work with steel armoured cables. Workarounds and/or other devices were used to create a full toolkit of non-invasive monitoring system for most LV - 33kV situations that can be used without interrupting customer supplies. The benefits of monitoring were demonstrated using a custom-built demonstration tool and recommendations for a monitoring strategy and pilot demonstrations made.

This change in approach did not impact the performance against the objectives and success criteria, and allowed for a much broader investigation of possible monitoring solutions and approaches. Further details of this can be found in Appendix B and the results discussed in section 5.7.

7.4. Additional analogues

The development and testing required to remotely upgrade the existing RTUs to report the new analogue values to PI was significantly greater than that originally estimated. Part way through the project we were able to undertake a manual remote upgrade of about 500 RTUs, but the remaining upgrades happened later than first planned due to the length of time taken for the automated upgrading system to be developed and tested. The upgrade of the 500 RTUs allowed all functionalities to be developed and demonstrated on selected areas of networks and these functionalities are now available for all RTUs since a total of 9,885 have been upgraded.

The manual upgrade minimised the impact on the learning of the project and the data from the 500 RTUs was sufficient to demonstrate the defined benefits and ensured there was no impact on the project achieving the objectives or success criteria. These functionalities are now available for all RTUs since a total of 9,885 have been upgraded.

8. Significant variance in expected costs and benefits

8.1. Project cost and Variance

	Planned	Actual	Difference	% Difference
Project Management	**£385,127**	**£254,514**	**-£130,613**	**-34%**
Of which UK Power Networks	£230,780	£61,357	-£169,423	-73%
Of which PPA Energy	£40,947	£79,757	+£38,810	+95%
Of which Capula	£113,400	£113,400	£0	0%
Visualisation tools development	**£751,060**	**£933,435**	**+£182,375**	**+24%**
Of which Capula	£583,309	£636,533	+£53,225	+9%
Of which PPA Energy	£167,752	£296,902	+£129,150	+77%
RTU Investigations and advanced monitoring	**£515,124**	**£345,052**	**-£170,072**	**-33%**
Of which Powersense	£385,879	£133,868	-£252,011	-65%
Of which PPA Energy	£129,245	£211,183	+£81,938	+63%
UK Power Networks internal resources	**£1,048,012**	**£119,626**	**-£928,386**	**-89%**
Of which operational staff/materials	£220,032	£69,291	-£150,741	-69%
Of which other business units and contingency	£827,980	£0*	-£827,980	-100%
Of which contractors	£0	£50,335	+£50,335	N/A
IT Hardware/Software	**£190,900**	**£204,329**	**+£13,429**	**+7%**
Totals	**£2,890,224**	**£1,856,956**	**-£1,033,267**	**-36%**
IFI	**£917,459**	**£846,000**	**-£71,459**	**-8%**

Table 12: Variance in planned expenditure by project area

**See Internal Cost section below*

Project management

UK Power Networks spent less money than expected on project management. This was due, in part, to the fact that PPA Energy took over the day-to-day programme management activities of the project for the final phase of the project, which is reflected in the increase in their costs. UK Power Networks had a project manager and regular business engagement up to senior management level throughout the entirety of the project.

Development costs

The project was reviewed along with the planned functionalities to be delivered following each stage. Following these reviews, an increase in the need for required development by Capula was identified.

It was also recognised that a significant increase in involvement would be required by PPA Energy to define the underlying processes and algorithms behind the functionality to ensure they reflected the user's needs and technical requirements. In particular Data Quality and related RTU health were identified as needing significant attention. This provided a way to reduce the burden on teams within the business to develop detailed functional specifications.

RTU investigations and advanced monitoring

Investigation into the advanced functionalities of the RTUs was originally intended to be facilitated through the existing operational infrastructure. Due to the major risk to the operational performance that this could cause, a different approach was required as described in section 7.1. The original approach was replaced with a trial of 27 independently commissioned RTUs managed and implemented by PPA Energy, in addition to their initially planned involvement which increased their associated cost.

The advanced monitoring sensor trial was scaled back following a review of outputs and impact of other changes in the project. This resulted in lower expenditure with sensor supplier Powersense, and also contributed to the increased PPA Energy cost due to their increased involvement in detailing the deployment of monitoring solutions, creating and demonstrating the toolbox of solutions to meet challenging installations and analysis of the data and outputs including the load flow analysis.

Internal costs

The installation of the advanced monitoring sensors and site visits to investigate network anomalies identified by the tool were originally planned to be delivered by UK Power Networks' internal field staff. Limited availability of these staff meant that this work was carried out by contractors.

Initial discussions with various parties regarding the links to operational business systems suggested that dedicated proprietary links would have to be developed and established with multiple distinct business systems. Subsequently, a data warehousing approach was identified that would allow access to the data required, without the need for direct links. This resulted in a much lower cost of implementation, and accounting for the majority of the internal cost underspend.

The majority of the remaining IT related work for the project also coincided with business-as-usual activities which meant the project did not bear the cost. The time required from staff in other business units was less than initially estimated. This reduced requirement meant that their support was manageable within their day-to-day work, and was not recharged to the project.

As described above and in section 7.1, the network-wide deployment of the advanced features of the RTU did not take place. This meant that the resources and development of the network control system originally identified were not required.

8.2. Project Benefits and Variance

The benefits of the project and how they are expected to be achieved are discussed in section 5.1 and Appendix F of this report. At the time of project inception, an initial estimate of the benefits was made and this has been refined as the project has progressed. The final view of expected benefits has been assessed over the RIIO-ED1 period and is presented in the table below.

The table uses the same benefit categories as section 5.1 and Appendix F where further information can be found.

Benefit Category	Benefits explanation for Annual Quantification	ED1 Total
1.1 Real time network power flow	Rather than real time, this benefit is now estimated on the basis that operational staff inside and outside the control room can now access a wider range of analogues up to 30 mins old. Cost of one fault estimated at £25k	£200,000
1.2 Prevention of LV interconnected network cascade following HV faults	This benefit is related to the interconnected network in London which is resilient to a first fault. It assumes that 1 fault per year is avoided by identifying fuse failures by seeing unbalance. This allows the fuse to be proactively replaced so customers don't go off supply when the next fault occurs. Cost of one Fault estimated at £25k	£200,000
2.1 Detection of faults and events on the LV networks	This relied on the advanced features of the RTU which are not being taken forward at this time.	£0
3.1 Voltage investigation	Availability of voltage information could save 2 unnecessary actions (installation of logging equipment) each year = £1k Annual saving of 1 day that planning engineers spend to manually manipulate the PI data = £0.5k Rising to £3k as it is expected that voltage issues will increase as additional generation is connected to the network	£21,000

3.2 Identification of areas with poor power factor	Not Quantified (see notes below)	Not Quantified
3.3 Identification of LV out of balance and harmonics	Not Quantified (see notes below)	Not Quantified
4.1 Information to support new customer load connection and general network reinforcement	Connections Engineers: Assist connections department save 2 man weeks by making asset and load information that is geographically relevant to points of new connection readily available to engineers. Planning Engineers: Assist planning department save 2 man weeks currently spent on maintaining and operating multiple IT tools and spreadsheets. 4 man weeks saving per year: 20 * £400 = £8k	£64,000
4.2 Load analysis and growth profiling to improve planning process	Avoidance of 2 Network reinforcement schemes: £30k*2 = £60k More efficient planning process results in 2 week time saving: 5k Infrastructure planning 1 week time saving: £2.5k Rising to £310k as planners will have to deal with increasingly complex load profiles and Low Carbon Technologies.	£1,163,000
5.1 Improved management of secondary substation ventilation	Saving of 1 distribution transformer a year = £10k Saving of 2 substation batteries not operating at time of fault due to extreme hot or cold temperatures (£25k/fault, 10% chance of fault coinciding with extreme temp): £2.5k	£104,000

5.2 Reduction in operational risk of failure of primary transformer tap changer	Prevention of 2 tap changer interventions (maintenance) each year as the company moves to a duty based maintenance regime = £20k This is evaluated from 2016. Avoid the capital cost of 1 tap changer failure every 2 years: £100k	£560,000
Additional benefits identified as a result of identifying and fixing issues early (Utilisation, voltage below limits)		£246,000
Total Benefits		**£2,558,000**
Total operational cost of achieving benefits		**£1,364,000**
Net Benefit		**£1,194,000**

Table 13: Expected benefits quantification by category and comparison with initial estimates.

Benefits 3.2 and 3.3 relating to power factor, imbalance and harmonics are not currently quantified in isolation as the financial benefits to a DNO are not uniquely attributable to these categories. However having greater visibility of these parameters is a contributor to the significant benefits identified relating to planning for future load growth and addressing routine network issues (categories 4.1 and 4.2).

The estimate of benefits at the inception of the project was £8,663,000, excluding any operational cost of achieving the benefits (such as carrying out maintenance tasks on the network once they had been highlighted by the tool). As described in section 7.1 and 7.2, as the project progressed it became clear that integrating the advanced features of the RTUs and real-time power flow tools into the live network control environment was not viable. As such the potential benefits associated with these areas (benefits categories 1.1, 1.2 and 2.1) have been significantly reduced against initial estimates, by £3.9m and £1.6m respectively. The remaining expected benefits in these categories are related to improved operational practices that will be achievable due the greater availability of network loading conditions available through the DNV application.

Expected benefits associated with analysis of historical load data and load growth and profiling (categories 4.1 and 4.2) remain broadly similar to initial expectations. There has been a shift towards a greater expectation on load profiling and load growth analysis to deliver benefits by improving planning processes. This is expected to be particularly relevant as more Low Carbon Technologies are connected to the network in the future.

Potential benefits associated with the ventilation of indoor secondary substations have been identified (category 5.1) which were not included in the original estimate. This area was identified by the exercise involving stakeholders from within UK Power Networks to identify where improved visibility of network data can be of high value. This exercise also identified benefits associated with greater visibility of voltage on LV networks (category 3.1).

Benefits associated with tap changer data (category 5.2) have increased due to revised estimates and also the possibility of using the data to facilitate maintenance schedules that take account of asset duty.

9. Lessons learnt for future Projects

9.1. Data

9.1.1 Data Storage

While investigating the various functionalities delivered by the project, it was found that even for a specific network parameter (for example feeder current), the required way in which the parameter was measured, communicated and stored would differ depending on the intended use. These differing requirements and measurement frequencies mean there is not always a single method for collecting and storing the data. For example, there are vast differences in the way half hourly averages are handled compared to waveform data sampled at 4 kHz for fault event investigations. This is discussed further in section 5.7.

It is important to remember that the way in which data is measured, collected and stored is as much dictated by the intended use, as it is by the characteristics of the parameter being measured.

9.1.2 Data Measurement

It is important to have a good understanding of the underlying principles behind a measured network parameter when deciding how to treat the data. This is especially true when considering power and power factor values. For example, averaging rapidly varying values can sometimes give misleading results if the measurements fluctuate around a null point that is not zero (two parameters where this can be an issue are power factor and wind direction). Care should also be taken to understand if recorded actions (e.g. Tap Change operations) are measuring initiation requests or completed actions.

This requires sound engineering knowledge of the underlying systems and should not be considered as simply a data processing exercise.

9.1.3 Data Quality

Data quality is critical when dealing with large volumes of data. Methods for identifying data spikes, flat lines, etc. were found to be essential for efficient analysing of the data and for creating user confidence in a tool visualising it. This later point regarding user confidence was found to be especially important, as conventional sanity checks are difficult to perform on large data sets subject to complex calculations, which make the processes effectively invisible to the user.

All areas of the data measurement, retrieval, manipulation and storage processes from the transducer to the database need to be considered. Measuring equipment needs to be properly calibrated, and means to validate the data against other sources should be considered.

9.1.4 Data Anomalies

Following data quality analysis, the user can choose to ignore the data anomalies in the functionalities developed for the DNV application. It was decided not to remove or apply corrections to the original data so that it is always available as a reference. If improvements are made to the data quality algorithms, the cleansing process can be repeated.

If the data was to be automatically corrected, it is important that users are aware as it could hide system events such as low voltage.

Although data correction is essential to delivering the vast data analysis features discussed in this report, the process should ensure that identified data anomalies are reported. This is not only useful to allow users to confirm correct operation but also so that, if necessary, the source of the data anomaly can be rectified appropriately.

9.2. Software and tools

9.2.1 Developing software applications

Producing a production-quality software product is inherently subject to diminishing returns in terms of development effort and functionality available to users, and a large effort is required to go from a tool that demonstrates functionality to a fully integrated bug-free application.

It is important that users are aware of what stage of development an application is in, and what to expect in terms of user experience, when using early versions.

It is essential to be aware of this, both in terms of the approach to development and also from a user perspective to ensure positive user engagement.

9.2.2 Commercial/Third party tools

When making use of third party tools that are dealing with complex systems and analysis, it is important to be as detailed and clear as possible as to the expected functionality and outputs required. This will ensure that suitable tools and applications are identified and that the intended outcomes can be achieved.

The use of small “proof of concepts” is useful to identify any issues and gaps in capability before proceeding with larger demonstration trials.

9.3. Understanding business risk

When interacting with existing business operational systems, consideration must be given to their on-going reliability. Not only must the risk of the project to these systems be taken account of but also the risk that the project and its activities are exposed to when involved in the necessary processes that govern changes to these systems.

As an example, upgrading the 9,885 existing RTUs presented a challenge that dictated a remote automated upgrade solution. This required a carefully managed phased approach that included laboratory testing, followed by small numbers of selected upgrades to minimise the exposure of the related systems. There remained a perceived operational risk that meant a facility to remotely reverse the upgrade was required to reduce the impact of any consequent issues. This functionality and the associated comprehensive testing took longer than expected.

9.4. Stakeholder and User engagement

This project relied on the engagement of many stakeholders from various teams within UK Power Networks. This was necessary to ensure that the project addressed a wide variety of potential benefits from a wide range of network-related business activities. This was essential to ensure that the benefits identified were relevant, correctly prioritised and achievable.

As the project progressed, these stakeholders became users of the functionalities and their feedback was essential to ensure the development was delivering the intended outcomes. As mentioned in section 9.2.1, it is important that these users are aware what to expect from tools that are still in early stages of development, to ensure that any difficulties in using the functionality are expected and can be accounted for, ensuring on-going engagement.

9.5. Project Flexibility

Whilst carrying out an innovative project of this size, it is important that the project remains flexible with regard to its activities to ensure that findings from the project can be built on or unnecessary work avoided. As described in section 4, this project was conducted in a phased approach with defined "gates" to ensure that the learning of the previous phase was captured and project progress reviewed. At these gates, approval from the internal UK Power Networks project board was required and the initial project plan was adjusted to ensure that the project direction is followed.

Furthermore, it is important, particularly with the involvement of a large number of stakeholders, that the original objectives of the project are clear and well communicated to all relevant parties. This ensures that the project activities are focused on achieving its original objectives.

10. Planned implementation

10.1. DNV Application

The visualisation and analysis application developed as part of the project and described in this report is in the process of being adopted by UK Power Networks as a "business as usual" application supported by Capula through UK Power Networks' IT department. The DNV application data is automatically updated from various live business systems on a regular basis as the network asset data changes.

The Distribution Planning engineers already use a range of features particularly the planning and the connections tool. The consolidation of information in one place such as asset data, referrals database, PI data and MDI data means that the DNV application is the priority information system used by the planners. Other system issues such as voltage, unbalance and harmonics can be investigated using the DNV application.

The DNV application is also being used by the connections teams to assess connection capacity using the connections tool feature.

Asset Management engineers can use the DNV application dashboard on a daily basis to gain an overview of system health and particularly review ventilation and primary tap changes health.

Some benefits have already been realised such as deferring transformer replacement, more effective utilisation of existing assets by using the connections tool, preserving asset life by resolving ventilation issues and saving of man hours.

10.2. Real time power flow

As discussed in this report, this project has identified significant benefits to the visibility of HV power flow in an operations environment. The project undertook a trial of the DPF tool on a four ring feeder group, and highlighted areas of the GE DPF tool where modifications would be necessary in order to use the real time RTU data as a basis for the power flow and enable planned switching events to be considered. The project was unable to move this forward with GE within the required timescale and hence a separate project is recommended. The trial of the DPF tool in real time using RTU data should be undertaken on the Carslake North ring and the recommended DPF developments undertaken before a full system roll out is commenced. Preliminary costs were obtained from GE for the required development.

The project identified developments that will be required before the tools can deliver the anticipated benefits of having load flow information available to control engineers. These developments are described in section 5.5.

10.3. Visualisation of LV events

The advanced features of the Callisto 1 RTU event recorder allow for the capture of alarm logs and disturbance events both of which would provide visibility of low voltage faults and incipient faults. Whilst a small trial system was set up, the project was unable to demonstrate all the benefits of this system although they have been identified and are thought to be realisable. The new protocol convertor software which was developed for the Callisto 1 RTUs means a further long term trial could be undertaken to capture events, develop algorithms and a visualisation solution to enable realisation of the identified benefits.

10.4. Future RTU Specification

The DNV project has enabled UK Power Networks to demonstrate the value of network monitoring.

UK Power Networks' new standard secondary system RTU specification includes the following analogue requirements:

- Three phase HV current from HV Circuit
- Three phase HV current from HV Tee (or 2nd Circuit)

It also requires provision for expanding the analogue capability of the RTU to include the following requirements:

- Three phase LV current
- Three phase LV voltage
- Derived total apparent power (kVA)
- Derived total real power (kW)
- Derived total reactive power (kVAr)
- Derived power factor
- Total harmonic distortion
- Load unbalance
- Substation air temperature
- Transformer temperature

These will provide both instantaneous and averaged analogue measurements.

Under certain specific circumstances it is envisaged that provision will also be required for monitoring the three phase and neutral currents on each of the individual LV ways in addition to the transformer tails. This facility has been detailed in a separate RTU specification which may be incorporated as new or retrofitted to existing sites as necessary.

11. Facilitate replication

11.1. Cost and benefits of replication

The benefits and outcomes of this project are applicable to all DNOs, however the extent of features that will be possible to implement will be dependent upon the networks, the available monitored data and the availability of data from other information systems.

Figure 17 presents the cost of replicating the project and conservative estimates of the benefits that could be expected over the RIIO ED1 period.

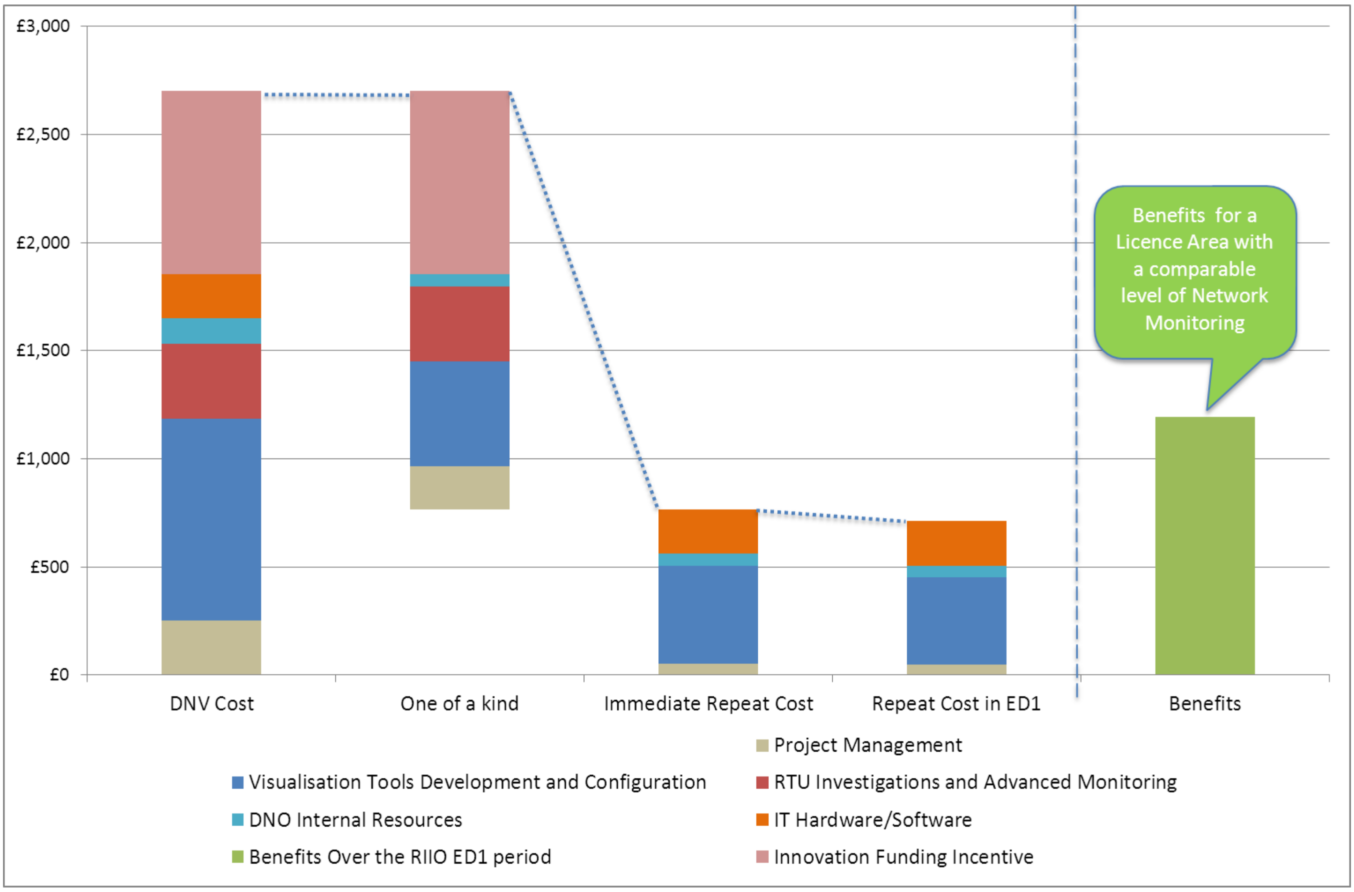


Figure 17: Cost and expected benefits from replication

The suitability and replication of the DNV project by other DNOs has been taken into account throughout the project, and consideration has also been given to a variety of types of networks and the development of generic solutions.

From the perspective of facilitating replication of the project, there are five main areas where knowledge has been generated.

11.2. IT Infrastructure

An IT white paper has been written, it explains the technical architecture of the DNV application and the background to why some of those technical choices were made. This document is aimed at IT architects from other DNOs wishing to replicate the IT infrastructure required to implement the DNV Visualisation application and supporting systems. The white paper will be available to other DNOs on request.

11.3. DNV application

The project has generated the following software components which are owned by Capula, but for which a Royalty-free license would be supplied to all GB DNOs on request. To gain access DNOs should contact Capula to discuss a suitable way to implement these functionalities on their own systems.

Custom User Interface

In order to satisfy the customer's requirements for specific graph types, GIS visualisations and reporting facilities, a Silverlight-based front-end user interface has been developed to provide easy and flexible access to the information held in the PI System and PI AF, tailored to the customer's business needs.

Visiblox Charting

Development of charting approaches using a third party application (Visiblox Charts). This is a Silverlight based graphing library, and is used to generate the interactive line, area and bar charts within the DNV front-end user interface.

Custom Map Pins

Custom map pins have been developed within the Silverlight DNV front-end user interface to display up to four variables at a geographic location on a Bing Maps canvas, using colour, size, shape and style.

Quick launch

Due to the wealth of configuration options within the DNV front-end user interface, a quick-launch mechanism has been developed to configure the displays with default settings for specific pre-agreed investigations.

Various Utilities, including

An 'AF-Builder' application has been developed to construct a complete PI AF Asset Hierarchy, using asset data from a SQL database specific to the customer. AF builder can interface to third party applications either using an intermediate SQL server database or MS Excel spreadsheets.

A 'Data cleansing' mechanism has been developed whereby a background analysis task monitors new time-series data and logs anomalies conforming to pre-agreed profiles. These anomalies are then used by a custom 'Cleansed Data' PI AF Data Reference which applies cleansing rules for each anomaly to the original data, producing a cleansed data stream which can be used by the other components as an alternative to the raw data.

A 'Reporting Mechanism' has been developed where specific report types can be requested from the DNV front-end user interface. These are stored in a SQL database and a server-based reporting service then processes these requests, retrieving data through PI AF and summarising it to produce reports which are stored on the server. They can then be viewed within the DNV front-end user interface and used interactively as jumping off points for further investigations.

11.4. Visualisation and algorithm development

The project has generated the following foreground intellectual property which is owned by PPA Energy, but for which a Royalty-free license would be supplied to all GB DNOs on request:

Various types of Geo-spatial-chrono visualisations including:

- Load profiles
- Dynamic heat-mapping and motion maps
- 3D heat-mapping
- Fault and alarm mapping

Advanced visualisations and viewers for:

- Fresnel phasor analysis
- Harmonic analysis
- Interconnected HV/LV network events
- Meshed MV
- Rural Small Section Networks
- Complex multivariable time series

Algorithms for:

- Load profile classification and analysis
- Transformer and substation temperature modelling with weather
- Dynamic transformer rating
- Source impedance measurement
- Detection of large motor and generator operation
- Detection of voltage and current unbalance
- Detection of unequal sharing and defect on dual conductors transformer tails
- Spare capacity
- Dynamic transfer capacity
- Data Quality and measurement health

11.5. Monitoring Solutions

The project has generated the following foreground intellectual property which is owned by PPA Energy, but for which a Royalty-free license would be supplied to all GB DNOs on request:

Network Monitoring Toolbox:

- Live installation and calibration of a wide range of optical and electromagnetic current and voltage sensors for LV-33kV cables and overhead lines and tee points
- Online alignment and calibration of MV cable sensors
- Monitoring transformer LV quantities from MV measurements
- Monitoring of transformer temperature

- Virtual RTUs for unmonitored substation measurements
- Rules for effective monitoring of MV networks
- Selective harmonic time series capture

11.6. Real time event monitoring

The project has generated the following foreground intellectual property which is owned by PPA Energy but for which a Royalty-free license would be supplied to all GB DNOs on request:

Faults and Disturbance events:

- Capture of fault and event waveforms
- Classification of events
- Harmonic analysis and classification of events
- Localization of LV events on radial and meshed LV systems
- Load and source impedance changes during faults

Communications:

- Product specific communication interfaces and configurations
- Operation of independent Multi-Network wireless sensor modems in areas with poor signal strength
- Methods for wireless signal enhancement in basement substations

Systems capable of further development and potential commercial exploitations:

- Non-invasive MV DEFFI

Appendix A: Glossary

AF	Asset Framework
ALE	Alarm Limit Excursion
APRS	Automatic Packet Reporting System
AVC	Automatic Voltage Regulator
CHP	Combined Heat and Power
CI	Customer Interruptions
CML	Customer Minutes Lost
CT	Current Transformer
DEFPI	Directional Earth Fault Passage Indicator
DINIS	Load flow planning tool used by network planning engineers in LPN
DOC	Directional Over Current
DNV	Distribution Network Visibility
DPlan	Distribution Planning software
DPF	Distribution Power Flow
EHV	Extra High Voltage
GIS	Geographic Information System
GMT	Ground Mounted Transformer
GSOP	Guaranteed Standards of Performance
GUI	Graphical User Interface
G59	Engineering Recommendation G59/2 Recommendations for the Connection of Generating Plant to the Distribution Systems of Licensed Distribution Network Operators
G83	Engineering Recommendation G83/1-1 Recommendations for the Connection of Small-scale Embedded Generators (Up to 16 A per Phase) in Parallel with Public Low-Voltage Distribution Networks
HV	High Voltage
I	Current
IFI	Innovation Funding Incentive
IIS	Internet Information Services (Microsoft)
IT	Information Technology
kHz	Kilo Hertz
kV	Kilovolt
kVA	Kilovolt Ampere
LCNF	Low Carbon Network Fund
MPAN	Meter Point Administration Number
MDI	Maximum Demand Indicator

MVA	Megavolt Ampere
OHL	Overhead Line
P	Power
PC	Personal Computer
pf	Power Factor
PI	Real Time Data Management System
PICAS	Paper Insulated Corrugated Aluminium Sheath
PILSWA or PILSWA/S	Paper Insulated Lead Covered Steel Wire Armoured
PMT	Pole Mounted Transformer
Q	Reactive Power
RPI	Rockwell Protocol Interface, a communication protocol used by some LPN RTUs
RTU	Remote Terminal Unit
S	Apparent Power
SCADA	Supervisory Control and Data Acquisition
SCT	Sequence Component Transform
TCIP	Tap Change In Progress
THD	Total Harmonic Distortion
TPI	Tap Position Indicator
V	Voltage
VRTU	Virtual Remote Terminal Unit
2D	Two dimensional
3D	Three dimensional

Appendix B: Details of Advanced monitoring deployment

Laboratory testing

Externally mounted optical current sensors manufactured by Powersense were proposed for measuring the three phase current on the full range of cables in use within LPN. As the majority of HV cables installed within the UKPN area were, until comparatively recently Paper insulated, Lead covered, Steel Wire Armour (PILSWA or PILSWA/S), it was important to check the suitability of the proposed sensor for use with these types of cables as well as with the more recently deployed Triplex cables. The tests on the Optical Current Sensors were undertaken in the HV laboratory at Southampton University during February 2011. The Remsdaq RTU was also tested (from a measurement perspective) at this time. The table below provides a summary of the test results:

Manufacturer	Equipment	Test Description	Result
Remsdaq	RTU	Measurement Accuracy	Pass
Powersense	Optical Current Sensor	Triplex Cable (Single core and plain lead)	Pass
		PILSWA Cable (Steel Wire Armour)	Unsatisfactory
		Unbalance System (currents in cores sum to zero)	Pass
		Unbalanced System (separate phase loops)	Unsatisfactory

Table B1: Test results

As a result of these tests, it was necessary to remove the Steel Wire Armour from PILSWA cables.

Carslake Road LPN cable measurements deployment summary:

<table>
<tr><th>Site</th><th>Measurement equipment installed</th><th>Opportunities</th></tr>
<tr><td>27/32 Old Jewry secondary substation, Paternoster MSS</td><td>External Powersense optical current sensors:
• 2 PILSWA cables of a RMU,
• Single core LV transformer tails</td><td>• Confirm long term measurement accuracy and temperature stability though a Kirchoff balance arrangement: 2 HV power flows + LV power flow = 0 (allowing for transformer losses).
• Validate a method of in-situ calibration for PILC cables using only LV measurements and standard transformer nameplate data together with an HV switching sequence.
• To compare the long term measurements of transformer loading between Powersense of optical sensors and an existing Remsdaq Callisto RTU with 1000A/0.34V Clamp CTs mounted on the same transformer LV tails.</td></tr>
<tr><td colspan="3">Installation Notes:
One side of RMU:
• Cut back and re-terminate the steel wire armours of PILSWA cable to expose the lead sheath. Undertaken with the circuit dead, earthed and under permit.
• HV cable sensor installations were performed live, as is necessary for rotational alignment of sensors.
• The LV transformer optical sensors fitted dead but could have been fitted live if necessary using optical sensors fitted within an insulated clamp.

It was necessary to produce software for calibration of the HV sensor. Symmetrical component star/ delta converter to account for the voltage ratio, phase angle and losses of the distribution transformer in order to identify the correct sensor sequence and determine calibration factors.

No customer supply interruptions were necessary.</td></tr>
<tr><td rowspan="2">Kenilworth Court secondary substation, Carslake Road MSS</td><td>External Powersense optical current sensor:
• 1 HV cable</td><td>• Understand HV directional power flow, Power Factor and out of balance.
• Measure load on adjacent substations supplied by circuit (open point beyond).</td></tr>
<tr><td colspan="2">Installation Notes:
Unable to do planned LV board sensor installation due to LV board defects</td></tr>
</table>

<table>
<tr><th>Site</th><th>Measurement equipment installed</th><th>Opportunities</th></tr>
<tr><td rowspan="2">Waterman St secondary substation, Carslake Rd MSS</td><td>External Powersense optical current sensors:
single triplex ring cable of a RMU
CTs:
3 outgoing LV ways - English Electric LV Board.</td><td>Monitor phase load current on triplex cable using non-invasive optical sensors at a substation located at the midpoint of a section of a feeder.
Fit standard Powersense CTs on the risers of English Electric LV Board using specially developed easy to fit CT clamps and cable grips.
Compare the sum LV feeder readings with the transformer readings measured by the Remsdaq Callisto RTU.</td></tr>
<tr><td colspan="2">Installation Notes:
Development of CT clamps and cable grips was necessary to enable fast simple installation of existing CTs in a confined space.
The installation was undertaken with the LV Board live following the approach developed during trial installations at the Sundridge Training Centre.
No customer supply interruptions were necessary.</td></tr>
<tr><td rowspan="2">1 Bective Road secondary substation, Carslake Road MSS</td><td>External Powersense optical current sensors:
single triplex ring cable of a RMU
Optical sensors:
5 outgoing LV ways of a Lucy Electric LV Board.</td><td>Compare optical HV phase measurement on triplex cables with the feeder readings from Carslake Road substation.
Insufficient space to allow installation of conventional CTs on Lucy Electric LV Board. Fit optical sensors on outgoing ways using easy to fit clamps and cable grips.
Compare the sum LV feeder readings with the transformer readings measured by the Remsdaq Callisto RTU.</td></tr>
<tr><td colspan="2">Installation Notes:
The HV triplex cables had to be separated slightly to allow passage of calibration instrumentation. This was straightforward and undertaken with the circuit live as there was no movement necessary in the vicinity of HV or cable joints.
The installation was undertaken with the LV Board live following the approach developed during trial installations at the Sundridge Training Centre. All fifteen sensors were installed on an LV board in less than an hour.</td></tr>
<tr><td>Putney High St ABC Cinema</td><td>External Powersense optical current sensors:
2 triplex 11 kV cables</td><td>Monitor power taken by a HV supply with restricted access and no metering information. P, Q, S and pf, directional</td></tr>
</table>

Site	Measurement equipment installed	Opportunities
secondary substation, Carslake Road MSS		power and currents on cables and at the HV supply. • Remote monitoring of sites where conventional CTs cannot be fitted without customer interruptions. • Unit substations where monitoring of transformer current is problematic.
Biggs Row secondary substation, Carslake Road MSS	Powersense optical current sensors: • 2 HV circuits • 4 LV circuits	• Demonstrate that full knowledge of HV, LV and transformer circuits can be obtained from n-2 circuits
Crown Lane R/O Library, Carslake Road MSS	Powersense optical sensors: • LV feeders	• Compare Powersense and RTU data from large services and 2 transformers. • Reveal masked load and generation. • Confirm understanding of real and reactive power flow in sites with load and generation.
60 Chelverton Road, Carslake Road MSS	Powersense optical sensors: • 2 triplex HV cables	• HV current directional HV power time series data. • Demonstration of transformer demand calculation.

Table B2: Deployment summary

Overhead line monitoring

33kV and 11 kV Tee poles

In order to measure the three phase current and voltages on overhead lines, Powersense combi-sensors using optical current sensors and voltage dividers embedded in insulators suspended from overhead lines were installed on both a 33 kV circuit and an 11kV teed circuit in the SPN area .

The 11kV circuit had adjacent 11kV generation with the potential for changing power flow direction and voltage fluctuations. It also had a history of poor voltage regulation under first circuit outage conditions. The 33 kV circuit was part of a five ended meshed system with potential for changing power flow directions and voltage fluctuations.

Installation observations

A 230V supply was required to power the monitoring system. This meant that a single phase pole mounted VT is required, unless there is an existing pole mounted transformer or an adjacent LV overhead line (OHL)/cable. The need for an LV supply is a significant constraint to the deployment on 33 kV overhead lines as UKPN do not currently use 33 kV VTs and few 33 kV poles will have adjacent existing LV supplies.

The installation was undertaken with the system dead using methods developed during trial installations at the Sundridge OHL Training Facility. Care needs to be taken in the correct handling, securing and termination of fibre optic cables, and in maintaining adequate electrical and safety clearances. 33kV installations in UKPN were undertaken with the system dead. 11 kV Live line installation should be possible for most line and Tee circuits once appropriate methods are developed, approved, documented and training delivered.

The actual cross section size of the line conductor needs to be known in order to calibrate the system.

The sensors are not currently suitable for tubular busbar type conductors.

There must be adequate signal strength for GPRS communications.

The optical current sensors can be used without the need to strip insulation on covered conductors.

The voltage divider embedded within the insulator needs to have direct contact with the energised conductor on an earthed structure. It could be deployed at a location with either a cable termination, a three phase transformer or lightning protection devices. Alternatively, the voltages can be derived from LV voltage measurements.

Small section circuit monitoring trial

Trial location details

The East Grinstead 11 kV network has a mix of circuit sizes, some having small sections with 100A summer rating, which introduces export generation and line constraints. The SPN East Grinstead feeder 14 network area was selected for the pilot because it was generally representative of a type of small section network found in some areas of both SPN and EPN. The network presented a wide variety of monitoring equipment installation issues.

The trial network circuit area comprises some 95 ground mounted transformers (GMT) and pole mounted transformer (PMTs) with a similar number of 11 kV circuit sections. In order to meet the objectives of the trial for the determination of power flow, unbalance, and small section dynamic loading issues, it was not practical, necessary or economic to monitor every individual section. The approach adopted was to divide the feeder circuit into five monitoring zones comprising:

- The East Grinstead 11 kV feeder circuit breaker to its normal open points, for nominal balanced current and substation busbar voltage.
- Four main branches:
  - For HV current and voltage measured at each root from the main feeder.
  - For HV voltage measured near extremities or at normal open points.

This enabled a network overview to be used in the analysis as shown in Figure B1.

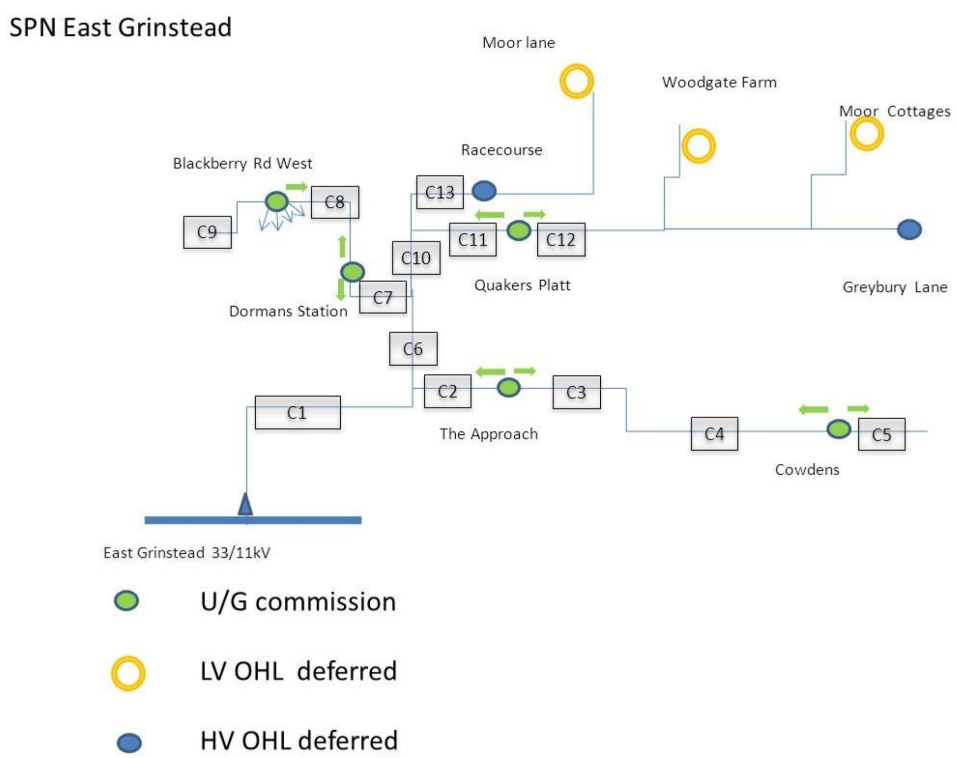


Figure B1: Overview of East Grinstead trial circuits.

Outdoor MV cables and Ground Mounted (GM) substations

Real time monitoring was undertaken at five Ground Mounted substations, each with specific and different installation challenges to measuring:

- Unbalanced 11kV circuit currents, voltages and directional power flow.
- Unbalanced transformer phase loadings and LV voltages.
- Current sensor installation in the vicinity of live LV boards.

This monitoring was achieved using the Powersense Opti MV ring circuit current sensors, plus 3 phase voltage LV measurements using existing potential fuses, LV fuse holders or voltage fuses inserted into spare LV ways. The arrangements at each ground mounted substation is detailed in the following Table:

Ground Mounted substation monitoring summary:

Substation	HV Cable	SS type &Measurement Solution Demonstrated
Quakers Platt	Triplex	RMU/Transformer/LV Pillar • Two external 11kV cables.
Dormans Station	PICAS	RMU/Transformer/LV Pillar • One internal 11kV end box. • One external 11kV cable.
The Approach	Triplex	RMU/Transformer/TF mounted LV cabinet • Two external 11kVcables.
Blackberry Road West	PICAS	Package s/s • One internal 11kV end box. • Transformer loading by Rogowski LV way summation. • 2nd 11kV ring circuit measurement by Kirchoff balance calculation.
Cowden	Triplex	RMU/Transformer/LV Pillar • Two external 11kV cables.

Table B3: Ground Mounted deployment summary

Specific issues were identified with operational arrangements at Dormans Station and Blackberry Road West substations. A standard two ring circuit monitoring approach would have required overhead line work and earthing, current sensor installation in vicinity of live LV boards or customer outages.

As these types of sites and constraints are representative of many that are found on typical networks, alternative approaches were developed:

- Dormans Station had two PICAS ring cables, but one ring circuit had a teed overhead line that would have required overhead line switching and earthing for an internal end box sensor installation. A process was developed where a sample of PICAS cable was stripped, examined, and tested for external optical monitoring suitability. Optical sensors were then installed both in the endbox, and on the external cable of the ring switch that could be switched out and calibrated, but did not require earthing.

The external sensor was then removed and transferred to the other live ring circuit (with the OHL tee) aligned online, and the results from the two ring sensors compared for amplitude and phase angles at minimum transformer demand.

- Blackberry Road West also had two PICAS ring cables, but with one ring circuit having a teed radial underground circuit that would have required customer outages for switching and earthing for an 11kV endbox installation. In this case, a mixed 11kV/LV monitoring solution was adopted. Optical sensors were installed in the endbox on the external cable of the ring switch that could be switched out, earthed and calibrated. As this was a unit substation with no direct access to transformer circuits for LV monitoring, each of the four outgoing ways was fitted with Rogowski sensors in the LV cable termination box under the LV cabinet, and the results phase summated to produce the transformer demand.
- The results of the LV transformer measurement and the HV optical sensor were then summated to provide a virtual measurement for the other (customer tee) ring circuit.

Together, these approaches are suitable for a large proportion of sites with PICAS or Triplex cables, but not for PICAS if there are teed radial customer circuits or overhead line connection constraints on both ring circuits, or on one 11kV circuit with no simple way to monitor the Transformer LV side without installing CTs on live LV boards or interrupting supply to customers.

For circuits with these type of constraints and those with PILSWAS cables, the Klik fit ring sensors, which has been designed to be suitable for multicore and wire armoured 11kV and LV circuits, may prove to be suitable but was not included within the current DNV scope. Adaption of the Ring Sensor for steel tape armour cables may also be possible.

Meshed network monitoring trial

Trial location details

The LPN-Hyde Park B-Central-five feeder (7, 9, 10 and 13) 11kV group network was selected for the trial because it is generally representative of a type of 11kV/LV interconnected network with limited meshed 11kV interconnection via DOC/EL protected circuit breakers, common in central areas of LPN,. The network has a high load demand from a wide mix of major retail, corporate HQ, commercial offices, hotels and high value domestic property with significant air conditioning and motive power (lifts and escalators). The area is under constant development with the network constantly being modified and operated under abnormal running/switching arrangements for periods of time. The network presents a wide variety of monitoring equipment installation challenges. It also has higher than average fault rate providing a reasonable chance of capturing and visualising relevant events.

Measurement of HV cables and Distribution Transformers

Pilot installations were undertaken at eleven distribution substations each with specific and different installation challenges to measuring:

- Unbalanced 11kV circuit currents, voltages and directional power flow.
- Unbalanced transformer phase loadings and LV voltages.
- Current sensor installation in vicinity of live LV boards.
- No 11kV or LV customer outages.

This was achieved using Powersense Opti and CT HV ring circuit current sensors plus transformer LV 3 phase voltage measurements using existing potential fuses or LV fuse holders with voltage fuses inserted into spare LV ways as detailed in the following Table.

Hyde Park B Distribution substation monitoring summary:

Substation	Monitoring Requirements	Measurements
Bird Street	DPF 11kV & LV	LV current and voltage 11kV current (one measured, one calculated)
Wigmore St 39-49 T1	DPF 11kV & LV	LV current and voltage 11kV current (one measured, one calculated)
Wigmore St 39-49 T2	DPF 11kv & LV	LV current 11kV current (both measured)
Substation	Monitoring Requirements	Measurements
Oxford St 358 Lil & Skin	DPF 11kV & LV	LV current and voltage 11kV current (one measured)
Stratford Pl 7-8	DPF 11kV & LV	LV current and voltage 11kV current (one measured, one calculated)
Portman Sq 15 Portman C	Directional Earth Fault Passage Indicator (DEFPI) Transformer LV only	LV current and voltage 11kV current (both measured)
James St C&A Modes T1	DPF HV & LV DEFPI Transformer LV only	LV current and voltage 11kV current (both measured)
James St C&A Modes T2	DEFPI Transformer LV only	LV current and voltage 11kV current calculation from T1 measurements
Welbeck Way 2-3	DPF 11kV & LV DEFPI Transformer LV only	LV current and voltage 11kV current (both measured)

Portman Sq Orchard Court	DPF 11kV & LV DEFPI Transformer LV only	LV current and voltage 11kV current (one measured, one calculated)
Easleys Mews	DEFPI Transformer LV only	LV current and voltage (measured)
Oxford St 360 Lil Skn E RTU1	DEFPI Transformer LV only	LV current and voltage (measured)
Wigmore Street 101 RTU 2	DEFPI Transformer LV only	LV current and voltage (measured)

Table B4: Hyde Park B monitoring summary

Sequence Component Transform

Monitoring 11kV voltages and currents directly is possible and in some situations necessary, but this solution is relatively expensive in terms of hardware, skilled resource and Senior Authorised Person (SAP) time. The LV Sequence Component Transform (SCT) was originally developed for use in calibrating optical cable sensor installations in LPN where we successfully demonstrated the possibility of using LV monitoring devices in order to calculate voltages on the 11kV side of a standard DY11 distribution transformer.

This approach has the potential to significantly reduce the cost associated with 11kV monitoring devices and was found to be equally applicable to measurements on the trail associated with the SPN small section network

Virtual RTUs

Currently about 67% of secondary substations on the LPN system have RTU's which measure three phase current and voltage and hence can provide real time load information to Power On. If the monitored substations are distributed evenly there are opportunities to estimate the real time three-phase power flow for the remaining substations without monitoring devices, which can be referred to as virtual RTUs. The accuracy of virtual RTUs depends on distribution of monitored secondary substations and the 11kV monitoring devices. Use of 11 kV feeder monitoring increases the accuracy of the load allocation.

Calculating virtual RTUs has significant benefits in terms of costs, resources and can overcomes problem with restricted access for monitoring legacy equipment, unit substations, sites with poor communications and/or difficult access.

An example of virtual RTUs is given in figure B2 below.

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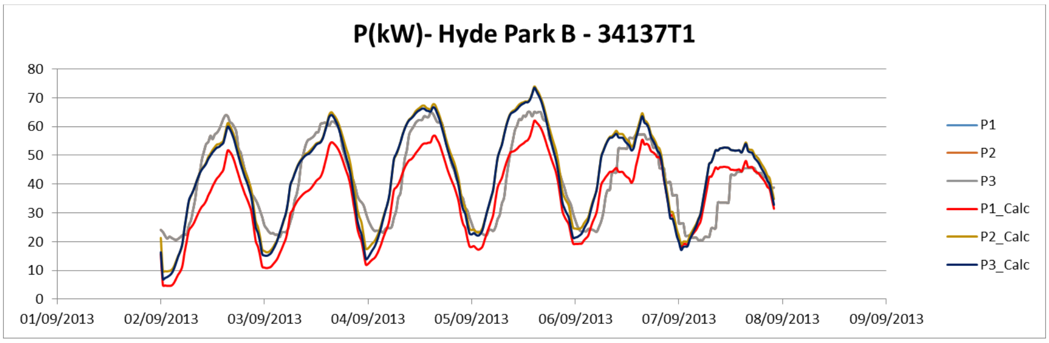


Figure B2 Virtual RTU compared with actual measurements

In this example, the results from a virtual RTU has been compared with actual measurements to verify the calculations.

Appendix C: Summary of evaluation of visualisation applications

C3 Amulet	Offers a good visualisation solution. Has its own proprietary calculation engine that can connect to both PI and AF, but it does have limited map functionality.
Iconics Genesis	Offers a good visualisation solution, and a good display creation tool. Has the ability to publish to a web page providing easy access for users. Connection with the AF data stored on the SQL database is an issue.
GE's Smallworld GSA	Strong and powerful mapping tool. It allows a lot of information to be displayed via the map on a collection of layers. Has an easy to use interface but requires users to have Smallworld GSA installed on their machines. It would have to be deployed as an enterprise wide solution. Trends, graphs and reports do not meet the standards of the other solutions and some vital requirements may have issues with connecting to the AF data stored on the SQL database.
FactoryTalk Vantage Point	This solution can display information including maps, tables, graphs and charts, and save reports to a central server which can be opened by other users on the system. To change certain settings and options of the data, users must use client side tools which could be complex. May have issues with connecting to the AFdata stored on the SQL database.
Visiblox	Strong and flexible charting visualisation application – used with Microsoft Silverlight. Can be used within a developed solution to display data in a variety of forms such as graphs, tables, charts and maps, with easy-to-change options like time range, limits, etc. Can link to PI and AF simultaneously so users will easily be able to find a site and see the KPI data for that site very quickly. Very flexible, good value for money and fits well with the OSIsoft roadmap of closer corporate alignment to Microsoft-based data visualisation and analysis applications.

Appendix D: DNV Application - User Interface

User Interface

Users with access to the application will be presented with the screen below, illustrated in Figure **Figure** D1, once they enter the application.

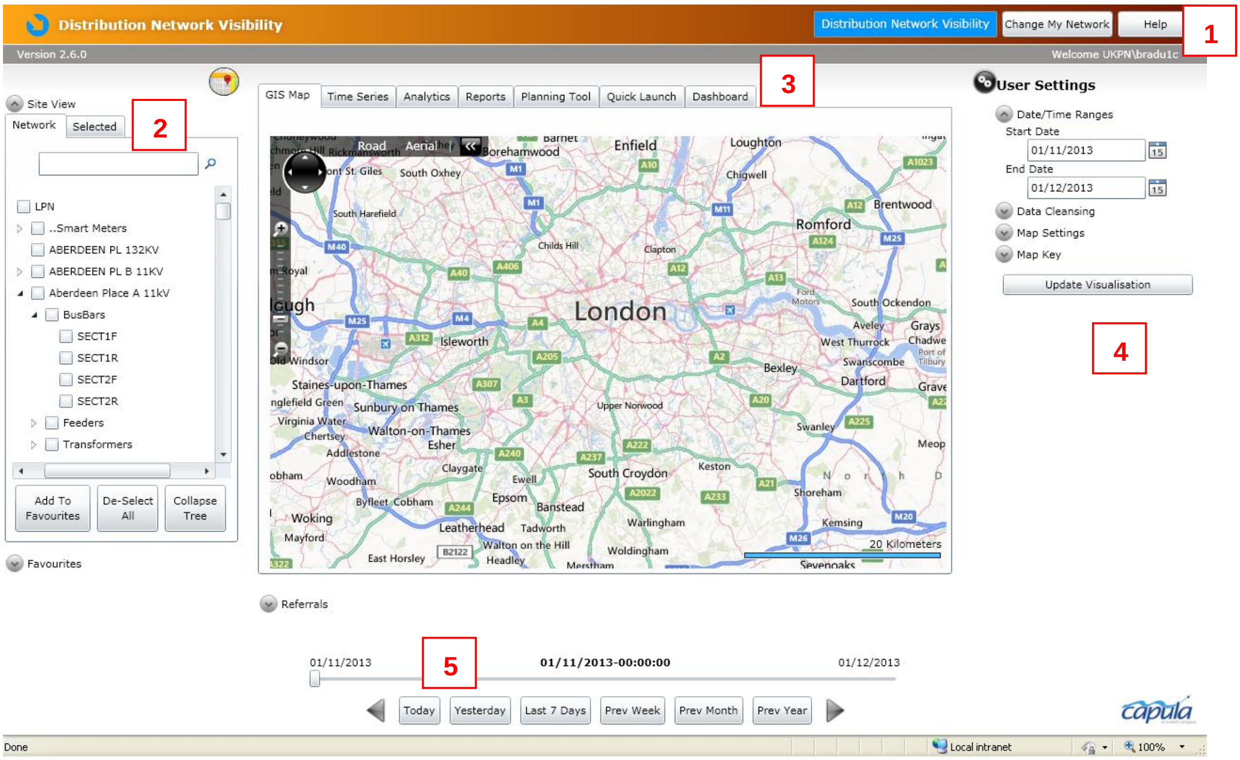


Figure D1: DNV Home screen

The Figure D1 highlights the following:

1- Help Option
2- Navigation and Favourites Sidebars
3- Application View Tabs
4- Settings Sidebar
5- Quick Date Range selections and GIS Map time slider.

Side-bars and Help System

The application has a wealth of configuration options and these are accessible through two side-bars. These may be collapsed in order to devote more screen space to the main body of the application.

- The Navigation sidebar on the left allows users to drill down through the asset hierarchy and select assets of interest. Since the asset hierarchy is large, the side-bar includes a live search box and various options for selecting multiple assets based on several criteria.
- The User Settings side-bar on the right contains options for configuring the time period of interest and for adjusting limits and viewing preferences and calculation limits for each data stream type.

The 'Help' button on the title bar takes the user to a help page with links to an online user guide and short videos demonstrating the key aspects of the application.

Application Views

The DNV application allows asset and real-time data to be displayed and analysed in a number of differing and complimentary ways in an intuitive tab-controlled interface. The following sections describe the options available on each tab.

GIS Map

The GIS Map provides a geographical view of the network using maps provided by Bing Maps. When a substation, transformer or feeder is selected from the network hierarchy, a pin will be displayed on the map. A number of variables can be applied to these pins to view changes over time.

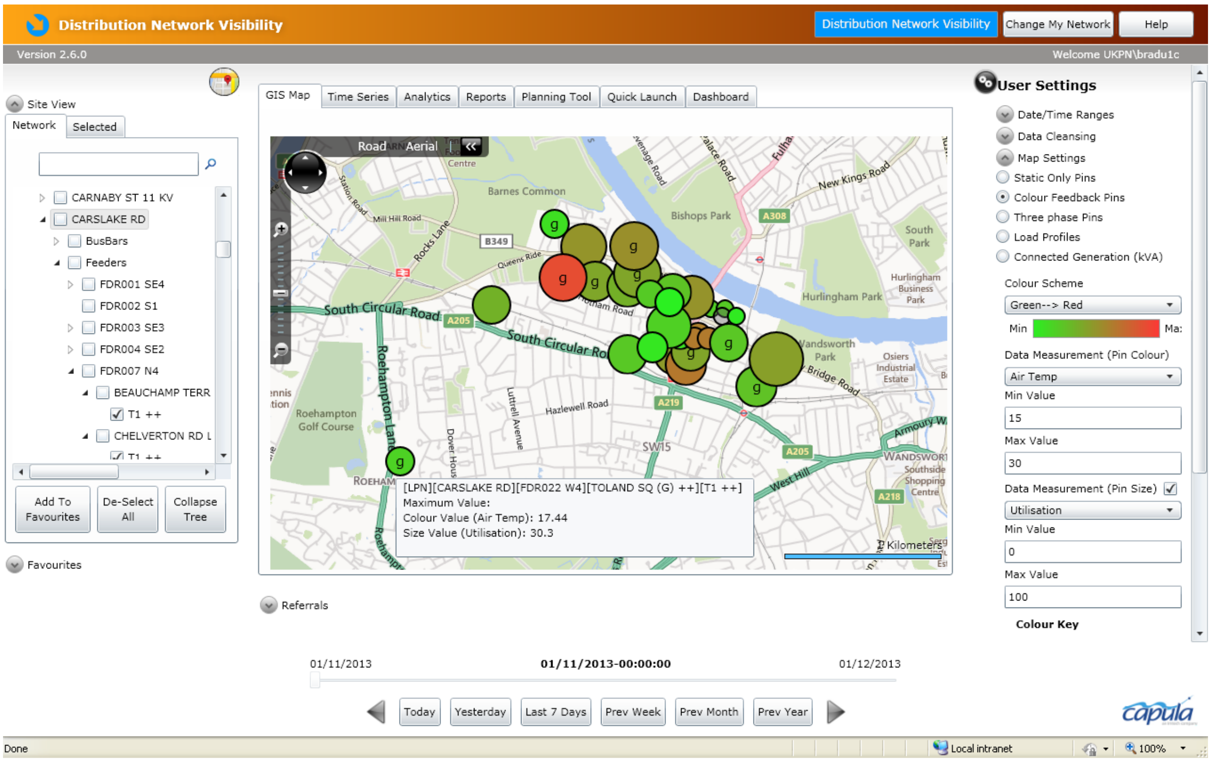


Figure D2: GIS map showing air temperature (colour) and utilisation (size) at secondary substations

Functionality includes:

- Double clicking the left mouse button to find nearby substations, new connections (referrals), smart meters or to show the spare capacity of nearby substations for extra load or to meet specific demands.
- Using the scroll wheel to zoom in and out.
- Panning, by holding down the left mouse button and moving the mouse in the required direction.
- Time slider control, to pan data values during the selected time range.

The maps can be zoomed and panned with the mouse. The Maps Settings section of the collapsible User Settings sidebar allows the map pins to show the following data:

- Static pins showing the location of the selected assets. Clicking on one of these pins will display the Site Information Window. (see below).
- Colour-feedback pins representing a data value at the site as a colour on the pin. The size of the pin can also represent a second value. The data measure represented is selectable, as is the calculation: the actual values at an instant of time can be shown and the time-slider used to see these values changing over time, or a simple summary value (maximum/minimum/average) can be shown.
- 3-Phase Pins: rectangular pins with 3 sections representing the voltage, current or Total Harmonic Distortion on each phase. Again, these pins can show the raw time-series data or a single summary value for each phase.
- Load Profiles show the load profile colour that the site profile most closely matches for the current day on the time slider. This can be used to discover changes in load profile at a site over time.
- Connected Generation uses colour to show the amount of connected generation at secondary sites.
- Quadrant Pins use colour within each segment of a pin divided into 4 quadrants to show a transformers capacity to meet an additional load during summer and winter and at weekends and weekdays.
- Referrals Pins are triangular and show the size and status of existing new connection (referral) requests.

UKPN's Referrals database of new connection requests is imported into the application and can be leveraged within the GIS tab. Double-clicking on the map allows users to view triangular map-pins showing details of all the referrals within an area. This information is also used, alongside historical load information, to calculate and display the spare capacity of substations for a given load profile type (commercial/Residential/Etc.) or to show their ability to service a load of a given capacity and profile type.

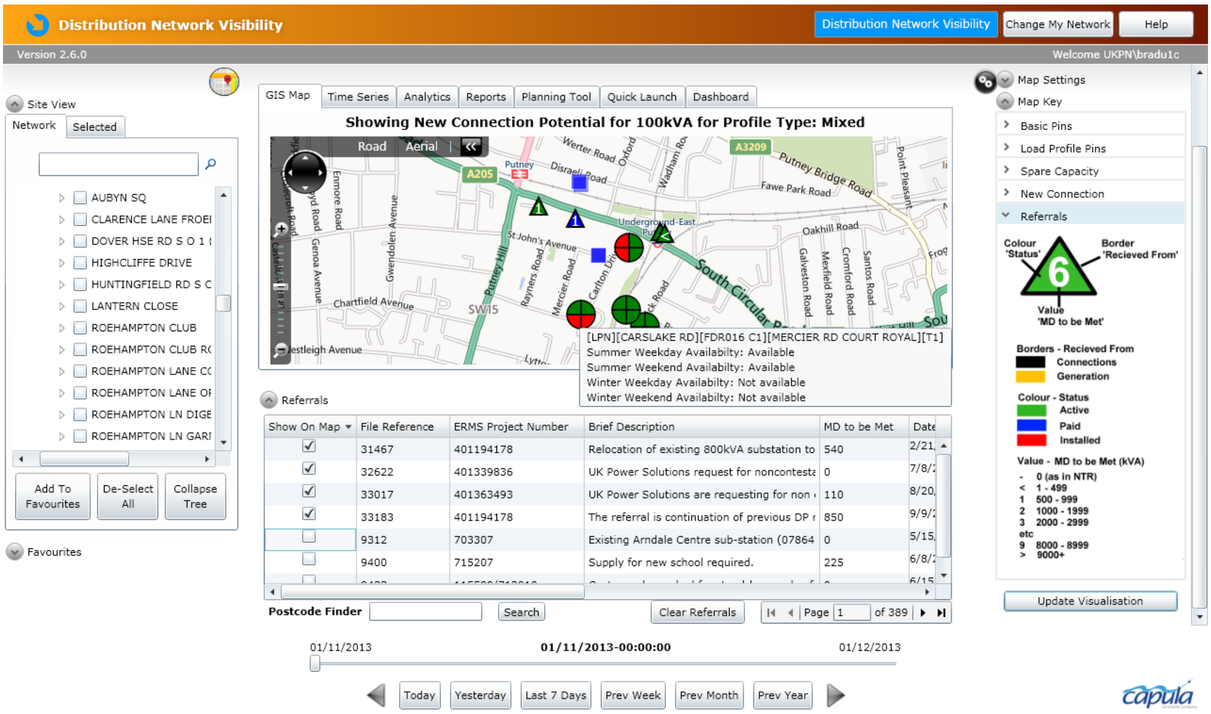


Figure D3: GIS map showing referrals and nearby capacity to support additional load

GIS Map Site Information Window

To view further information on a map pin, a left click of the mouse button, on the chosen map pin is required and a site information window will appear, as shown below in **Error! Reference source not found.**D4

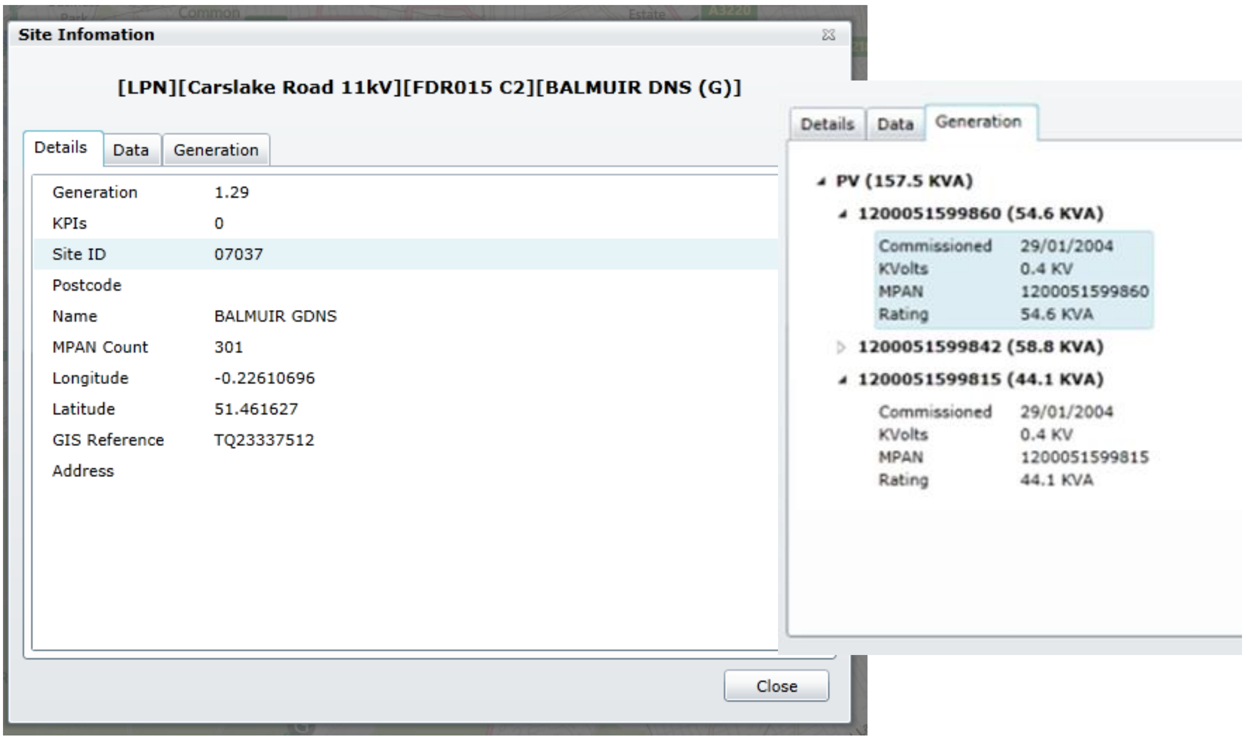


Figure D4: Site Information Window

This site information network window displays up to three tabs of information:

- The Details tab displays static information about the asset, retrieved from UK Power Networks' Data Repository and through that, from asset databases such as GE Power-On and Ellipse. The details displayed vary depending on the kind of asset.
- The Data tab displays the latest values of all data streams held in the PI historian for that asset.
- Secondary sites which have connected generation will show a 'Generation' tab with details of each item of generation connected to the site. This information is retrieved from the G83 and G59 data held in UK Power Networks' Data Repository.

Quick Launch & Shortcuts

Since there are many configurable options and settings in the application, a Quick-Launch / Shortcuts facility has been provided. This gives rapid access to the configuration settings for the most commonly needed scenarios as analysed in collaboration with UK Power Networks operations staff. This improves the user's experience and efficiency when investigating network assets and data measurements.

These options are expected to increase following the initial implementation of two quick launch and five shortcut options. As the users begin to use the application more additional quick launch options can be implemented and grouped by investigation types or the user groups.

Figure D5: Quick-Launch Dashboard

Each Quick Launch / Shortcut opens a settings window showing all applicable settings in one place, automatically pre-configured to the agreed default values. In most cases the only aspect the user must select are the root assets on which to run the Quick Launch / Shortcut.

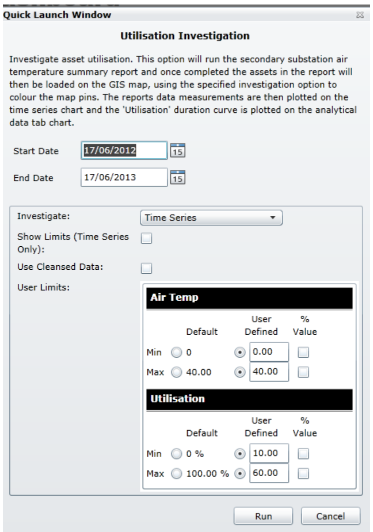


Figure D6: Quick Launch Options

Shortcuts configure a single screen for a specific purpose. For example the “Average kVA by Time of Day” shortcut will select all secondary transformers with RTUs below the selected assets and calculate their average kVA over the last year, collated by time-of-day and plotted in the Analytical data tab as an ‘Area under line’ graph.

Quick-Launches are slightly more complex and run a report before using its results to populate multiple visualisation tabs. For examples, the Utilisation Investigation quick-launch runs an air temperature report across secondary substations. When the report is completed, the utilisation is plotted on the GIS tab, air temperature and utilisation on the time-series chart and the utilisation duration curve is presented on the analytical tab.

Quick Dates are a third kind of shortcut, available on all screens as a series of buttons at the bottom of the display. These allow the user to quickly set the application’s time range to one of a number of useful periods, and to pan backwards and forwards through the data.

Reports

The Reports tab allows the user to queue a report, from a list of reports, on selected network sites over a user defined date period. The report is generated by the server and its progress can be monitored from the application. Completed reports are stored on the server and can be viewed within the application. Reports can also be made public to share with other users and can be saved locally to load into third-party applications such as Excel.

The Report tab has three sections: Report Options for configuring and queuing new reports; an Available Reports list showing queued; in progress and completed reports, and finally a Report Viewing tab for viewing an individual report. These three sections are described below:

Report Settings

Report Configuration

1- The Asset Hierarchy is used to define one or more starting points for the reports. Reports will be run against all relevant assets below the selected root assets.
2- The time-range selection options are used to define the time period over which the report will be run.
3- Report Type List. This dropdown lists all the available report types. There are a number of pre-defined reports and an 'ad-hoc' option allowing the user to define their own sets of KPIs and calculations.
4- Report settings. For each report, the corresponding data stream limits are shown and can be adjusted to alter the limits used when running the report.
5- The Generate button adds the report to the application server's report queue.

The following reports are currently available:

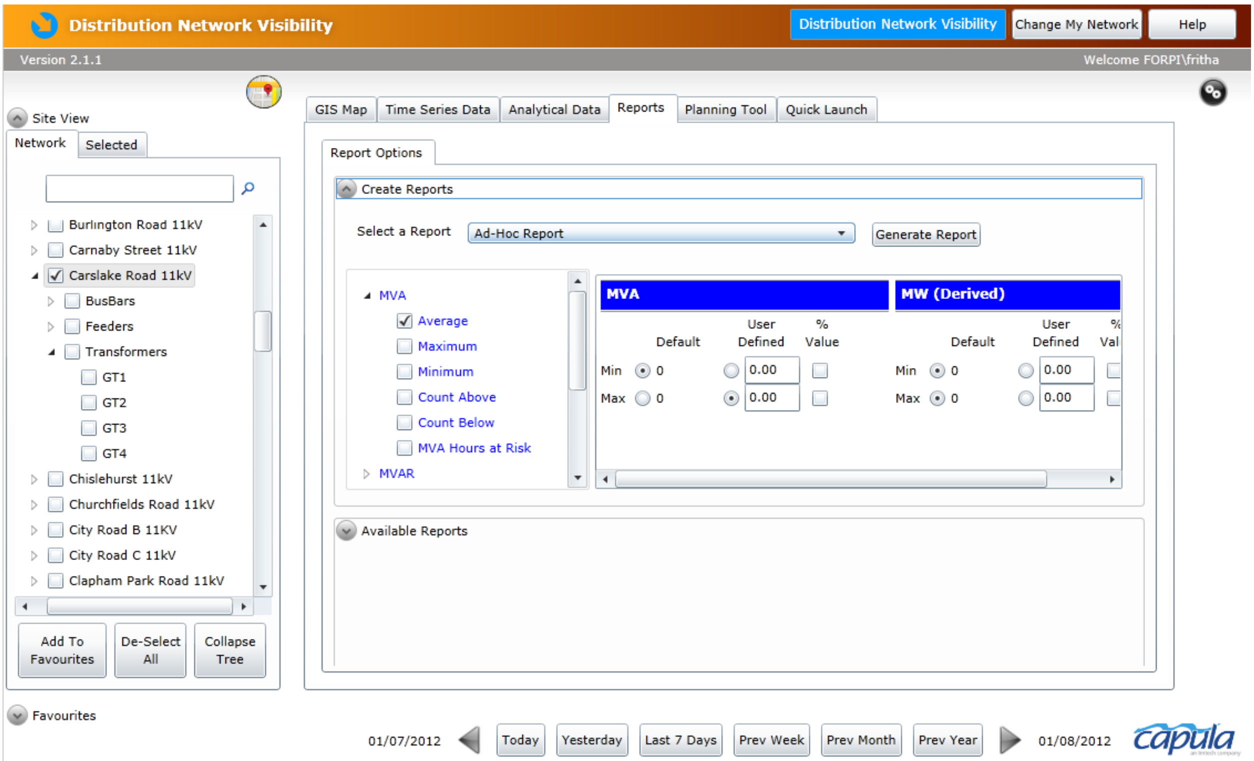


Figure D7: Report Parameters

- Primary Substation Tap-Change report detailing the number and average duration of tap changes using both Tap Position Indicator and Tap-Change In Progress data streams where available.
- Primary substation MVA Hours at Risk report showing the results of multiplying the length of time each primary substation went above its firm capacity, multiplied by the amount by which the Firm Capacity was exceeded.
- Secondary Substation Air Temperature Report showing the Average, Maximum, and Minimum air temperature and utilisation for all secondary substations whose maximum air temperature exceeds the set limit during the report time period. Also shown is the percentage of time the air temperature exceeded that limit.

- Secondary substation Voltage Report showing the average, maximum and minimum voltage, time spent above the voltage threshold and the percentage of time above the threshold that is considered 'load-related', across each phase.
- Secondary Substation Voltage and Current Unbalance Reports showing the average and maximum unbalance of each phase, along with the number of times the unbalance exceeded the set threshold and the percentage of time spent above that threshold.
- Secondary Substation Harmonic Report showing the average and maximum Total Harmonic Distortion on each phase, along with the number of times the THD exceeded the maximum limit and the percentage of time spent above this limit.
- Secondary Substation Utilisation Report showing the maximum, minimum and average utilisation and power factor, along with the number of times the utilisation exceeded its set limit and the percentage of time spent above this limit.
- Secondary Substation MDI Report showing the Oil Natural Air Natural(ONAN) Rating, latest manually recorded MDI reading and the date of that reading, and the calculated MDI reading from the maximum kVA recorded in PI over the period of the report.
- Ad-hoc report allowing the user to define their own data streams and calculations.

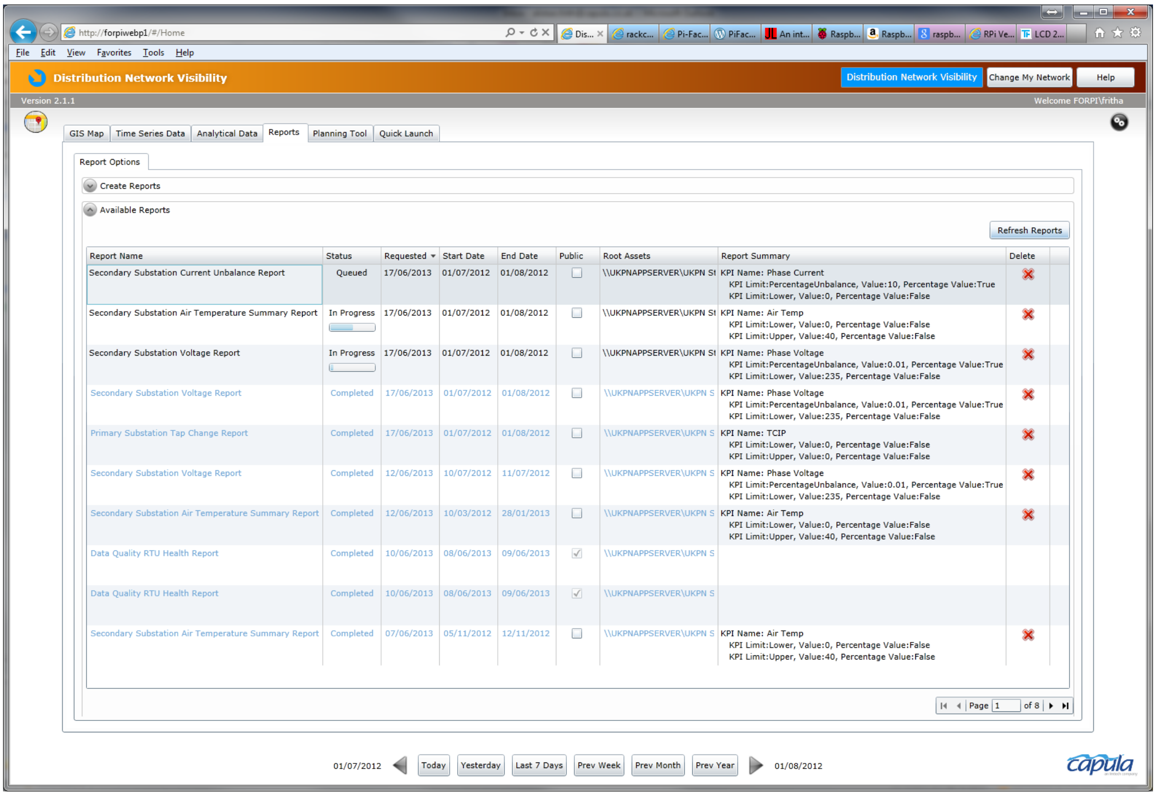


Figure D8: Available Reports List

The Available Reports List shows all reports that the user has requested and all those that have been made public by other users. From this screen, the user can see the status of their queued reports, view a completed report, delete unwanted reports and make reports public or private.

Report Viewing Tab

Clicking on a completed report in the Available Reports list will open that report in the Report Viewer tab

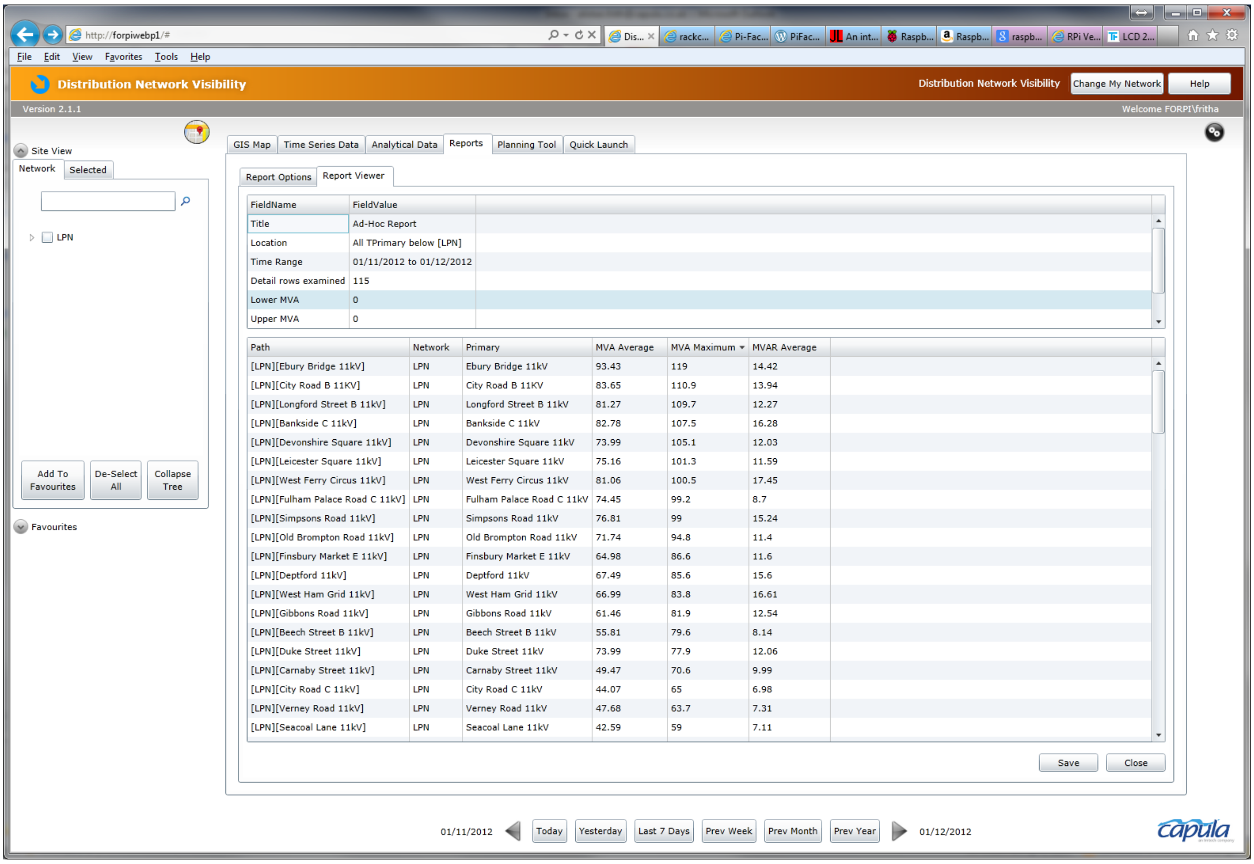


Figure D9: Report Viewer Tab

When viewing a completed report, the user can select one or more rows from the report and choose to visualise the selected assets on the GIS map, time series data tab, or analytical data tab. The user is then presented with additional options to further configure the way the information will be presented.

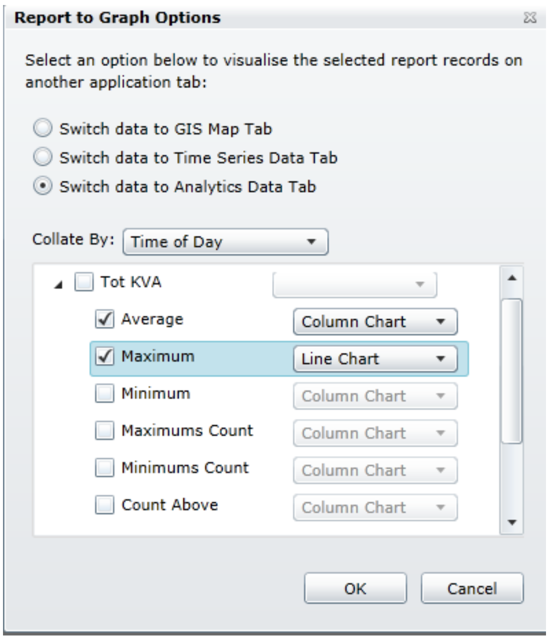


Figure D10: Report Data Visualisation Options

Planning Tool

The planner's tool provides the functionality to view feeders and feeder group loadings. The tool displays loading values for individual feeders and for the summed group over a year and a week. The tool has been designed to replicate the existing functionality of the clients pre-configured spread sheet, but within the DNV application.

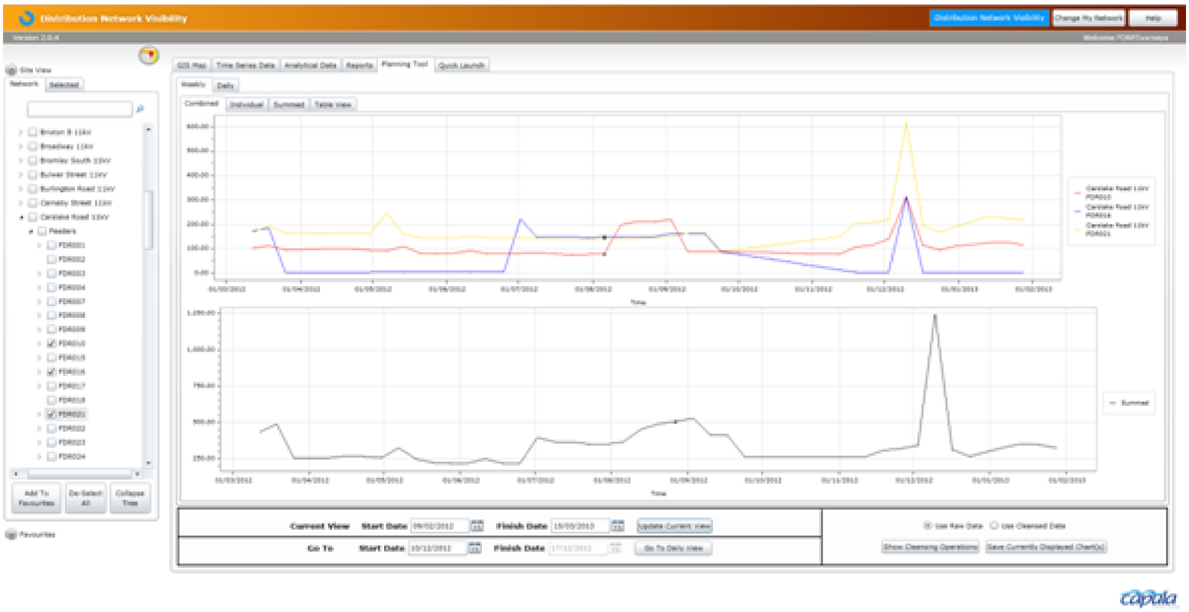


Figure D11: Planning Tool

The initial, 'Combined', tab of the planning tool shows the maximum individual loads of each feeder in the upper graph and maximum combined load in the lower one, summarised for each week over the last 400 days.

There are buttons to toggle between this 'Weekly' view and a 'Daily' view showing one week which by default is the week of the highest group loading. This 'Daily' view is summarised by each day.

In addition to the 'Combined' tab, there are 'Individual' and 'Summed' tabs which each show the corresponding graph from the 'Combined' tab in more detail. Finally there is a 'Table View' tab which shows the actual values displayed in the graphical tabs but displayed a tabular form.

A button click will populate a template spreadsheet with the information currently held in the Planning Tool. This spreadsheet is designed to be easily imported into the DINIS planning application.

This tool allows planning engineers to quickly assess the loading on a feeder group and to see how that loading is distributed among the constituent feeders.

Time Series Data

The time series data tab allows the user to generate time series data graphs, illustrating data measurements over a user defined period of time on selected sites.

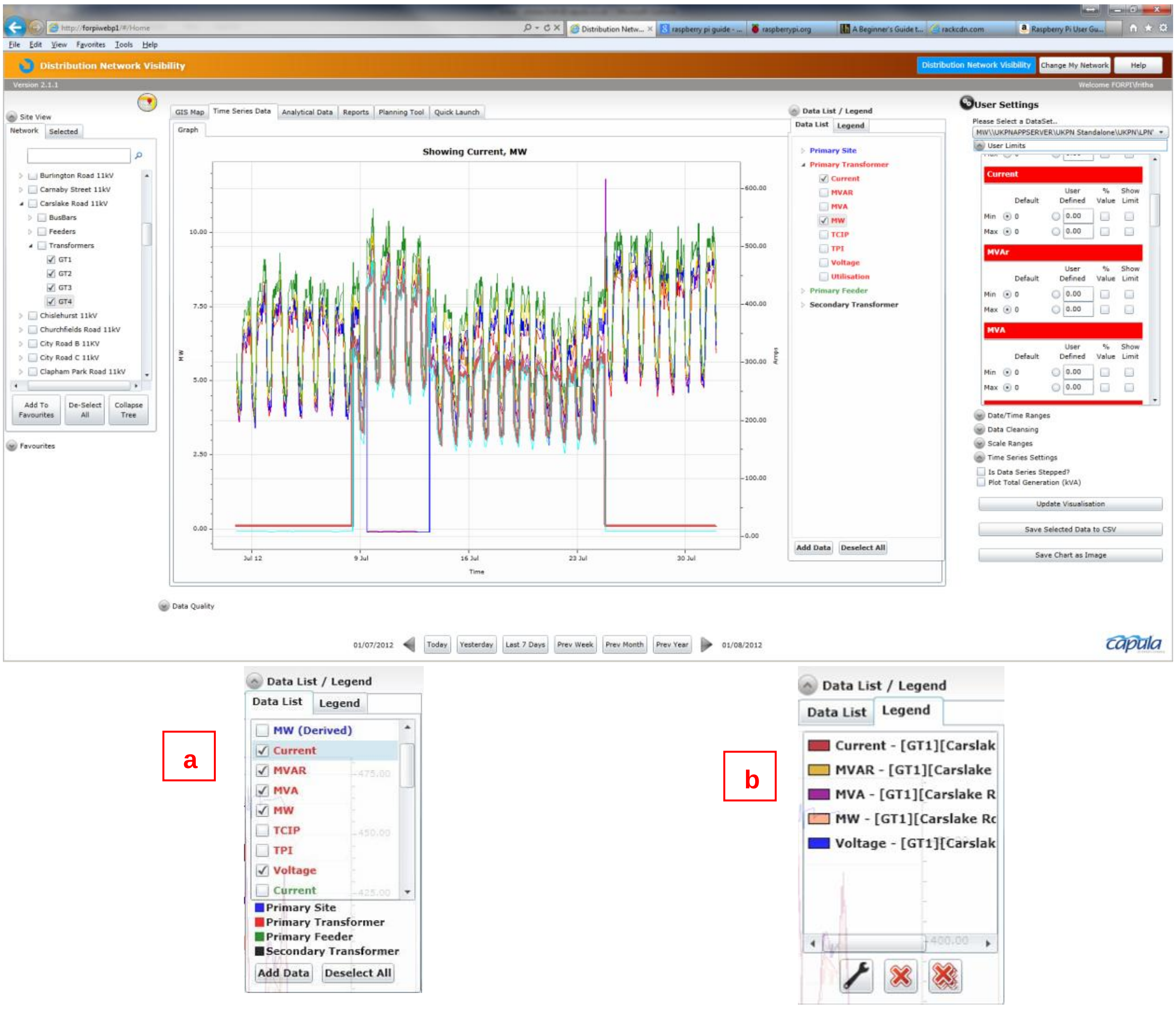


Figure D12: Time series view

It consists of these elements:

Chart Area. This displays the retrieved data and is easily zoomed and panned by clicking and dragging. It is also possible to display cross-hairs to enable precise analysis of values

Data List/Legend Dropdown. This has two tabs:

a) The Data List tab displays all the possible data streams that are applicable to the assets currently selected in the asset hierarchy. These can then be checked and added to the graph using the buttons at the bottom of the tab
b) The Legend tab lists the data streams currently displayed on the graph. These can be selected (highlighting the corresponding trace on the graph) and configured or removed from the graph using the buttons at the bottom of the tab

User Settings. This collapsible side-bar allows the user to change upper and lower thresholds for the selected data stream and to add these limits to the chart. There are also options to save an image of the chart and to save the data in a tabular form for loading into third-party applications such as Excel.

Analytical Data

The analytical data tab allows the user to produce analytical graphs on data measurement calculations over a user defined collation period (e.g. by hour-of-day), for selected sites.

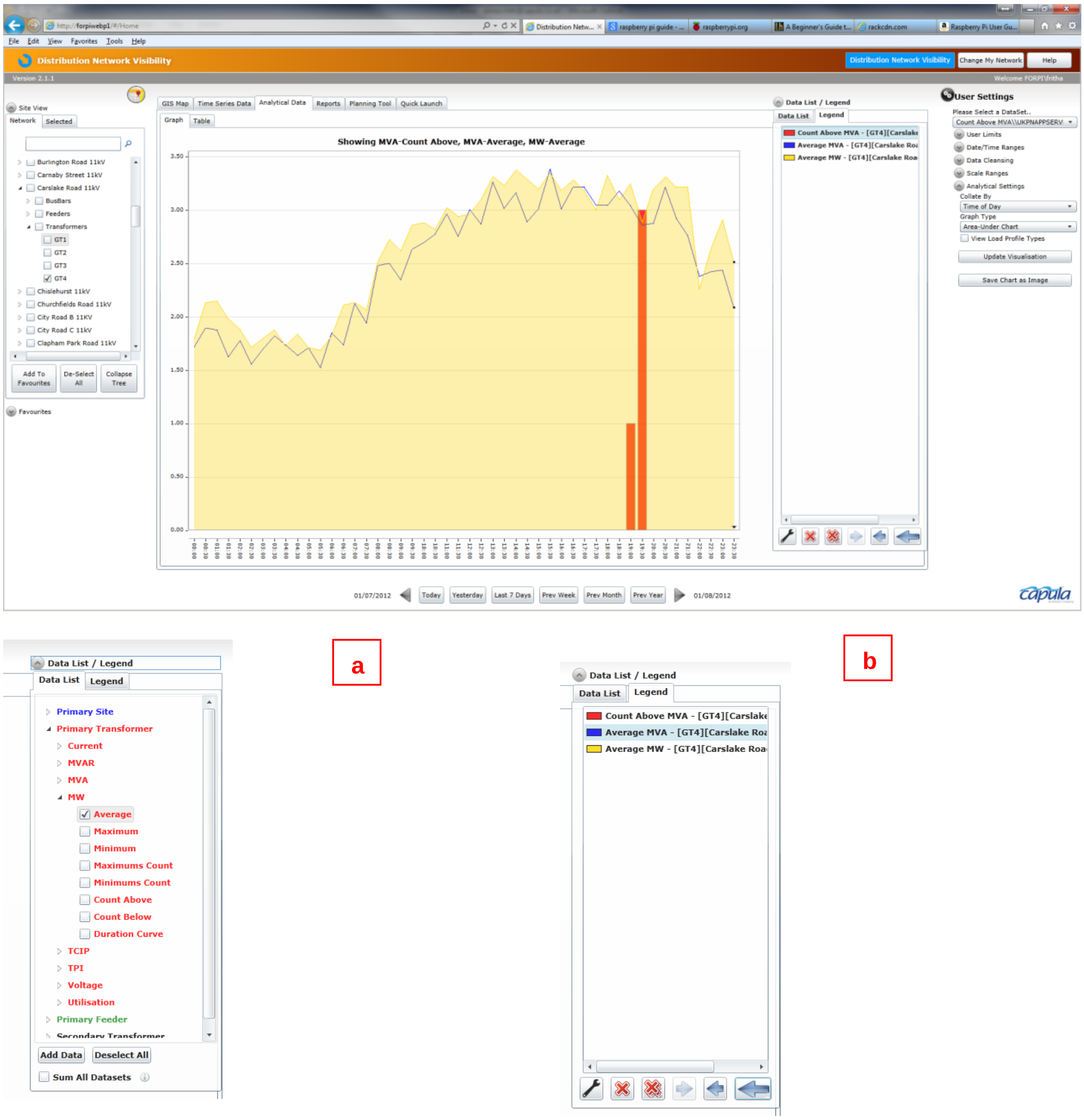


Figure D13: Analytical Data Tab

This consists of these areas:

Chart Area. As with the time-series tab, this graph can be zoomed and panned

Data List/Legend Dropdown. Again, this has two tabs

a) The Data List tab displays all the possible data streams that are applicable to the assets currently selected in the asset hierarchy, along with the analysis operations available for the data stream. These analyses can then be checked and added to the graph using the buttons at the bottom of the tab

b) The Legend tab lists the analyses currently displayed on the graph. These can be selected (highlighting the corresponding trace on the graph) and configured or removed from the graph using the buttons at the bottom of the tab

The User Settings collapsible side-bar allows the limits used in various calculations (such as ‘count above’) to be adjusted for each data stream displayed. The Analytical Settings section also allows the display type to be changed for each trace and the ‘collation type’ for the entire graph (e.g. ‘Time-of-Day’ or ‘Week’) to be altered. An image of the graph can also be saved

Graph/Table Tab Selection. The analytical values are available within the application on this tab and can also be saved to a text file

Summary Dashboard

The summary dashboard is powered by an automatic daily report. This report collects data across the entire distribution network and summarises it into a handful of key performance indicators that are then displayed on the dashboard as shown in figure D14 below.

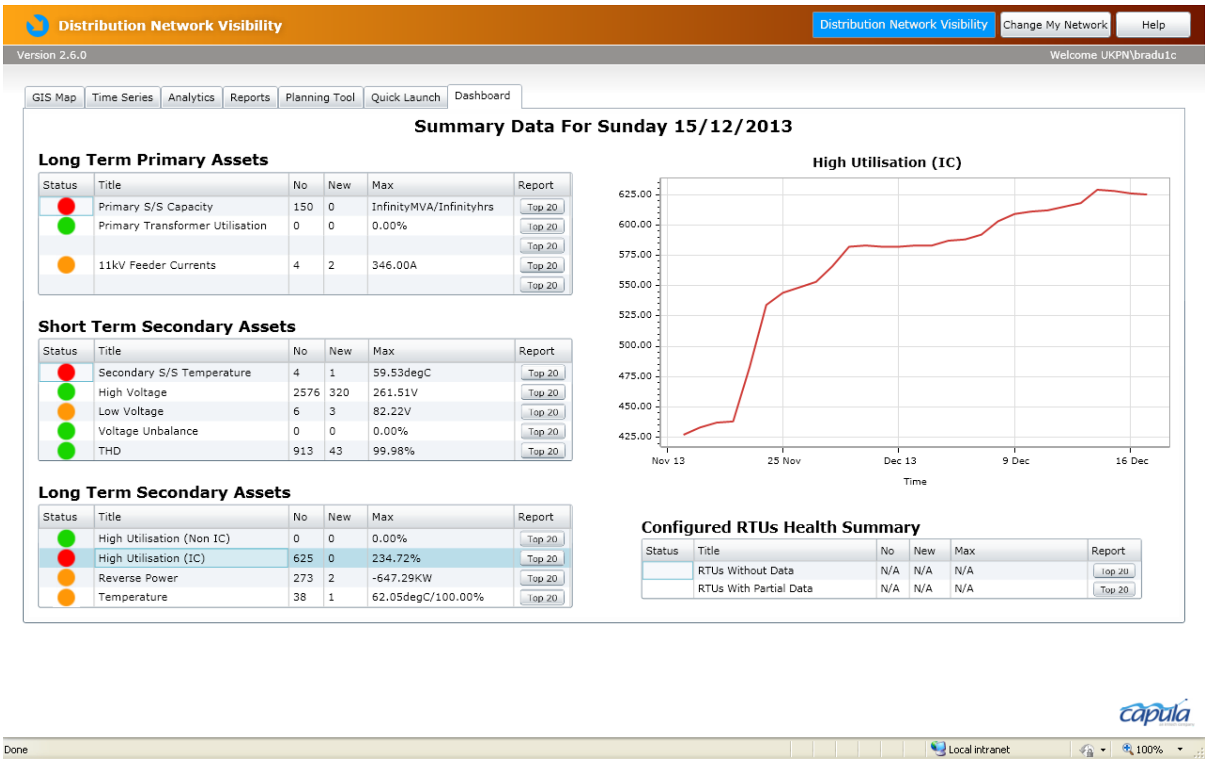


Figure D14: Summary dashboard

The dashboard can be used as a jumping-off point to other parts of the application. The ‘Top 20’ buttons each load a pre-run report summarising the worst-offending assets for the KPI and from there, assets can be selected for investigation on the Time-Series, GIS and Analytical tabs. The graph shows recent history for the selected KPI.

Appendix E: Overview of reports issued

The following reports are available to other DNOs on request.

DNV application:

REPORT TITLE	ISSUED BY	ISSUE DATE
Report 1: Quick Wins	**PPA Energy**	**February 2011**
Paper detailing the proof of concept solution to be implemented at the end of the Scoping Phase.		
Report 2: Standalone Solution Interim Report v1	**PPA Energy**	**March 2011**
Details the components of the Standalone solution identified during the scoping phase.		
Report 3: Standalone Solution Visualisation Tools Evaluation	**Capula**	**February 2012**
Evaluation of a number of visualisation technologies and comparison with the DNV requirements This resulted in a web-based solution to be selected for the Standalone phase.		
Report 4: Standalone Solution Learning Points Report	**Capula and PPA Energy**	**March 2012**
Details of the learning developed from the scoping and standalone phases The report concludes that the proof of concept highlighted a number of learning points including: Difference between GMT and BST, Half hourly averaging on power factor is not suitable, incompatibility of GE Enmac PowerOn with latest OSIsoft PI System, continued feedback benefits for the development of the visualisation solution, data quality algorithms need constant refining, significant learning was achieved from the RTU pre-commissioning tests.		
Report 5: Report on Load Profiles	**PPA Energy**	**April 2012**
This document describes the process and algorithms developed to establish a dynamic map of the secondary substation load profiles in LPN. The work covers: Clustering of the data from the RTUs in secondary substations, conception of a library of load profiles, visualisation of a dynamic map.		
Report 6: Load profiles: Library type assignment	**PPA Energy**	**June 2012**
Following the report on load profiling, this document proposes a daily process to apply to the new daily data from the RTUs. This process determines either that a new load belongs to one of the library types, or might be stored in a summary table and eventually classified as a new load type.		
Report 7: HV and LV Faults Visualisation using the DNV application	**PPA Energy**	**January 2013**
The DNV application enables currents and voltages at the LPN primary substations and secondary substations where RTUs are present to be visualised. The aim of this report is to establish what is observed before, during and after a fault. Whilst a fault is a single very short incident on network, the report considers the series of events before, during and after the fault which may be		

observed. The report concluded that most HV faults can be observed using the DNV application and the primary substation feeder current measurement, the secondary substation half hour measurement voltage dip. At present, the Control Engineers do not have visibility of an LV fault until they are informed by customers, which is usually sometime after the fault actually occurs. This report has shown that for the LV faults where the secondary substation fuse operates, a reduction in current can be observed using the DNV application. The intention was that the secondary substation event recorder data would provide further visibility of LV faults. The examples confirmed that it is necessary to use both event alarms and near real time information in sub 5 minutes samples, for the period between event inception and network stabilisation, for the effective monitoring and management of faults, rather than 30 minute averages.		
Report 8: Dynamic Visualisation of LV interconnected Networks Concept Demonstrator. Case study- LV Cascade following HV Fault	**PPA Energy**	**January 2013**
This report presents some initial examples of visualisation of a delayed LV cascade on an LV Interconnected network following an HV fault, using a concept demonstrator. It includes HV feeder and HV Group summaries providing indications of key events, estimates of load lost (MVA) and duration, and 2D and 3D visualisation techniques. The demonstration illustrates the power of these types of visualisation and logic techniques to reveal sequences, patterns, flows and risks in new ways. They point the way to improved understanding in real time of how systems perform, and the real opportunity to optimise their performance both before and during such events. Even with the limited and incomplete data set available for the case study, it was clear that there was a considerable potential for use of these techniques in both operational and other business contexts.		
Report 9: Design Document	**Capula**	**March 2013**
Detailed design of the DNV application.		
Report 10: IT White Paper	**Capula and UKPN**	**June 2013**
Document explaining the technical architecture of the DNV application and the background to why some of those technical choices were made.		

Network Monitoring:

Report 11: CRE-11-PPAE 3 phase current measurement	**Southampton University HV test lab**	**February 2011**
RTU and Powersense current measurement test report.		
Report 12: Powersense and RTU Tests at Southampton University and Installation Review at Sundridge Training Centre	**PPA Energy**	**March 2011**

Results and findings from the tests carried out at the University of Southampton and the Sundridge Training Centre to assess the suitability of the proposed Powersense externally mounted optical current sensors, for use with PILSWA, or PILSWAS steel wire armoured cables and Triplex cables.		
Report 13: Powersense Locations for Cable monitoring revised options to account for results from Southampton tests on PILSWA cables	**PPA Energy**	**March 2011**
Review of key issues and recommendations for the Powersense installations on the LPN cable networks and overhead line systems to deliver tangible knowledge about HV and LV system monitoring options for the future.		
Report 14: CT test results	**PPA Energy**	**June 2011**
The report details the results of the initial tests undertaken to determine the CT response of 3 x 1000A CT's between 0 and 8000 A. It Includes the test report issued by the testing house, Narec.		
Report 15: Procedures for the installation of Powersense monitoring on LV boards 3 phase monitoring of the LV feeder circuits of standard English Electric and Lucy LV Boards	**PPA Energy**	**September 2011**
The report details the procedures for the installation of Powersense optical current sensors on LV feeder circuits at secondary substations.		
Report 16: Procedures for the installation of Powersense monitoring on HV cables and TF tails to install 3phase optical monitoring on HV 3/c cables, HV Triplex, VV Single core and LV transformer Tails	**PPA Energy**	**September 2011**
The report details the procedures for the installation of Powersense optical current sensors on 11 kV cables and transformer tails.		
Report 17: Powersense installation review and future programme recommendations	**PPA Energy**	**September 2011**
The report details the results and findings from three Powersense installations undertaken on the LPN network, and arrangements for future 11kV and 33kV overhead line trial sites in the SPN area. It also discusses potential applications for the optical sensor technologies.		
Report 18: Powersense Standalone Phase report, Selected Case Studies and Recommendations	**PPA Energy**	**March 2013**
This report considers case studies and learning from the five Powersense sites that were commissioned under phase II of the Powersense workstream and makes recommendations for phase III consistent with the overall programme objectives for Phase III. The report covers case studies from Carslake North Ring Demonstration Network and an installation at a complex double substation, with large services and CHP generation with existing RTU transformer monitoring.		

Real time power flow:

Report 19: GE Distribution Power Flow Tool Carslake Road North Ring trial	PPA Energy	February 2013
This report details the GE DPF trial undertaken on a 4 feeder group in LPN. The basis of the DPF is load profile data which is set up for each secondary substation. A load allocation algorithm uses the measured primary feeder current and the secondary substation load profiles to determine the power flow in the 11 kV circuits. The main concern in respect to the methodology of the DPF tool is the dependency on generalised load profile data. This could be an issue as the industry moves to Low Carbon economy and the load profiles are expected to change significantly. The DPF tool produces a real time three phase load flow, the accuracy of which depends on the number of monitored secondary substations and the accuracy of the load profile data for the non-monitored substation. Strategically placed HV monitoring would provide additional input to the DPF to enable an accurate load flow to be produced. The DPF tool as it stands could be rolled out to provide a real time power flow for the LPN system. However, the report details the issues which require addressing before a full roll out to the LPN system is considered. The main ones being the need for development of a load forecaster for the secondary substations with RTU data (in order to undertake a proposed switching operation study which would allow the Control Engineers to plan outages with confidence), meshed network load flow capability and negative load allowance in the allocation algorithms.		
Report 20: SPN Small Section Networks Pilot	**PPA Energy**	**November 2013**
This report details the standalone pilot undertaken on SPN 11 kV rural networks with small section conductors. The study includes an evaluation of real time modelling tools to calculate and visualise virtual line and transformer measurements where actual measurements are not cost effective, to perform real time load flows for operational purposes and profile based planning studies.		
Report 21: City Centre Interconnected HV/LV Network and Monitoring LPN Hyde Park B Pilot	**PPA Energy**	**November 2013**
This report details the standalone pilot undertaken on a representative central London interconnected network. The study includes evaluation of real time modelling tools to calculate and visualise virtual HV cable and transformer measurements where actual measurements are not available, to perform real time load flows for operational purposes and profile based planning studies. A comprehensive toolkit of solutions is presented which can be used to monitor the majority of practical network configurations likely to be encountered and without customer outages.		
Report 22: Notes on Dynamic Rating of Transformers	**PPA Energy**	**November 2013**
The report outlines a solution to integrate the dynamic rating and the remaining life of any transformer equipped with a RTU into the DNV application. The life of a transformer, in economic and technical terms, is related to its insulation life. The project has investigated a cost-effective method for the distribution operator to determine by how much and how fast the transformers are ageing, and to identify the optimal way to operate them in real time without compromising their life. The solution adds to the benefits of Remote		

Terminal Units, located in substations, collecting and sending a number of measurements including air temperature and load.

RTU advanced features:

Report 23: Options for using enhanced capabilities of Remsdaq Callisto1 RTUs	**PPA Energy**	**October 2011**
The report details the work undertaken to understand and validate the advanced features of the RTU in order to provide additional information (including categorising events), to provide knowledge to the system users as to the status of networks and the probable cause of events.		
Report 24: Interim RTU validation arrangements – Development RTU network	**PPA Energy**	**October 2011**
This report details the work undertaken to investigate the full functionality of the Callisto I RTU, using a single RTU with an additional communication board to allow testing of the facilities and connection via DNP protocol. The RTUs have a significant number of data points and advanced features that were not currently being used by UKPN, these include ALE to identify voltage, current and harmonic excursions, and the disturbance recorder to capture fault events. These facilities were tested on a RTU in a laboratory with known disturbance events and faults		
Report 25: Remsdaq Callisto1 Calibration Summary	**PPA Energy**	**December 2012**
This report summarises the variety of test that have been undertaken on the Remsdaq Callisto 1 RTU and Clamp CTs.		
Report 26: Standalone Phase Report on Advanced RTUs	**PPA Energy**	**March 2013**
This report details the work undertaken to explore the potential of using the RTU advanced features through a small scale trial of ten Independent RTUs.		
Report 27: RTU Advanced Analysis Tools Trials with Independent RTU Network	**PPA Energy**	**November 2013**
This report details the results of the trial of independent RTUs used to examine the advanced measurements and analysis capabilities of the standard Remsdaq Callisto 1 RTUs. The disturbance recorder, alarm limit excursion and harmonic functionalities were investigated.		

Appendix F: Benefits

Benefit 1.1 Real time network power flow

Background
Control engineers currently have access (through PowerOn) to real-time data from primary RTUs, and trend graphs are available for primary substation analogue values. There are three default values for timescale: 1 hour, 8 hours or 24 hours up to the current time, users can pan and zoom the graph, trends can be added, up to 2 years of data is available, and basic calculations can be done such as the summation of feeder loads. The Control engineers can interrogate each secondary substation RTU to obtain data before planned switching, load transfers or during fault management. This benefit is associated with the provision of real time power flow information to the Control Engineers to help avoid overloading, with post fault restoration and circuit balancing. It will also help understand power flow changes due to the connection of embedded generation or increase in demand. From discussions with the Control Engineers, it was clear that the introduction of another tool in the control environment would not be acceptable. The GE PowerOn system has a power flow add on module, Distribution Power Flow (DPF). A trial of DPF was undertaken with GE on a four feeder 11 kV ring using data from the 11kV feeders, secondary RTUs and advanced monitoring sensors. Recommendations were made in respect of additions that would improve the DPF tool to enable the realisation of the identified benefits. However, it has not been possible in the timescale or budget of this project to progress this further.
Functionality requirements
The required functionality is for a three phase real time power flow tool to provide visualisation of the primary transformers and substations, the 11 kV system and secondary transformers up to the 230V busbar in terms of circuit status and loading. The tool should use the measured primary and secondary RTU data to allocate three phase load on the system at 230V. The tool should be able to forecast load to enable switching actions to be planned. The tool should display the current flow on the cables and transformers in Amps clearly for one, or all phases on a schematic diagram. The display should also be able to show voltage, apparent, real and reactive power. The display should clearly highlight overloaded and close to overloaded equipment. A report should be available detailing the load flow results including the system losses by circuit and utilisation with substation names and numbers as reference. The power flow tool should take account of system impedances and measured voltages. A report detailing the input data by node and circuit, and using substation names and numbers as references should be available. Where there are no RTUs, it should be possible to store the allocated load values in the PI historian, with clear indication that they are estimated values, for use by the DNV application.

Real time data can be affected by anomalies, and the tool should be able to identify and ignore data input values that are consistently incorrect such as flat lining, zero data and out of range. However, spikes, dips and short term zeros may be representative of a system event and should not be ignored.
Benefits
The trials undertaken have demonstrated that a power flow analysis application could deliver the following benefits: • Higher visualisation of the power flows, demand and distributed generation. • Real time visualisation of three phase currents, voltage, power (including direction), power factor and unbalance. • Real time visualisation of overloaded circuits and areas requiring immediate attention. • On networks with little or sparse existing monitored data, monitoring zones have been used to enable the estimation of currents flowing through lines and cables in a cost effective way. • Provision of operational dynamic information when managing active or highly interconnected networks. Meaning more networks can (continue to) be run in such a fashion, meaning that higher loads can be supported on existing networks avoiding the need for reinforcement. • Running the system closer to an optimum configuration and anticipation of potential deviations from planned events, resulting in the existing network being capable of supporting more load, delaying the need for reinforcement. • A virtual measurement in real time of non-monitored transformers loads. • Ability to plan switching and see results before committing the action. Resulting in fewer customer interruptions. • Highlighting of data anomalies and SCADA inconsistencies, resulting in better data that will support other tools and therefore their associated benefits. The two existing commercial power flow packages reviewed as part of the work require modification before all these benefits could be realised.
Assessment of business process improvements
Control Engineers would be able to use the load flow tool to manage the system in an optimal way to avoid overloads, plan switching, understand the effect of embedded generation and manage fault levels in real time.
Data

RTU Data	Primary Substation feeder current, load, voltage, tap changer data Secondary substation three phase current and voltage, real

	and reactive power
Other Data Sources	Asset database DINIS impedance data, generation data
Data sampling	Continuous sampling at 1 second intervals or better. Data to control tool at 1 min, 5 min or 10 min as remotely specified. Local system to make intelligent decisions re variance of the data and storage period.
Monitoring location	Primary Substations Secondary Substations
Trial details	

Carslake North Ring Pilot

The Carslake Road North ring trial demonstrated that the DPF application as it stands could be rolled out to provide a real time power flow for the LPN system. However, issues which the project considers require addressing before a full roll out to the LPN system is considered are:

- Development of a load forecaster for the secondary substations with RTU data in order to undertake a proposed switching operation study, which would allow the Control Engineers to plan outages with confidence.
- The load forecaster should allow for substituting of data following an RTU or communications failure and enable feeder loads to be used to determine load profiles for non-monitored substations.
- The application currently does not allow negative loads. In future, it is likely that power will flow from the LV system to the HV system as embedded generation increases, and the application should be able to cope with this scenario. On the interconnected LV networks this already occurs under some fault conditions (Consideration should be given to the use of the measured secondary voltage in the power flow).
- Consideration should also be given to the inclusion and use of iron losses in the losses calculation.

SPN Small section circuits trial

The trial demonstrated that installation of monitoring equipment on HV circuits can be undertaken in a non-invasive way to provide information to Control Engineers in real time about circuit power flows, loads and to allow visibility of changes in network behaviour due to embedded generation. By dividing the feeder circuit into five monitoring zones, the minimal amount of monitoring equipment was used to estimate the apparent power time-series.

Careful selection of networks, simple design rules and value engineering all have their place in reducing the costs of installation and ownership, but for the time being the overall costs per circuit mean that that application is likely to be gradual and based on specific need rather than an extensive independent roll out.

Using the data with the correct tool (e.g. an unbalanced Distribution Power Flow with a forecaster and line state estimation tools) would allow simulation of switching events to enable to Control Engineers to plan circuit outages with confidence especially in areas of small section circuits. During abnormal running conditions such as following a fault, the Control Engineers would have visibility of power flows and would be able to ensure equipment overloading was minimised.

Benefit 1.2 Prevention of LV interconnected network cascade following HV faults

Background
Some areas of network in central London are run with an interconnected LV network to reduce interruptions, or the duration of interruptions and to support higher load densities. The operation of these networks is complex, particularly under HV earth fault conditions which can cause up to full load power to flow in the reverse direction on some transformers and on sections of HV cable. During HV faults, the interconnected LV systems can remain stable for some time before cascading. Typical designs provide support for 2-3 hours but the actual period is heavily dependent on the load at the time of the fault, and the pre and post fault running arrangements. This provides a short window to secure supplies and address overloads. At present, control staff have very limited visibility of the state of the network until field staff are on site and able to report in the status as found. During HV network faults on LV interconnected networks, power flows from adjacent HV feeders via the interconnected LV networks until the HV network can be restored. During this support time, transformers, cables and fuses are heavily stressed and unless prompt action is taken, the operation of a single fuse can lead to a cascade of fuse operations resulting in widespread and prolonged outages. Visualisation of the 11 kV circuit currents, directions, transformer loadings and directions, and LV voltage will identify areas without supply or at imminent risk. This will enable Control engineers to visualise the state of such networks under both normal and fault conditions, and for Control Engineers to initiate remedial actions, target staff to priority sites, reduce the risks of prolonged overloading damage to plant, and keep customers and staff informed in near real time.
Functionality requirements
As for Benefit 1.1 Additional use of heat maps and or 2D or 3D displays to visualise the network status by phase.
Benefits
The visualisation may improve the performance of the central area networks by reducing the customer minutes lost and customer interruptions in the network. Visualisation of real time information would enable field staff to be targeted to the affected locations, without waiting for customer notifications, both immediately after an HV fault occurs and throughout the securing and/or restoration process.
Assessment of business process improvements
Control engineers will be able to see abnormal loading such as high, low or reverse power

flows and low phase voltages, and the evolving status of the system to enable them to direct resources appropriately. The following will be visible:

- The real time load and direction of the secondary transformers, which can be rapidly changing, against user defined overload and time of overload limits. Real time secondary substation temperature.
- The secondary substation three phase voltage, where depending on the evolution of the fault one phase voltage may be low, whilst the others are high.
- An estimation of the utilisation of the HV circuits.

Identification of fuses that may have operated and those that are heavily stressed will allow targeted deployment of field staff to take appropriate prioritised action to replace fuses, and alleviate overloading by manual switching or reclosure of ACBs. This will remove stress from the LV network operating in a support mode, and thereby reducing the risk of LV cascades.

Data	
RTU Data	Primary Substation feeder current, load, voltage, tap changer data Secondary substation three phase current and voltage, real and reactive power
Other Data Sources	Asset database DINIS impedance data, fault level data, generation data
Data sampling	Continuous sampling at 1 second intervals or better. Data to control tool at 1 min, 5 min or 10 min as remotely specified. Local system to make intelligent decisions re variance of the data and storage period.
Monitoring location	Primary Substations Secondary Substations (If LV power flow is required, monitoring at the secondary substation outgoing feeders and other points on the LV network is required)

Trial details

Hyde Park B meshed networks trial DPlan

This trial demonstrated that installation of monitoring equipment on HV circuits can be undertaken in a non-invasive way to provide information to Control Engineers in real time about circuit power flows, loads, and allow visibility of changes in network behaviour due to embedded generation. A selection of monitoring devices were used, resulting in a toolkit of solutions that can be used to monitor the vast majority of practical network configurations likely to be encountered in Urban HV networks, without the need for customer outages. Design rules for the placement of monitoring devices were established.

The pilot has demonstrated that accurate real time HV cable and transformer monitoring can be achieved without requiring physical equipment monitoring at every substation. Use of sequence component transforms across transformers to calculate non monitored circuits has been demonstrated.

Using the data with the correct tool (e.g. an unbalanced Distribution Power Flow with a forecaster and line state estimation tools) would allow simulation of switching events to enable Control Engineers to plan circuit outages with confidence, especially in areas with heavily utilised assets and small section circuits. During abnormal running conditions, such as following a fault, the Control Engineers would have visibility of power flows and would be able to ensure equipment overloading was minimised with the benefits of dynamic ratings of cables and transformers.

The DPlan study confirmed that creating an accurate power system model of the LV system is time consuming and challenging. The study has shown that discrepancies in the order of 30-40% can exist between load flow results based on measured RTU data and a load flow using MPAN metering data. In order to validate an LV model, it would be necessary to have information in respect of LV feeder power flows and voltages at the substations, and at points throughout the LV network (i.e. link boxes) together with knowledge of customer phase and circuit connection.

Interconnected network demonstration tool

An interconnected network tool demonstration tool was developed to demonstrate the benefits associated with visualisation of parameters such as load, voltage, power factor as it changed over a four hour fault event, whilst the LV system was operating to support the HV system.

Due to the limitations with three phase data at the time of the fault for which the analysis was undertaken, the tool was only able to provide an overview of the visualisation ideas. Over time, as system data associated with faults in the studied area is collected, this work could be developed and the benefits fully assessed.

The demonstration tool developed in Excel and Visual Basic considered visualisation of a cascade event which occurred following a fault on the HV network on an LV interconnected area at Hyde Park B.

The visualisation examples included HV feeder and HV Feeder Group summaries providing indications of key events, estimates of load lost (MVA), duration, and 2D / 3D visualisation techniques. The demonstration illustrated the power of these types of visualisation and logic techniques to reveal sequences, patterns, flows and risks in new ways. They point the way to improved understanding in real time of how systems perform and the real opportunity to optimise their performance both before and during such events. Even with the limited and incomplete data set available for the case study, the considerable potential for use of these techniques in both operational and other business contexts has been demonstrated.

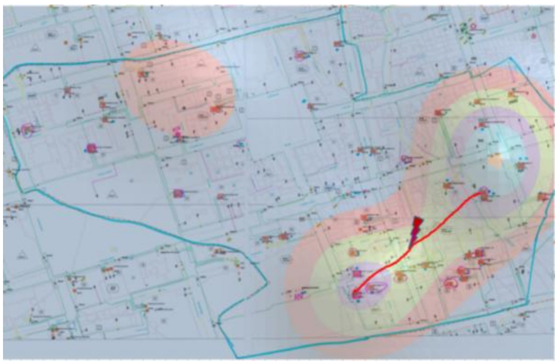


Figure F1: Example of 2D information

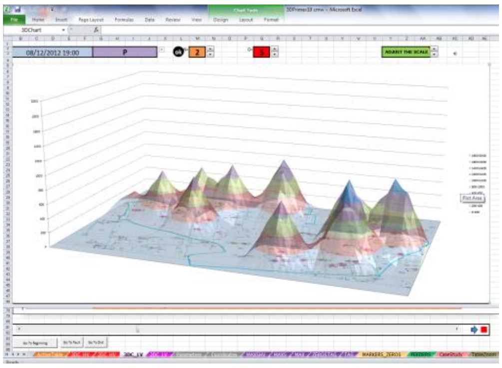


Figure F2: Example of 3D information

The tool demonstrated the following benefits:

- Sensor and Data Management – importance of consistent reliable information
  - Status and actual operation type of RTU.
  - Identification of Reversal of CTs.
  - Prolonged abnormally High, Low or Static sensor values.
  - Summaries of missing data points.
- Operational Visibility
  - Determining that previously invisible events have occurred.
  - Listing events in sequence so that the fault evolution can be tracked in real time.
  - Knowing where events occurred from both an HV and LV perspective.
  - Drill down and overview of a full set of parameters and composite calculated values.
- Identification of potential intervention points – directing resources
  - Prior fuse failure and prior ACB trips.
  - Pre-warnings of imminent events and cascades (cumulative alarms and missing data points).
  - LV fuse operations.
  - ACB events (Open/Close).
  - Loss of voltage / very low voltage (overview diagrams).
  - Knowing where stress points are (event times and positions, stress diagrams).
  - Diverting resources to target areas and assets (immediate feedback on impact of actions).

Benefit 2.1 Detection of faults and events on the LV network

Background
At present, there is no visibility of faults on the LV system and network operators generally only become aware there is an LV fault when customers phone to report loss of supply. The extent of loss of supply is determined by the number of customers contacting the DNO, and confirmed once the DNO personnel have located the fuse or other asset which has operated to clear the fault. The LV control engineers can view the data from each RTU using PowerOn, to gain some knowledge of what has happened. Loss of one LV circuit is not always obvious from the RTU analogue data which measures the whole transformer demand. Operational engineers visit the secondary substations and LV networks to determine what has happened, repair faults, replace fuses, etc. The Callisto 1 RTUs, installed in over 9,885 substations on the London network, were designed with advanced features capable of measuring a multitude of points and reporting mechanisms. These include the 1st to 15th order harmonics, calculated total harmonic distortion (THD), the capture of fault disturbance waveforms, and alarm reporting when measurements such as THD, exceed a defined limit. Prior to the project, these advanced features have remained unused by UK Power Networks nor, as far as Remsdaq are aware, have they yet been used by anyone else. The advanced features of the Callisto 1 RTU were investigated using an independent RTU (iRTU) set up. The investigations considered the benefits associated with both the RTU Analogue Limit Excursions (ALE) and the Fault Disturbance Recorder (FDR) to identify opportunities for low voltage fault and incipient fault detection and location.
Functionality developed
From the RTU: 1. High/Low voltage and High current/power alarms: to provide warning of abnormal network conditions which need investigation, and potential of incipient or current fault conditions. 2. Voltage and current harmonic THD alarms: to provide warning of high levels of harmonic generation which need investigation, and possibly incipient or active fault conditions. 3. Excursion and disturbance alarms: to provide system wide awareness capability with historical trends visualised across time and geographically to reveal hotspots of network abnormalities. In order to achieve the benefits from the ALEs and FDR the following were carried out: 4. Protocol Converter upgrade to enable RTU reconfiguration completed.

5. ALEs remotely configured. 6. RTU configured for fault detection. 7. Active communications link to server in order to notify of RTU data capture. Before these could be displayed in the Distribution Network Visibility application, the following would need to be developed: 8. Modifications to GE FEP and central database to receive and store ALEs appropriately. 9. Reports of ALE and FDR operation by type: Geographical, historical, rate of change, used in conjunction with Fault Logs, include a means of validating that any incipient behaviour has been remedied by maintenance. 10. Generation of alerts upon configurable conditions. For example, if the number of FDR operations connected to particular primary substation exceeds a threshold for given period of time.
Benefits
The visualisation should improve the performance by reducing the customer minutes lost and customer interruptions in the network. This will also bring a reduction in the cost of customer enquiries and voltage complaints. The visualisation will also identify incipient faults before they result in an outage. Benefits may also be gained in having an overview of system health in areas such as asset degradation, power quality, trend assessment, performance indication (by area).
Assessment of business process improvements
The knowledge gained from the ALE and FDR operation may assist in the detection of incipient faults which can be removed before a failure occurs.
Data

RTU Data	Fault Event Recorder Alarm Limit Excursions
Other Data Sources	Fault data records, switching logs
Data sampling	Disturbance recorder 5 seconds of data, resolution > 4 kHz, settable trigger threshold and pre and post trigger point criteria Use of alarm limits
Monitoring location	Secondary Substations

Trial findings

The investigation has demonstrated the RTU capability to record ALEs and a 50 cycle window of phase voltage, phase current and neutral current waveforms within an internal buffer, notify control of the capture and store of waveforms (until manually erased via remote control or automatically erased after 4 days). The remote download of FDR data has been proven with the capture and analysis of more than 80 live network events.

Some examples of ALEs obtained during the trial follow:

Example of network event monitoring:

A series of "Low Voltage" transients of 40-80ms duration with a voltage dip of approximately 8% were reported across the iRTU network, which may reflect a transient dip event on the higher voltage systems as no relevant faults were recorded in the faults database at this time:

Time	Substation	PointALE	ALE Seconds	Peak Value	Average Value
21:42:05.464	Nella RdT2	<Low>Red Phase Volts	0.08	217.8	220.1
21:42:05.464	Nella RdT2	<Low>Blue Phase Volts	0.06	221.6	221.64
21:42:07.266	Clarendon Rd	<Low>Red Phase Volts	0.06	223.3	224.71
21:42:07.266	Clarendon Rd	<Low>Blue Phase Volts	0.06	224.2	224.71
21:42:07.364	Harts Lane	<Low>Red Phase Volts	0.06	223.1	223.98
21:42:07.636	Harts Lane	<Low>Blue Phase Volts	0.06	224	224.27
21:42:08.174	Floss St	<Low>Red Phase Volts	0.04	214.3	214.39
21:42:08.174	Floss St	<Low>Blue Phase Volts	0.04	216.8	216.88
21:43:58.147	Riley Rd	<Low>Red Phase Volts	0.08	216.6	219.37
21:43:58.147	Riley Rd	<Low>Blue Phase Volts	0.06	217.4	217.98

Table F1: Example of ALE data

Example of FDR available alarms:

During 2013, 2 faults occurred at Belgrave Street, Troon House substation, which had a history of reporting "fault data available" buffer alarms.

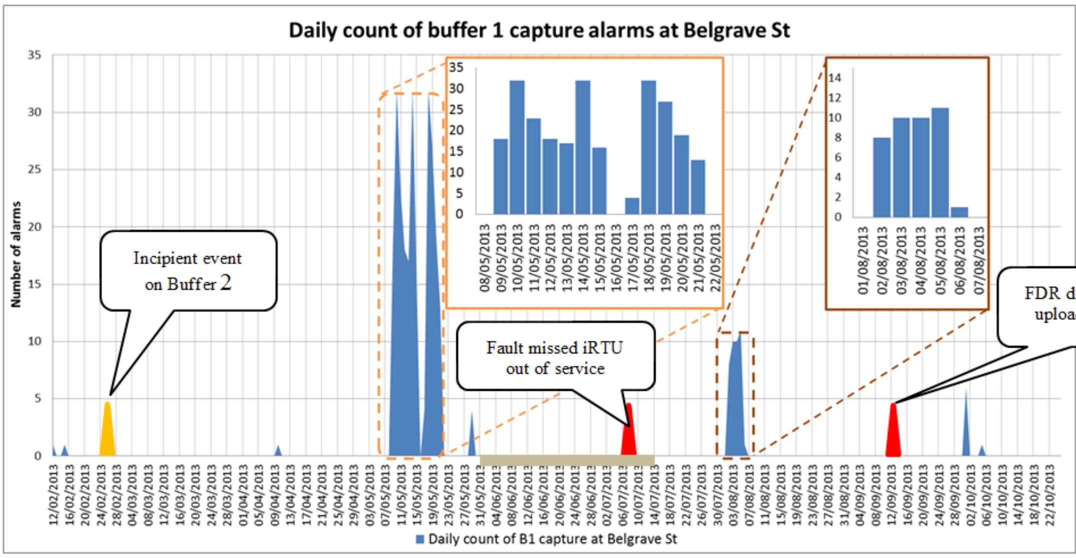


Figure F3: Example Daily count of Buffer capture alarms at Belgrave Street, Troon House

The disturbance on the current and voltage waveforms of the recorded incipient event (Figure F4 and F5) lasts more than 700ms:

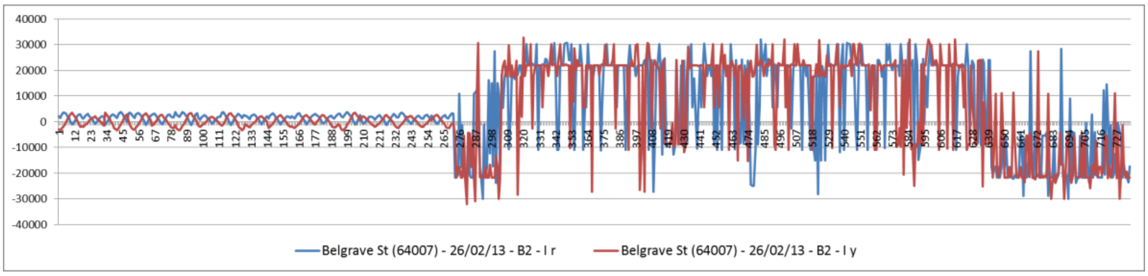


Figure F4: Incipient type current event capture from Belgrave Street, Troon House Buffer 2

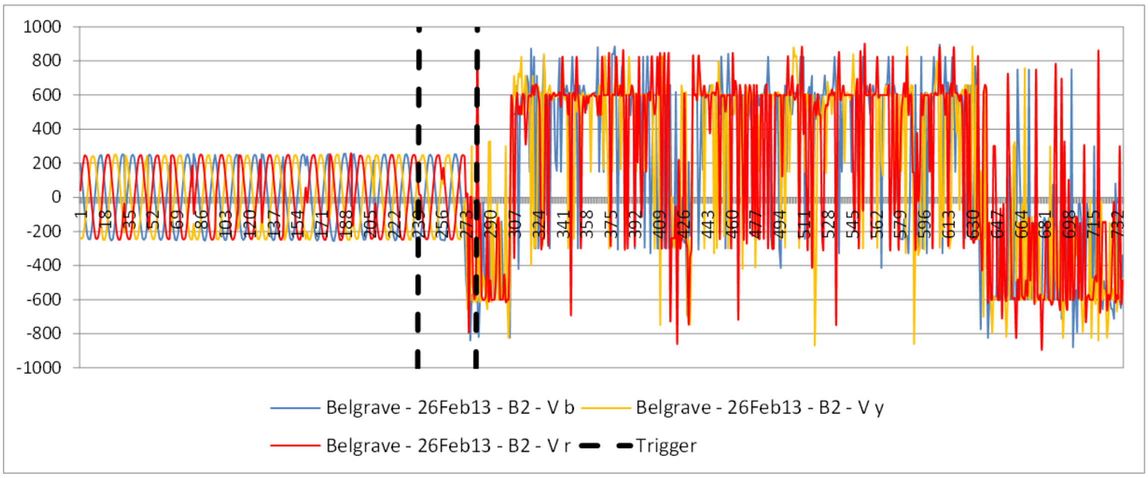


Figure F5: Three phase voltage

Benefit 3.1 Voltage investigation

Background
DNOs have a statutory obligation to maintain the voltage at the consumer meter at 230V +10%, -6%. This is presently managed by the Network Operations business unit responding to customer complaints. If the issue cannot be addressed through a simple system reconfiguration, it is referred to the Planning department for a reinforcement resolution. As additional demand is added to the distribution network, for example due to electric vehicle charging and heat pumps, the system voltage may fall. On the other hand as distributed generation is connected to the distribution network, the voltage may rise. The daily pattern of electricity use may change with future demands and the use of smart metering. As a consequence, it is anticipated that voltage control may become an issue.
Functionalities Developed
The dashboard reports the number of substations where the voltage at the secondary substation exceeds the set parameters.

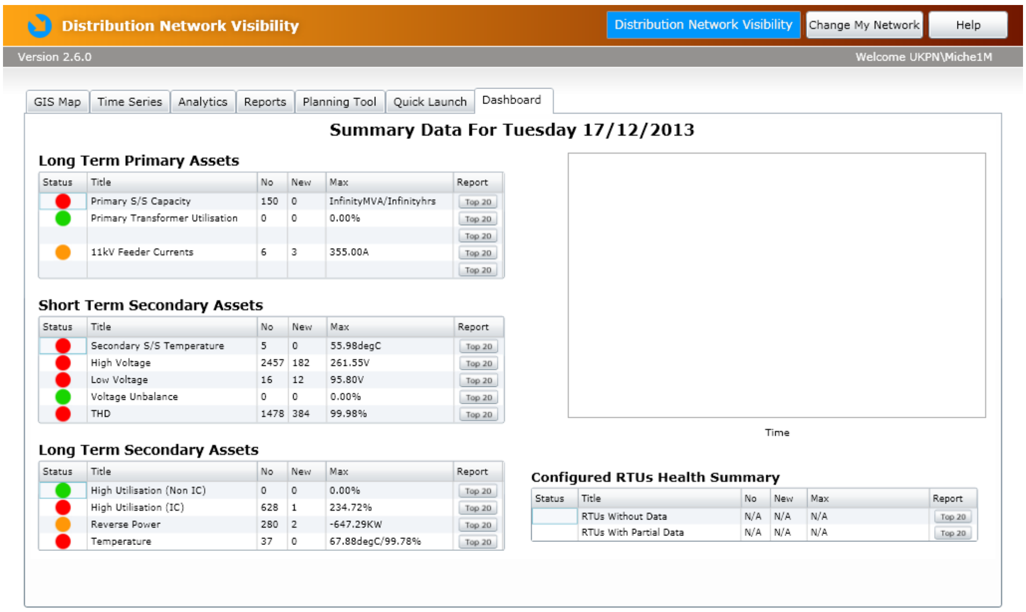


Figure F6: Dashboard

The DNV application can be used to obtain a report of secondary substations with voltages above and below limits for a user defined period. The statutory limits are used as a default, but the user can adjust the limits to account for voltage drop beyond the substation as required.

Network	Primary	Feeder	Secondary	Transformer	Red Average	Red Maximum	Red Minimum	Red Pct Time Above Total
LPN	ABERDEEN PL B 11KV	FDR003 S3	BAKER ST R O 38-52	T1	245.62	252.35	235.78	99.93
LPN	ABERDEEN PL B 11KV	FDR007 S5	GLENTWORTH ST BERKE	T1	245.2	252.34	238.88	99.93
LPN	ABERDEEN PL B 11KV	FDR013 N2	ST EDMUNDS TERR MWB	T1	248.8	252.32	251.66	99.93
LPN	ABERDEEN PL B 11KV	FDR001 S1	BALCOMBE ST 22-30 ++	T1 ++	248.01	251.35	242.06	13.07
LPN	ABERDEEN PL B 11KV	FDR003 S3	GLENTWORTH ST DORSE	T1	243.54	250.89	236.51	99.93
LPN	ABERDEEN PL B 11KV	FDR010 N4	WELLINGTON RD EMBAS	T1	247.6	249.57	249.19	99.93
LPN	ABERDEEN PL B 11KV	FDR006 S4	PADDINGTON ST KENRIC	T1	247.73	249.13	248.78	99.93

Figure F7: Report

The report identifies the percentage of time that the voltage at each substation is outside the limits, and whether the time of maximum or minimum voltage is load related. The three phase voltages can be displayed on a time series or analytical graph, and can be plotted with other parameters such as the primary substation voltage.

A GIS view with coloured map pins can be used to view secondary substations and the range of voltages over time using a slider, or by maximum, minimum or average over a period of time.

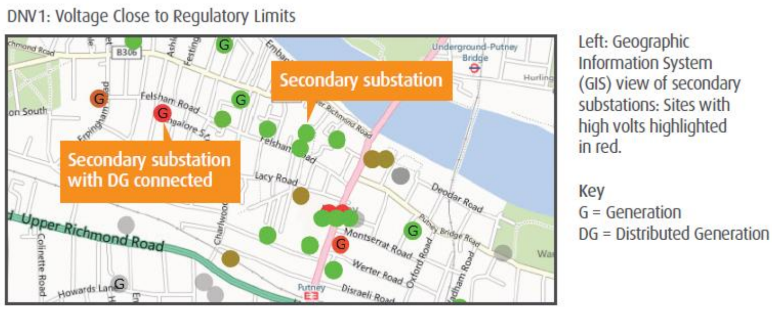


Figure F8: GIS Map

Benefits

The benefits of these functionalities are associated with network visualisation for Network Operations and Planning:

- Help engineers identify and understand the causes of high and low voltage issues, by quickly assessing the historic transformer voltage and load information. The analytical tools enable time of day analysis for voltage and load comparison, and visualisation of daily load profiles.
- Inform decisions as to whether to undertake LV monitoring to investigate a voltage issue.
- Help identify potential links between distributed generation and voltage issues.
- Assist the planning engineers to make robust decisions as it becomes necessary to adjust planning criteria in terms of voltage headroom, and transformer and feeder capacity to allow for the distributed generation.

Business process improvements

The DNV application highlights areas of maximum and minimum voltage for attention by Network Operations, possibly ahead of a customer complaint being logged. Engineers can use the application to gain an overview of the historical voltage / load profiles / generation, and either send someone to site to take spot measurements, install measuring equipment over a period of time, reconfigure the system or pass the issue to planning.

Planning engineers are using the DNV application to significantly speed up and improve the efficiency of data input to their planning tool, DINIS. This enables them to undertake studies to identify reinforcement actions that could resolve voltage issues.

Data

RTU Data	Primary Busbar Voltages Primary Transformer Tap Changer information Secondary Three Phase Voltages kVA
Other Data Sources	Distributed Generation records
Data sampling	Half hourly averages
Monitoring location	Primary and Secondary Substations

Case Study

This case study details an area of network where the voltage at the secondary substation exceeds limits when the utilisation is low. It is possible that at customers' premises close to the substation, the voltage limits are also exceeded.

The DNV application reported high maximum voltage for the last 12 months for substations in the St James area (Figure F9). Further investigation using the application provided historical data for Red Phase Voltage (Figure F10) and Utilisation (Figure F11) suggesting high maximum voltage during the night.

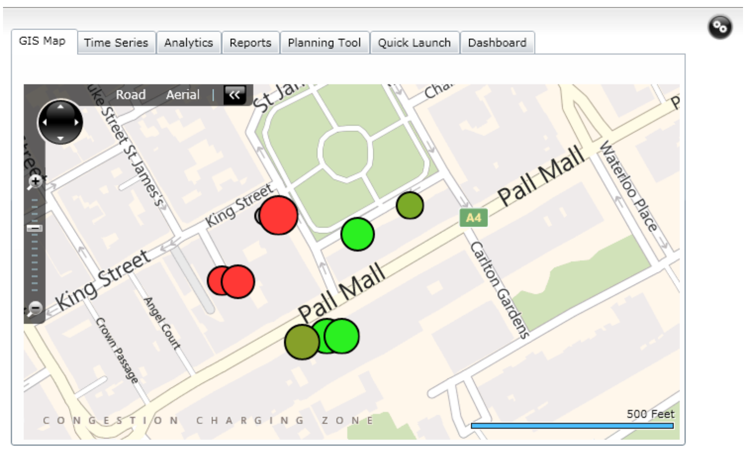


Figure F9: Maximum Voltage Substations in St James's Square during July 2013

Pin colour Maximum Voltage at substation: Red 253 V or greater

Pin size Maximum Utilisation at substation

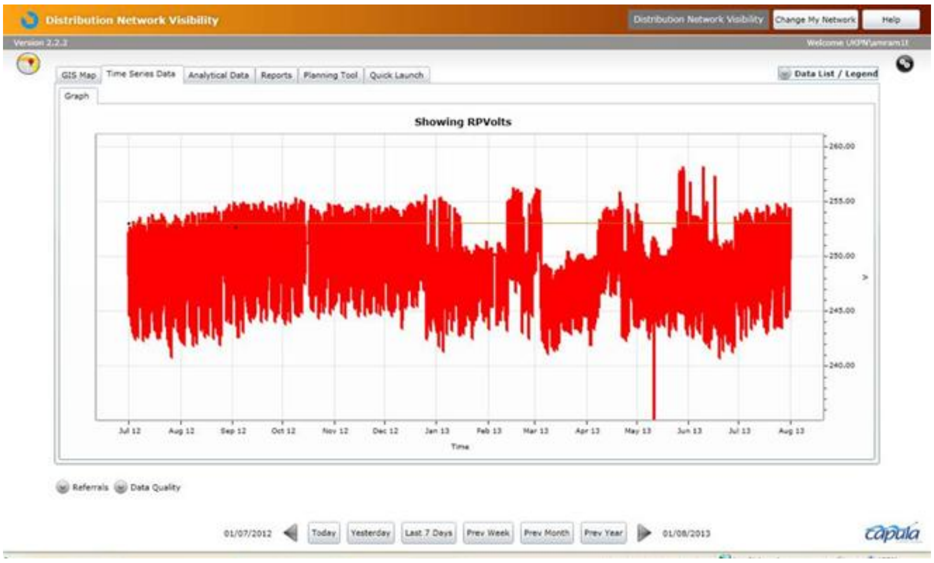


Figure F10: Substation half hourly average Red phase Voltage for last 12 months
Voltage exceeding limits

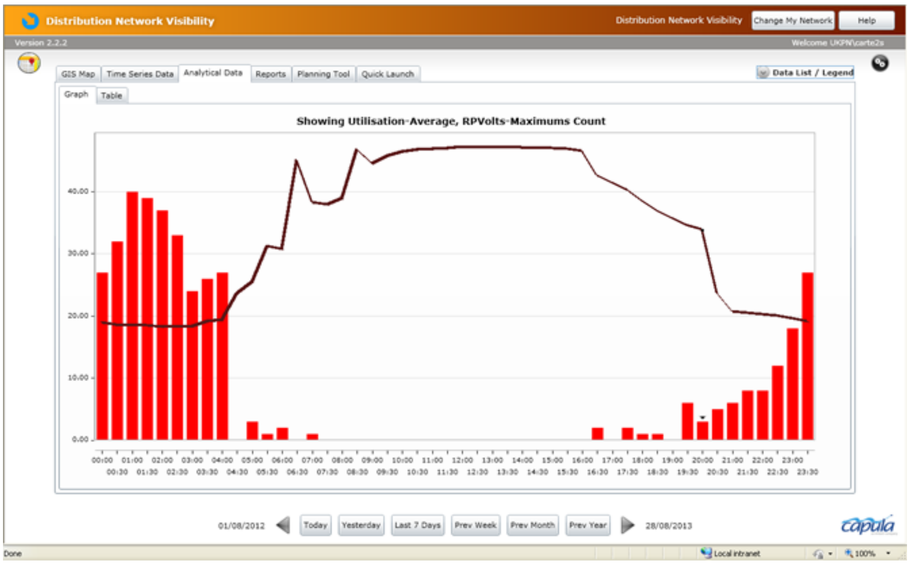


Figure F11: Maximum voltage and average load based on time of day
Number of red phase voltage excursions: Red; Utilisation: Brown.

Substations in the area have a commercial load profile, therefore low load during night. Although the primary substation voltage reduces at night the secondary substation voltage exceeds statutory limits (253 V) during the night.

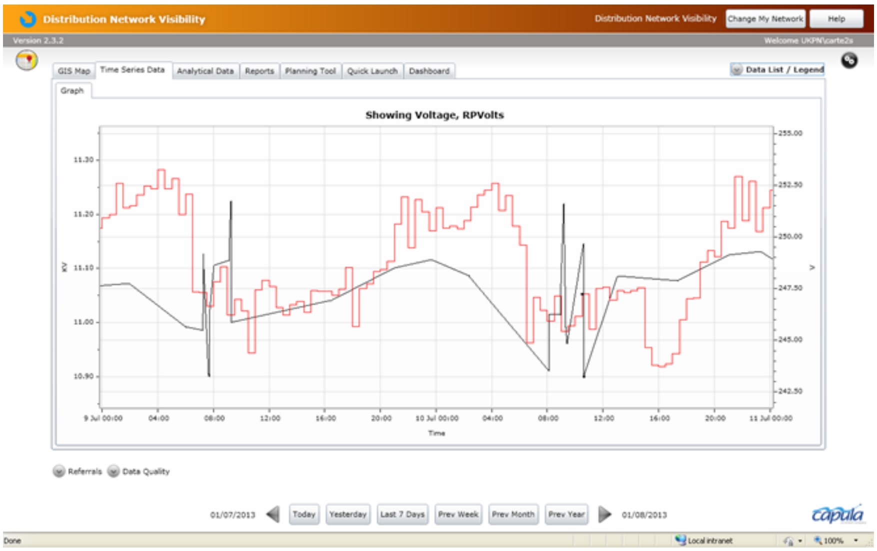


Figure F12: Primary substation and secondary substation voltage (2 days)
Secondary Substation red phase voltage: Red, Primary Substation GT1 voltage: Black

Benefit 3.2 Identification of areas with poor power factor

Background

To maintain voltage within limits, reduce system losses and extend equipment life, power factor should be typically kept between 0.9 lagging and 0.95 leading.

Where DG purely supplies active power such as LV-connected Photovoltaic (PV) generation, the reactive power demand is not met by the DG and has to be supplied by the DNO. In this case, the active power demand would reduce and the reactive power demand remain similar, leading to a lower power factor at the secondary substation and a possible increase in losses. Power factor can be managed by the DNO or the customer using power factor correction devices or by active correction using smart generators.

Functionalities Developed

The DNV application helps engineers to identify and understand the causes of abnormal power factor by quickly assessing the historic power factor and voltage information. The analytical tool enables time of day analysis.

The DNV application can be used to obtain a report of secondary substations with power factors above and below limits for a user defined period (Figure 13). The user can select to use a calculated power factor, which is generally more accurate than the RTU half hourly average.

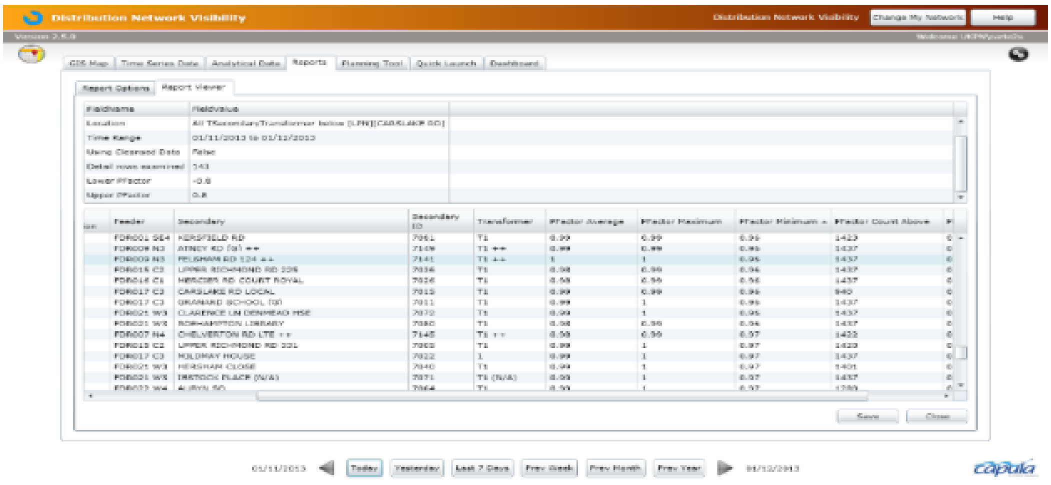


Figure F13: Report

Actual and calculated power factor can be displayed on a time series or analytical graph, and can be plotted with other parameters such as real and reactive power.

Benefits

The benefits of this functionality are associated with network visualisation for Network Operations and Planning: • Help to inform decisions as to whether to engage with the customer and/or consider the installation of compensation equipment or smart generators. • Whilst planning, a fixed power factor is typically used. The DNV application gives access to actual power factors. • Improvement of the power factor would improve voltage control, release system capacity and reduce losses.
Business process improvements
The DNV application highlights areas of the network where power factor is outside traditional limits and allows the engineer to assess the impact of distributed generation.
Data

RTU Data	Secondary Power Factor (RTU and calculated from kW and kVAr) Three Phase Voltages Real and Reactive Power
Other Data Sources	Distributed Generation records
Data sampling	Half hourly averages
Monitoring location	Secondary Substations

Example

This example combines the use of the DNV application visualisations with advanced monitoring sensor measurements to understand the real and reactive power flows around a substation with downstream connected CHP.

A report determining average, maximum or minimum power factors can be run for a user selected period of time across the LPN network. Either of, or both, the reported RTU power factor or the power factor calculated from P and Q can be used.

Secondary	Transformer	PFactor Average
CROWN LANE R O LIBRARY (G) ++	T1 ++	-0.77
CROWN LANE R O LIBRARY (G) ++	T2 ++	-0.8

Table F2: Example of DNV Power factor report

There is a 350 kVA connected CHP plant downstream of this site.

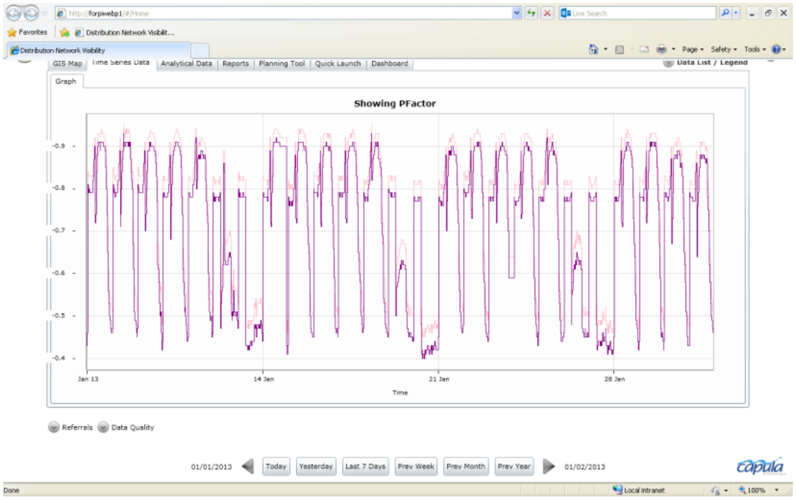


Figure F14: DNV T1 and T2 Power Factor, 25 days, January 2013

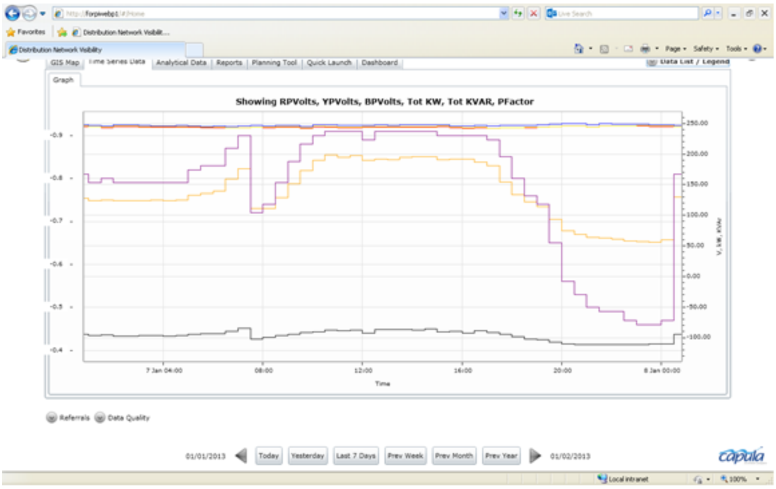


Figure F15: DNV T1 3 phase voltage, kW (orange), kVAr (black) and pf (purple), 1 day January 2013

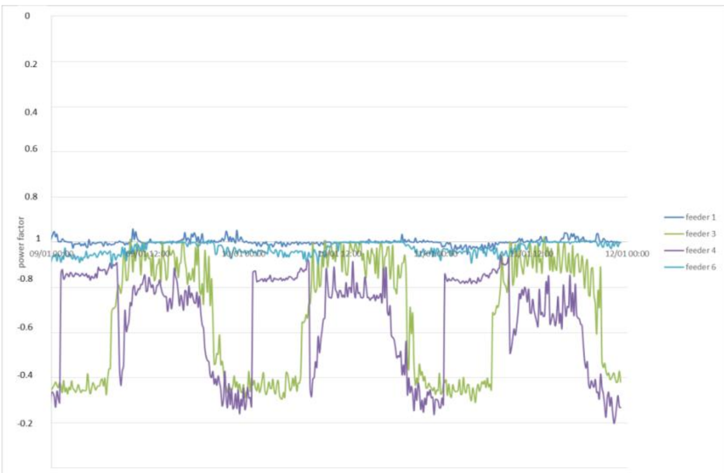


Figure F16: Individual Feeder Power Factor, 3 days in January 2013

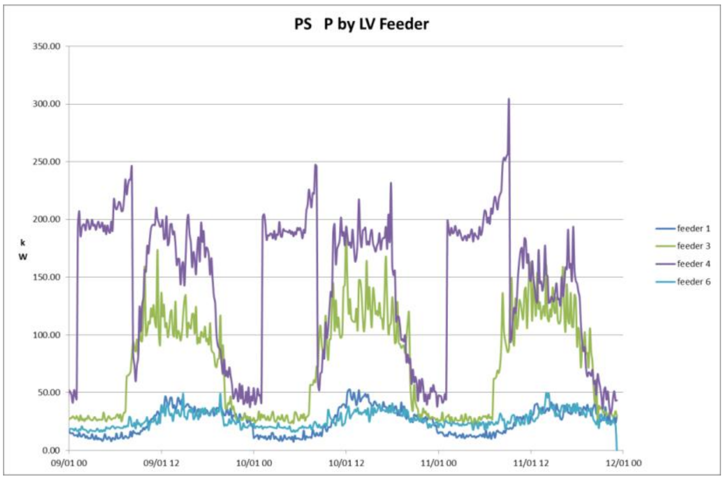


Figure F17: Individual Feeder Power 3 days in January 2013

Figure F18: Individual Feeder Reactive Power, 3 days in January 2013

The entire system operates at a leading power factor. Step changes in real power observed on feeder 4 are assumed to be due to the operation of the CHP plant. It appears that there is also some fixed power factor correction of approximately:
P3 70 kVAr
P4 150 kVAr lead

The leading power factor is probably due to fixed power factor correction equipment and the operation of the CHP plant. Typically to maintain voltages within limits and reduce system losses, power factor should be kept between 0.9 lagging and 0.95 leading. Understanding where the power factor is excessive, either lagging or leading, will identify areas where improvements should be made. A reduction in the leading power factor could be obtained by better control of the power factor correction equipment by the customer. This would reduce system losses and extend the DNO equipment life.

Benefit 3.3 Identification of LV out of balance and harmonics

Background

The secondary substation transformers are earthed on the LV side and any significant voltage unbalance is an indication that there is a physical problem. Current unbalance is to be expected as customers are connected to either all three phases or a single phase at LV, and it is unlikely the demand on each phase will be the same. A large level of current unbalance will result in a high neutral current and an increase in system losses. When this is consistent throughout the year, mitigating measures should be considered.

Voltage harmonics are generally considered of greater importance to the network operator as a distorted voltage supply poses a risk to customers, as well as protection and control equipment. However, current harmonics can result in increased current in the neutral conductor which cause temperature rise in transformers and switchgear. This accelerates asset aging as well as significantly increases system losses in the transformer windings and core, as well as in transformer tails and LV network cables. If harmonics are observed to be high, mitigation measures can be considered.

Functionalities Developed

The dashboard (shown on figure F6) reports the number of substations where the voltage unbalance exceeds 3% and where the voltage THD at the secondary substation exceeds 3%.

The DNV application can be used to obtain a report of secondary substations with Voltage unbalance, Current Unbalance or THD above limits for a user defined period. The user can adjust the limits to consider different levels of unbalance or THD.

The report identifies the maximum current and voltage unbalance or voltage THD at each secondary substation, and the percentage of time that it is above the limits. The parameters can be displayed on a time series or analytical graph, and can be plotted with other parameters such as load.

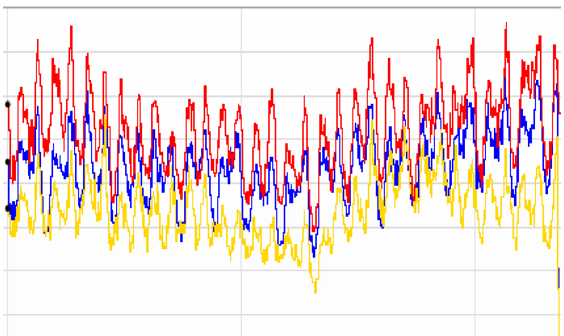


Figure F19: Time series graph showing current unbalance

Benefits

The benefits of these functionalities are:

- Visualisation of the level of voltage unbalance on the low voltage side of the secondary transformers provides information about the health of the assets.
- The DNV application helps engineers to identify substations with consistent long term large current unbalance and hence high neutral currents. Mitigations such as monitoring and phase balancing large 3-phase service loads, re-configuring link box open points to improve the phase balance, re-jointing single phase services to swap phases or installing a phase balancer can be used. The neutral current would be reduced, resulting in a reduction in system losses.
- Observation of significant changes to harmonic distortion may alert the businesses to a connected customer load or generator which needs attention.
- The harmonics measured may be a useful input into primary substation harmonic studies.

Business process improvements

The DNV application highlights areas where there is a physical problem with the assets, alerting Network Operations to the issue and allowing them to respond to the issue immediately, rather than waiting for the next scheduled substation visit, which may not detect the issue.

Planning engineers can use the current unbalance information when reconfiguring an LV network to assist with rebalancing the phases.

The DNV application highlights areas where the THD is high, allowing for further investigation including monitoring of the full set of harmonic voltages and currents with the RTU, and mitigation measures to be investigated.

Data

RTU Data	Secondary Three Phase Voltages Secondary Three Phase Currents Secondary THD • RTU advanced features: Individual Harmonics and Currents
Other Data Sources	Distributed Generation records
Data sampling	Half hourly averages
Monitoring location	Secondary Substations

Case Study: Voltage Unbalance

Voltage unbalance was reported as above 3% at a substation using the DNV application. Investigation of the historical three phase voltage and three phase unbalance voltage percentage identified that there had been a step change in voltage unbalance, as shown in Figure F20.

Figure F20: Detailed one week view of voltage change

A site investigation identified that the substation was unlocked, and the earth bar had been stolen. This left all of the substation equipment disconnected from the main earth mat. The earth sheaths were left bonded together and to the LV board frame. This may mean that the neutral was partially floating with respect to earth, and the RTU earth was floating giving unbalanced voltages. Replacement of the earth bar rectified the voltage unbalance (Figure F21).

Figure F21: Detailed one week view of voltage change

The benefit of being able to identify this type of situations is clearly significant as it could have resulted in a life threatening situation, had a member of the public entered the substation.

Example: Current Unbalance

The DNV application identified a substation with high current unbalance for the last 12 months.

Time Range 25/09/2012 to 25/09/2013

Secondary		Max Pct Unbalance	Time Of Max Pct Unbalance	Red Max Pct Unbalance	Red Avg Pct Unbalance
Substation A	T1	118.23	17/12/2012 17:30	118.23	65.88

Table F3: Example of high current unbalance

The DNV application provides historical data for three phase currents and calculates the % unbalance (Figures F22 and F23). Optical monitors were also used to monitor the LV outgoing ways.

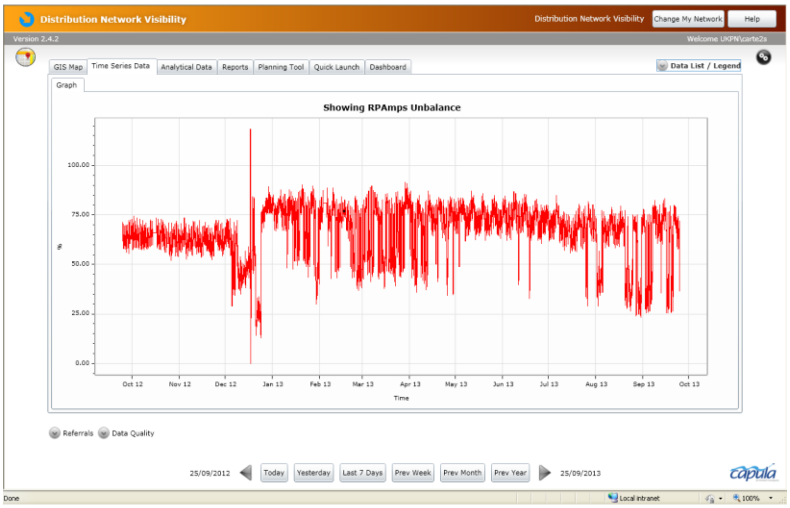


Figure F22: % Current unbalance on Red Phase, Oct 2012 – Sept 2013

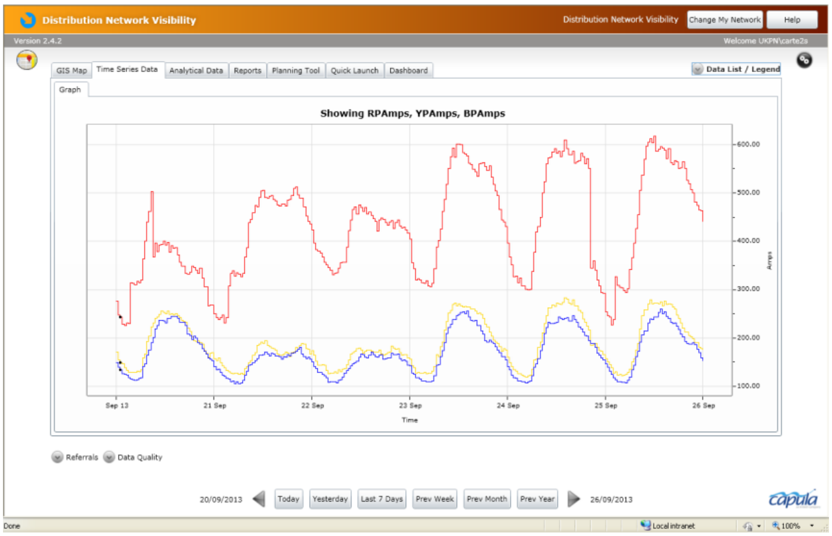


Figure F23: 6 days phase currents (RTU) Sept 13

Optical monitoring devices (denoted 'PS' in figure F24) were installed on both transformer tails as part of the Hyde Park B monitoring trial. This highlighted that the transformer tails were not uniformly sharing the current and provided confirmation that the phase currents were significantly unbalanced. Over the 34 days of optical measurements available, the unbalance on the transformer had been greater than 20% for 95% of the time; ranging from 14% to 54%.

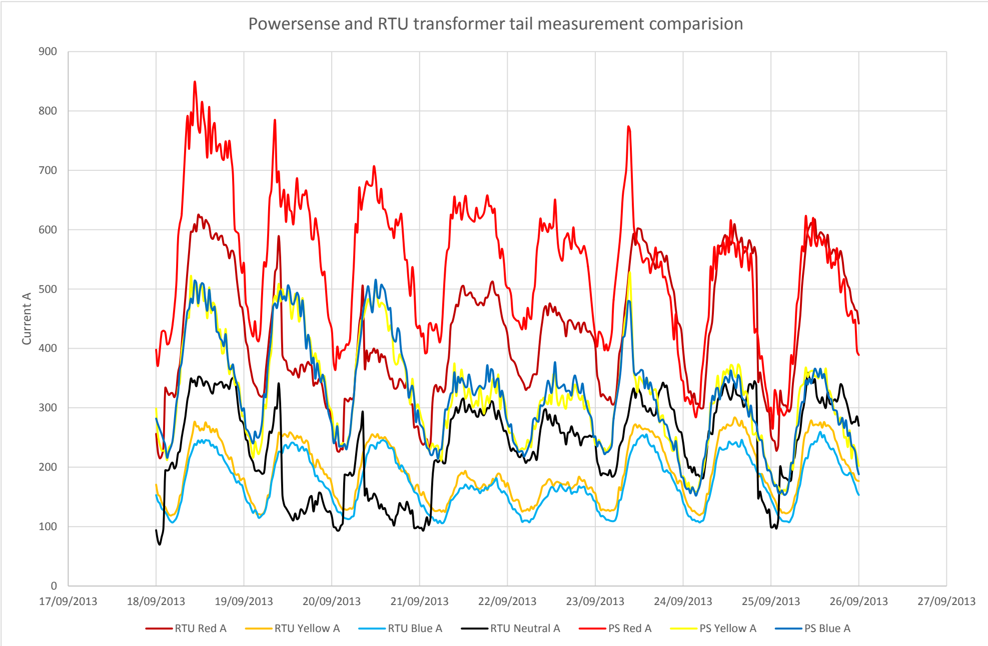
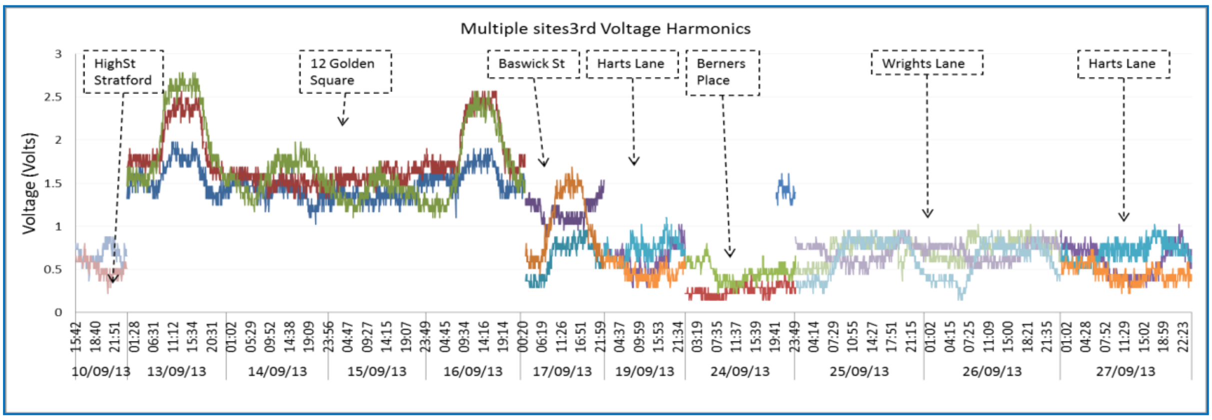


Figure F24: LV way current from advanced monitoring Sept 13

A large permanent red phase current unbalance at the substation was sustained over the period of one year. Monitoring of the LV ways would provide an indication of whether re- distribution of LV load is worth consideration.

Example: Harmonics

Using the independent RTU system, the individual harmonics at multiple sites were examined. Figures F25 and F26 illustrate the differences of harmonic magnitude and wave shape between substations and phases.



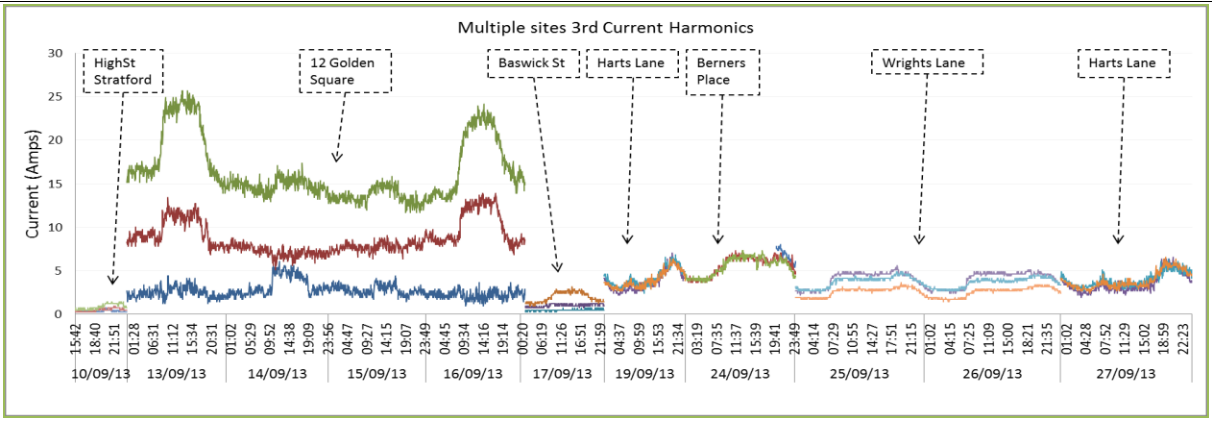


Figure F25: 3rd Harmonics of voltages (top) and currents (bottom) at 6 substations

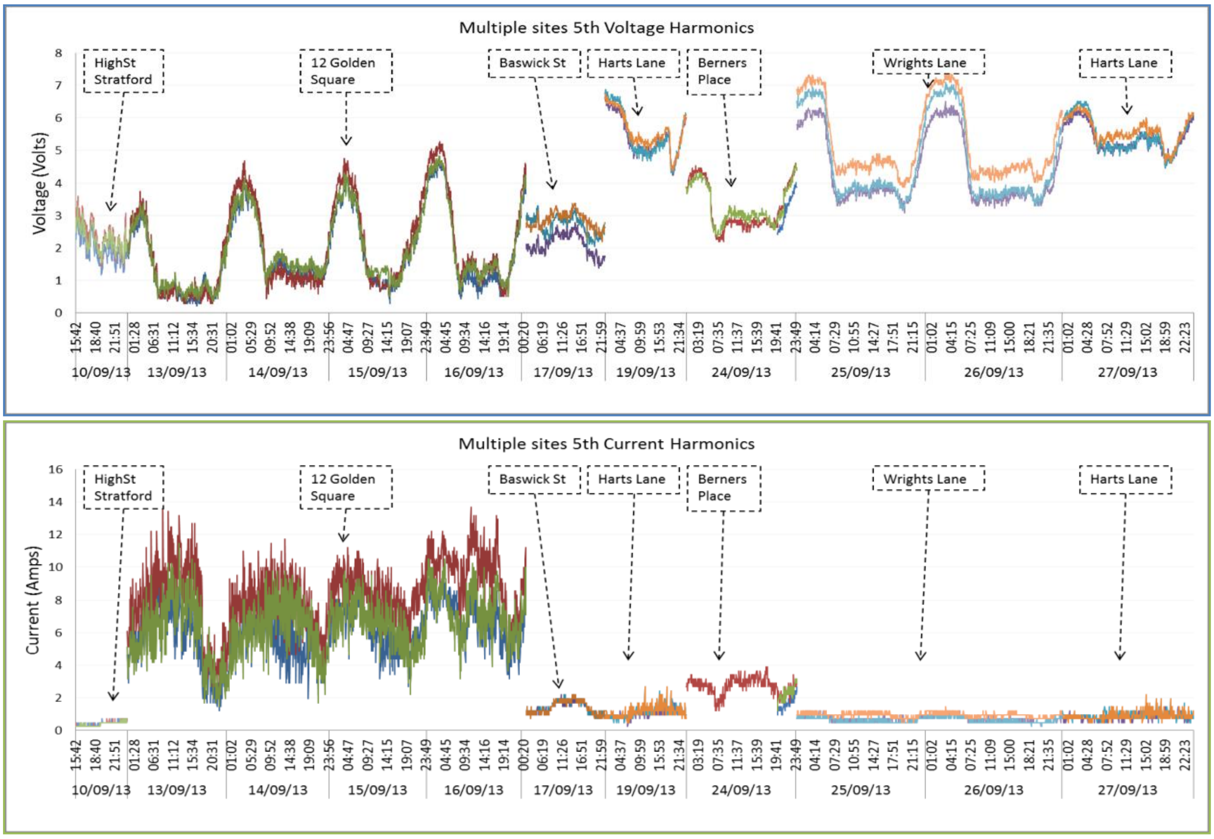


Figure F26: 5th Harmonics of voltages (top) and currents (bottom) at 6 substations

The figures show the variation of 3rd and 5th order voltage and current harmonics at six substations, in volts and amps, from which numerous observations on harmonics can be drawn:

- The Magnitude of voltage and current distortion can differ significantly between substations, noticeably high at 12 Golden Square.
- Weekend and weekday profiles can be seen to vary significantly, highlighting the harmonics relationship to load.

- The profiles can differ between phases for both voltage and current.
- 3rd order current harmonics appear consistently larger than the 5th, whereas the opposite is true for voltage harmonics.
- 5th order harmonics display similar wave-shapes between phases, for both voltage and current.
- 5th order voltage harmonics appear more cyclic than the 3rd, again highlighting a relationship to load.

The sample size suggests substations may have a multitude of harmonic profiles. A larger sample size would enable classification of substation harmonic profiles, separate from classification of load profiling.

To broaden the sample size of this study and provide greater insight into benchmarking harmonic profiles, a number of the substations on the iRTU network were studied for a weekday to explore how different order voltage harmonics vary throughout a day.

Figure 27 below shows the voltage harmonic profile of one phase over 1 day on four sites. Hours are displayed around the outside (in a "clock face" fashion), and the distance from the centre of each pattern indicates the magnitude of the harmonic distortion at that time.

A number of further observations can be made:

- The 5th and 7th voltage harmonics have far greater significance than the other frequencies.
- The most prominent profiles do not appear to be linked and do not have the same profile, but can make significant contribution to overall distortion at the same time.
- The 5th appears to be most prominent during the night and can have little contribution during the day.

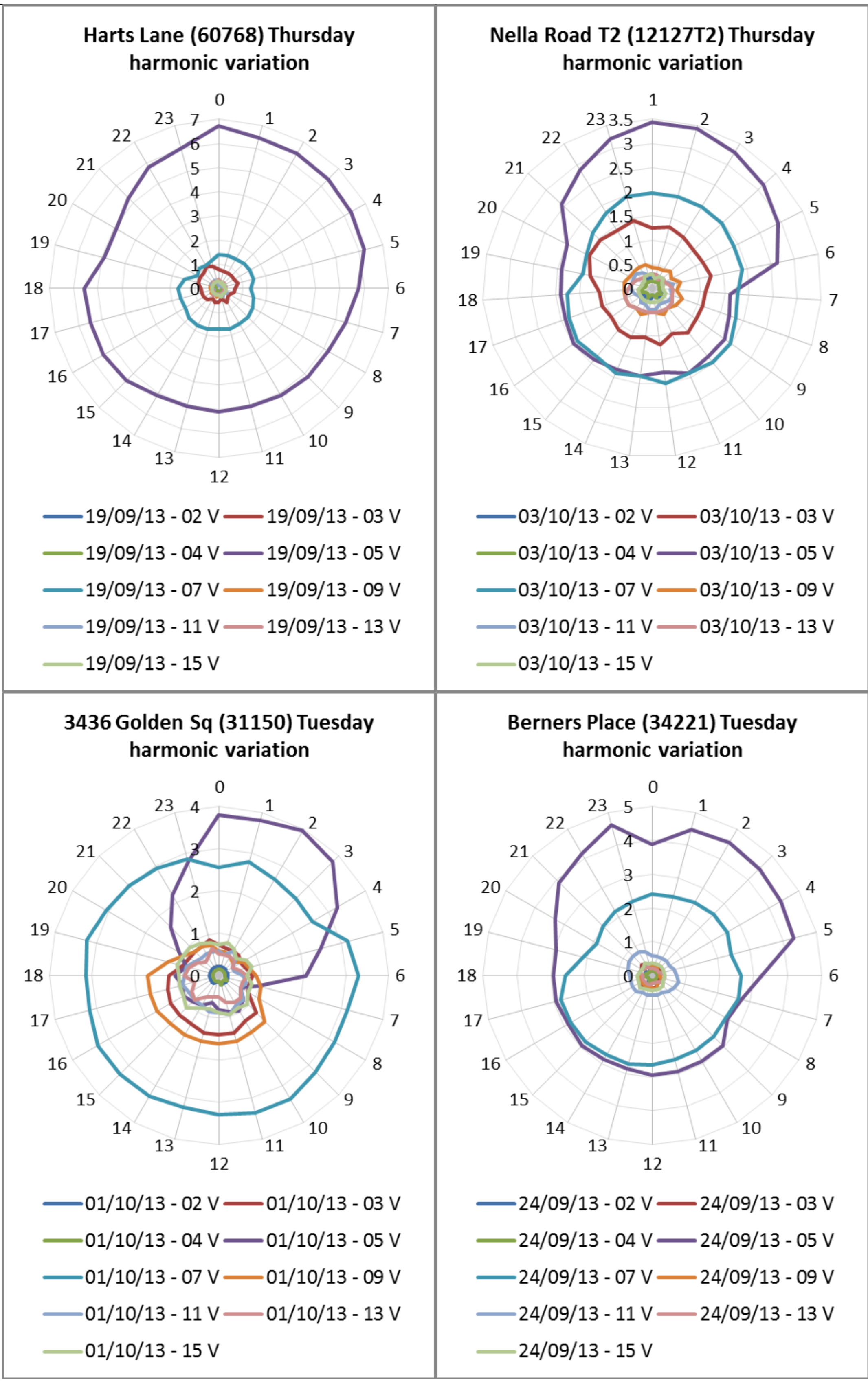


Figure F27: Daily variation of all voltage harmonics from four substations

Benefit 4.1 Information to support new customer load connection and general network reinforcement

Background
To assess existing transformer loading, the maximum demand readings taken routinely in the secondary substations is used. Where available, the PI historic kVA data was analysed to determine the maximum demand and other utilisation statistics, in order to assess the existing utilisation. Having an understanding of the range of load profiles across the secondary substations in London and use of the load profiles when considering additional load may enable additional load to be accommodated. Some LV areas in London, typically in the City area run interconnected in order to improve the reliability to the customers. In these regions, 80% of the nameplate rating is used for the secondary transformers to allow for the higher loading expected under post-fault running conditions. DNOs have an obligation to respond to customer requests for new connection within the timescales set by Ofgem's Guaranteed Standards of Performance (GSOP). DNOs typically split the task between a Connections team who respond to smaller connection requests, and Distribution planners who assess the larger requests and any requests referred by the connections team.
Functionalities Developed
The dashboard (shown on figure F6) highlights Primary and Secondary Substations where the load exceeds the capacity. The utilisation of each primary or secondary transformer can be reported, plotted on a GIS map, as time series data or using the analytical tools to display, for example, the load duration curve. The DNV application allows the user to plot time series secondary substation kVA, and overlay this with the known generation (taken from G59 and G83 records) associated with the substation. This enables the planner to take account of the hidden load when considering the utilisation of the substation. Other parameters which may be affected by generation are voltage and current phase unbalance, which are calculated and can be plotted in time series, or an unbalance report obtained. Power factor and THD can also be plotted and a report obtained. Some work has been undertaken to automatically detect the step changes which can be observed when large generation switches on and off. Whilst an initial algorithm has been implemented in the DNV application, this needs further work. Spare capacity is determined using the substation load profile and its ability to accommodate a typical residential, commercial, mixed or flat load profile. A report of the spare capacity for each secondary substation transformer is available. Spare capacity can be visualised using a quadrant pin for minimum spare capacity for the summer weekday / weekend and the winter weekday / weekend. The spare capacity can be calculated for each load profile type, and existing referrals are also considered in the calculation and can be plotted on the GIS map.

Figure F28: Spare capacity Overview

The DNV application can also be used by the Connections Engineers to identify which substations in the vicinity of a connection request can accommodated the demand (Figure F28). The user can use the map to locate the connection request, input the size of the request and the profile type and the application will display the ability of the surrounding substations to accommodate the connection using red and green quadrants. Where the substation does not have an RTU, the maximum demand readings are used to provide an indication of capacity.

Benefits

Knowledge of transformer loading over time will identify transformers which are overloaded, for what period of time and how frequently. From a system losses perspective it will show which transformers are lightly loaded where the fixed iron losses are higher than necessary, together with those that are under-rated and therefore running at higher levels of loading than is optimal. This provides an opportunity to optimise the transformer loading for each location.

The DNV application provides an overview to connections and planning engineers in respect of load demands and profiles to assist with determination of spare capacity. Rather than just using maximum demand to assess the accommodation of new capacity the existing substation load profile and the new load profiles are considered to maximise the use of the assets.

The tool may enable planners to understand the effect of LV generation connections, and potentially might allow more generation to be connected without reinforcement.

The system overview provided by the DNV application will highlight areas of the network operating close to limits, where additional embedded generation may not be able to be accommodated without measures such as compensation equipment being put in place.

The time taken to assess a small connection request is reduced, as all the information required is available within the application.

Business process improvements	
The utilisation reports highlight substations which are operating in excess of their capacity (nameplate rating or 80% nameplate rating for interconnected substations), and enables Planning Engineers to assess if a replacement is required. When undertaking a connection or asset replacement assessment, the DNV application provides visibility of embedded generation. The DNV connections tool enables Connections Engineers to get a quick answer to the available capacity at the substations adjacent to a requested referral, taking into consideration the existing substation load profile, demand and existing referrals. The Planning engineers are using the DNV application to significantly speed up and improve the efficiency of data input to their planning tool, DINIS, to enable them to undertake studies to consider the connection of new load.	
Data	
RTU Data	• Primary transformer MVA • Secondary transformer kVA • Load profiles
Other Data Sources	Distributed Generation records ONAN rating / age MDI readings Interconnected / Non interconnected status Planning referrals database
Data sampling	Half hourly averages
Monitoring location	Primary and Secondary Substations

Example: New Connections request

A school asked for an additional 220 kVA to be directly supplied from a nearby secondary substation. The DNV application can be used to undertake an assessment of the spare capacity of the substation is the vicinity, taking account of any existing referrals.

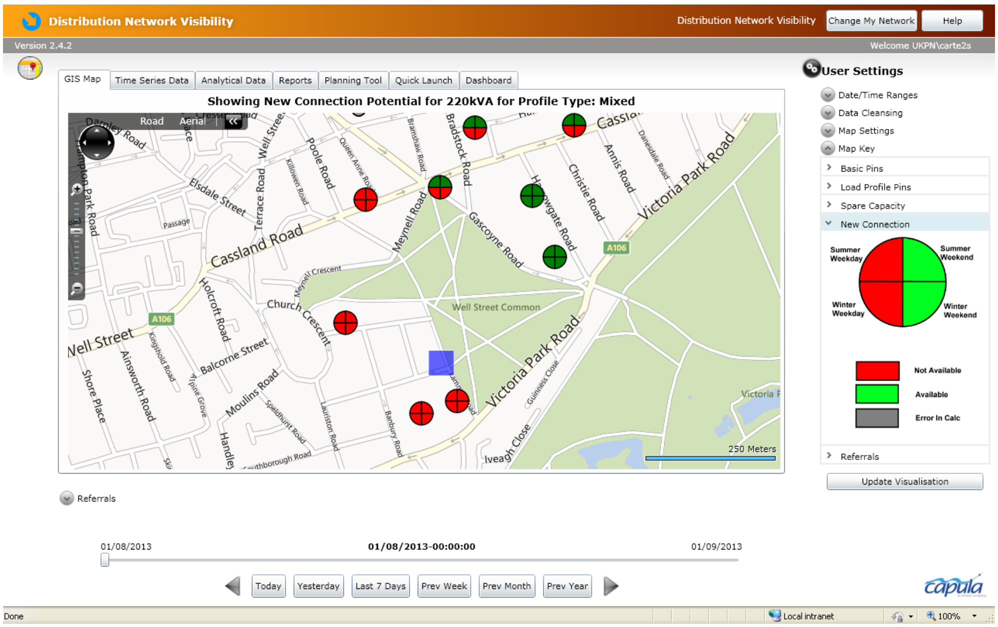


Figure F29: Spare capacity of substations around School (radius of 500m) that can accommodate a mixed 220 kVA profile Blue Square: Referral location

The DNV application identified that the substations in the immediate location of the school have residential load profiles (Figure F30), and they do not have the capacity to accept the additional load required by the school (Figure F29).

The LV system was assessed using a separate software tool and this identified that as there was limited opportunity to transfer load, a transformer replacement would be necessary. Being able to quickly assess the historic transformer utilisation enables the business to confirm MDI readings and correctly identify transformers needing replacement.

The analytical tools enable the time of day of maximum demand and the average daily load profile to be visualised as well as the load duration curve to enable an assessment of the effect of load growth and the connection of new load (Figure F31 and F32). The new connection map shows clearly which substations in the vicinity are available for connection of the additional load.

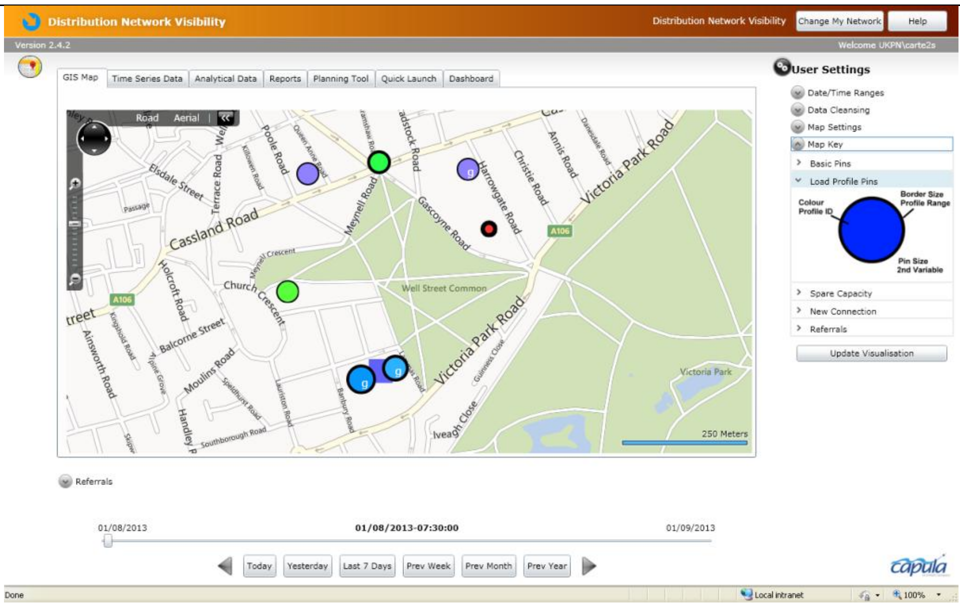


Figure F30: Load Profiles for surrounding substations

Load Profile scheme: Blue-Green: residential, Yellow: Commercial, Orange - Red: Night load

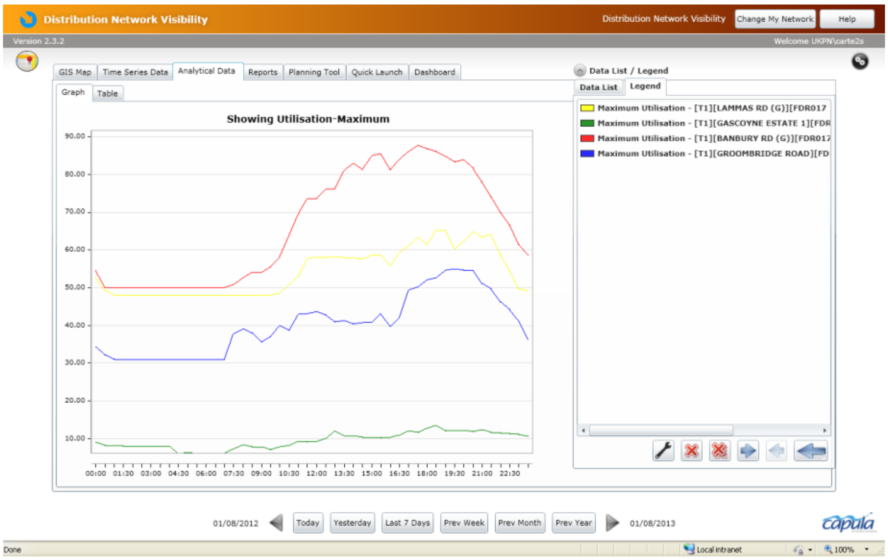


Figure F31: Profiles of Maximum Utilisation (one year, hourly maximum)

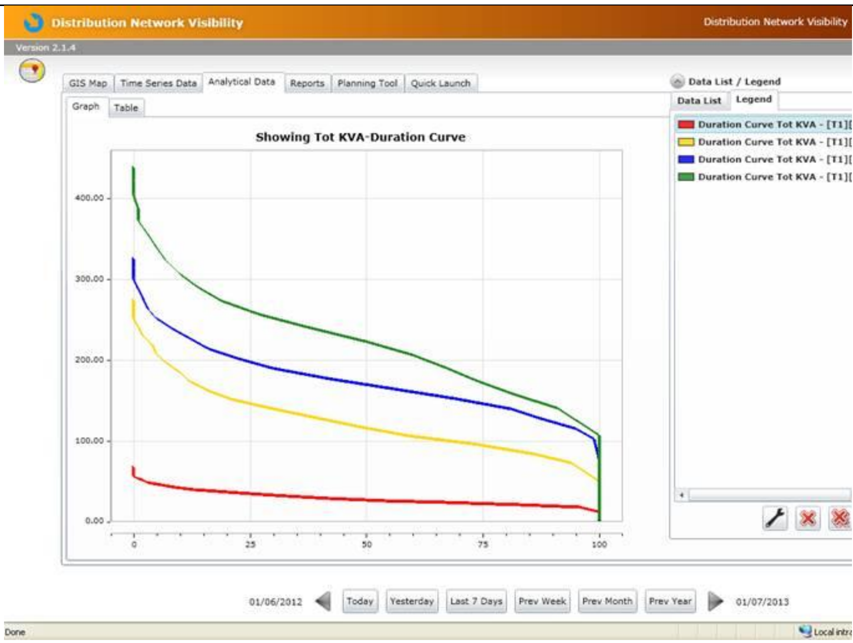


Figure F32: Duration curve for Load and Utilisation for adjacent substations

Case Study: New Residential Connection Request

Investigation of a heavily loaded secondary substation with a request for additional 53 kVA residential load. The DNV application utilisation report showed that the substation closest to referral was already heavily loaded:

Time Range 01/09/2012 to 01/09/2013

Secondary	Transformer	Nameplate Rating	Utilisation Average	Utilisation Maximum
Substation A	T1	500	63.36	118.87

Table F4: Utilisation of substation close to referral

Figure F33: Half hourly average Air Temp and Utilisation for last 12 months. Peak Utilisation from Dec 12 to Mar 13 (winter)

Air Temp: Green; Utilisation: Brown

The substation appears to be well ventilated as the temperature does not exceed about 25°C (Figure F33). The transformer is overloaded at peak time and heavily loaded for the majority of the day. Load Duration for winter weekday (Figure 34) shows that the transformer is loaded above 100% for 25% of the day however the maximum load is less than 120%.

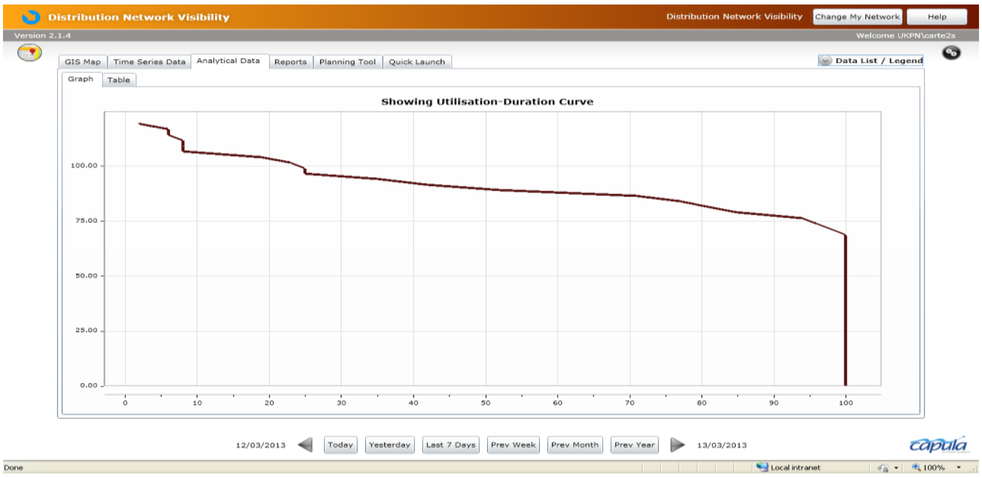


Figure F34: Load Duration curve for winter weekday

Consideration of the variation in Load Profile for 12 months identifies that the substation has a night load profile during the winter and a mixed load profile during the summer (Figure 35). Night peak during winter is typical for storage heating load. This transformer is loaded above 100% for 25% of the day, but not above 120%. The new load request is residential and can be accepted, deferring the need for an expensive transformer replacement.

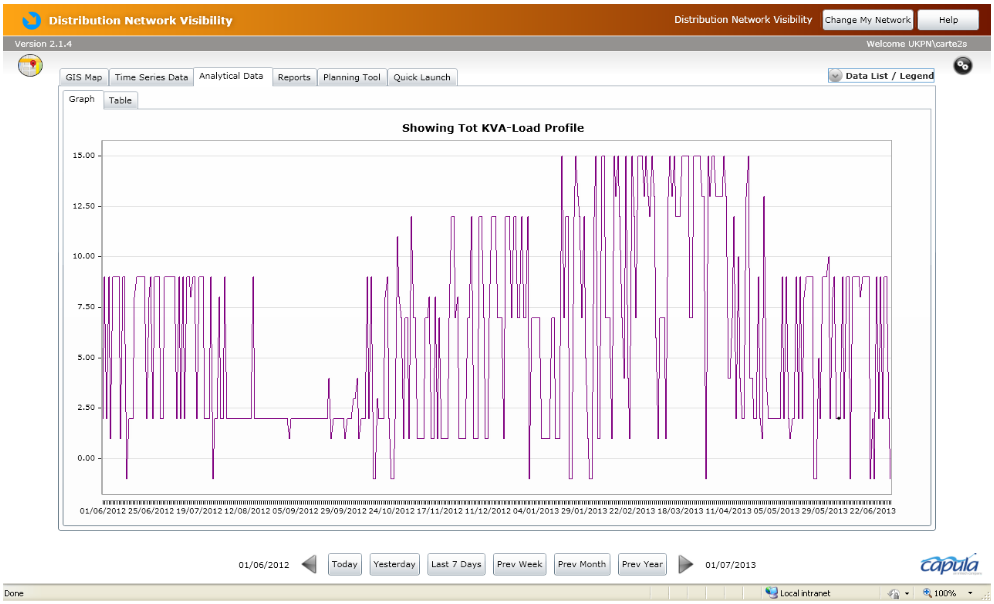


Figure F35: Variation in load profile

Load Profile: Purple. 1-6 residential; 8- 12 commercial, 12-15 night load

Case Study: Secondary Substation Deferral of Overloaded Transformer Replacement

The Maximum Demand Indicator Readings suggested a 500 kVA transformer was overloaded and should be replaced (Figure F5).

2006	300 kVA
2007	576 kVA
2009	792 kVA
2011	756 kVA

Table F5: MDI

The DNV application provided load history for past 5 years suggesting very little time was spent above 500 kVA (Figure F36), and that transformer does not need immediate replacement.

The maximum load occurs at night probably due to storage heaters.

The Load duration curve for past 5 years shows percentage of time transformer has been above 100% utilised is very small and the transformer has never been above 120% utilisation (Figures 37 and 38).

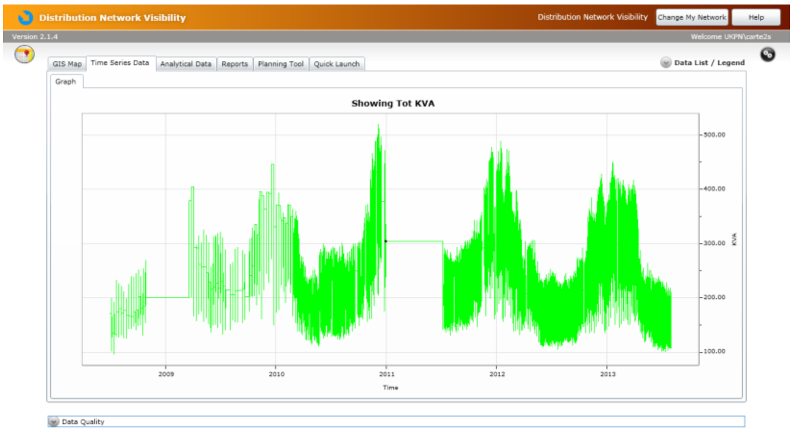


Figure F36: Half hourly average kVA for past five years shows typical winter peak demand
Tot kVA: Lime

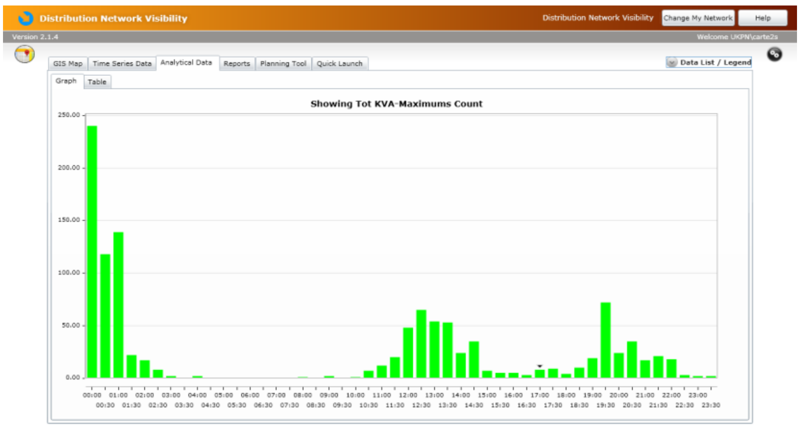


Figure F37: Number of half hours kVA > 500 over five years by time of day.
Maximum count Tot kVA: Lime

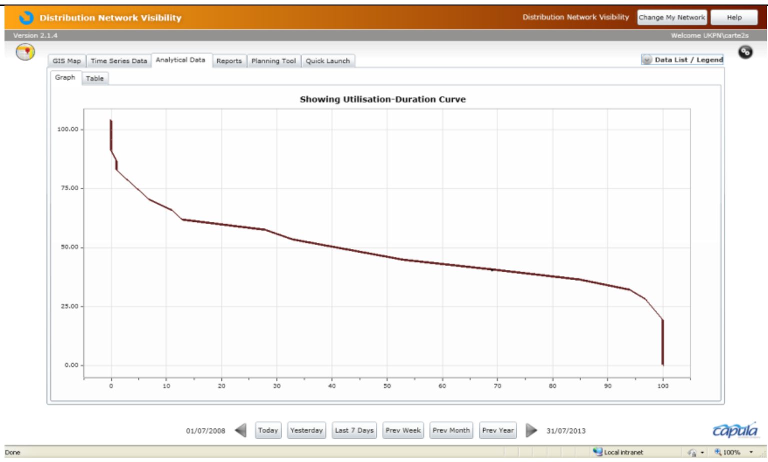


Figure F38: Utilisation Load duration curve

Planning undertook a site visit which confirmed the RTU measurements were correct and reset the MDI meter. The transformer is overloaded for short periods of time in non-interconnected area of LPN. Immediate replacement is not necessary, any future increase in night load can be observed using DNV. Replacement of the transformer has been deferred.

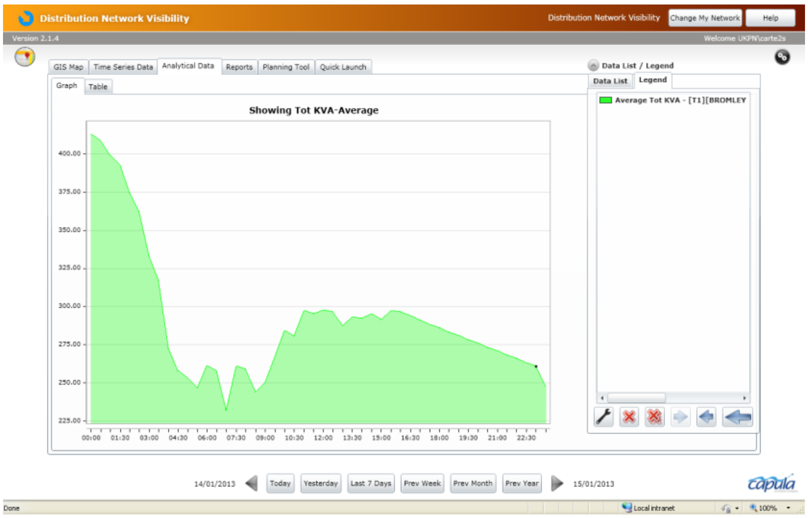


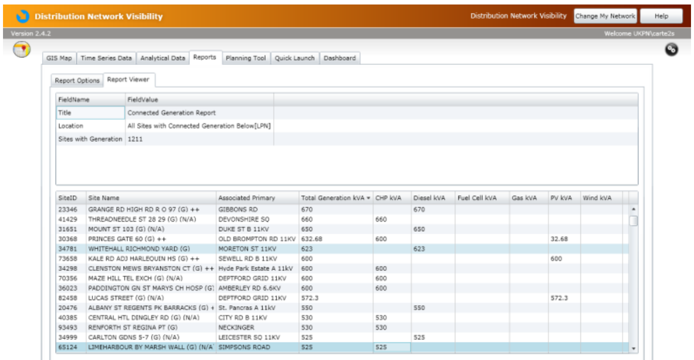
Figure F39: *Average daily kVA for January 2013 shows the available capacity during the day*
Daily Total kVA: Lime

Example: Connection of Embedded Generation

The connection of embedded generation downstream of the secondary substation may affect the distribution system in a number of ways:

- The apparent demand at secondary substation is reduced (hidden load).
- Real power supplied by a substation is reduced but reactive power is unchanged resulting in poor power factor.
- Voltage rise can occur, particularly at times of light load.
- Some DG use harmonic producing devices such as inverters which may lead to increased harmonics.

The DNV application reports connected generation (G59 and G83 records, Figure F40), Voltage and total harmonic distortion by time of day can be investigated. Level of recorded generation can be added to the substation utilisation charts. Algorithms to automatically detect step changes in generation are in initial stages of development.



FieldName	FieldValue
Title	Connected Generation Report
Location	All Sites with Connected Generation Below[LPN]
Sites with Generation	1211

SiteID	Site Name	Associated Primary	Total Generation kVA	CHP kVA	Diesel kVA	Fuel Cell kVA	Gas kVA	PV kVA	Wind kVA
23346	GRANGE RD HIGH RD R O 97 (G) ++	GIBBONS RD	670		670				
41429	THREADNEEDLE ST 28 29 (G) (N/A)	DEVONSHIRE SQ	660	660					
31651	MOUNT ST 103 (G) (N/A)	DUKE ST B 11KV	650		650				
30368	PRINCES GATE 60 (G) ++	OLD BROMPTON RD 11KV	632.68	600				32.68	
34781	WHITEHALL RICHMOND YARD (G)	MORETON ST 11KV	623		623				
73658	KALE RD ADJ HARLEQUIN HS (G) ++	SEWELL RD B 11KV	600					600	
34298	CLENSTON MEWS BRYANSTON CT (G) ++	Hyde Park Estate A 11kV	600	600					
70356	MAZE HILL TEL EXCH (G) (N/A)	DEPTFORD GRID 11KV	600	600					
36023	PADDINGTON GN ST MARYS CH HOSP (G)	AMBERLEY RD 6.6KV	600	600					
82458	LUCAS STREET (G) (N/A)	DEPTFORD GRID 11KV	572.3					572.3	
20476	ALBANY ST REGENTS PK BARRACKS (G) +	St. Pancras A 11kV	550		550				
40385	CENTRAL HTL DINGLEY RD (G) (N/A)	CITY RD B 11KV	530	530					
93493	RENFORTH ST REGINA PT (G)	NECKINGER	530	530					
34999	CARLTON GDNS 5-7 (G) (N/A)	LEICESTER SQ 11KV	525		525				
65124	LIMEHARBOUR BY MARSH WALL (G) (N/A	SIMPSONS ROAD	525	525					

Figure F40: Connected generation report, size of generator by type at each secondary substation

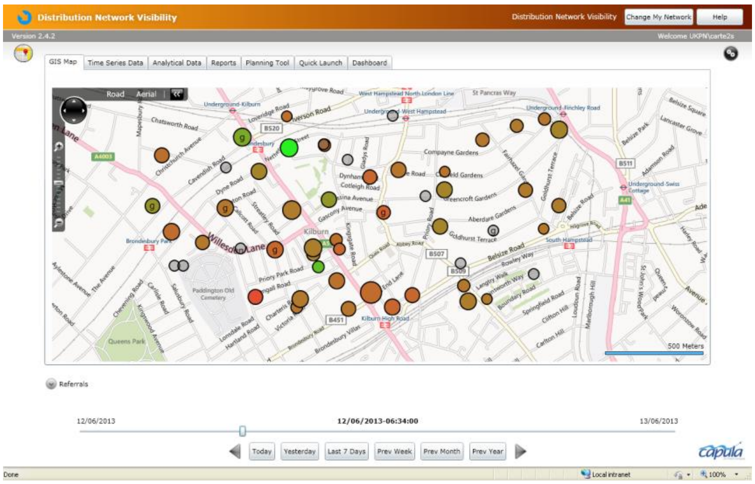


Figure F41: Voltage for specific time of the day / Sites with generation identified with “g”
Colour pin Green – Red 230 – 253 V, Size pin reflects utilisation

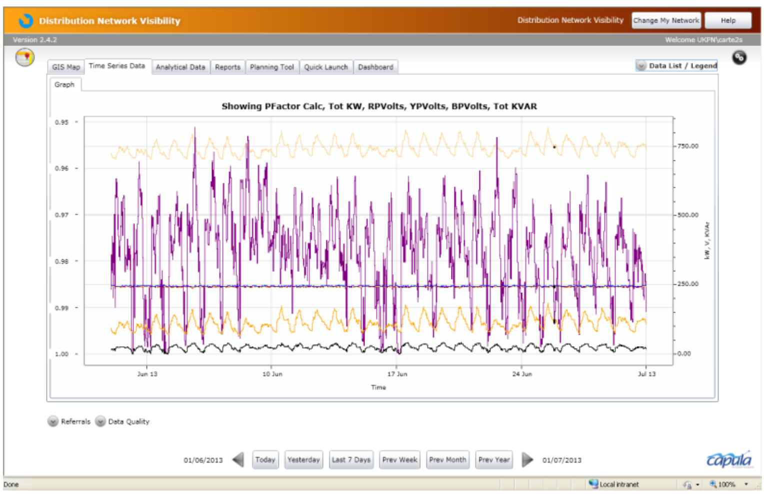


Figure F42: CHP and PV Generation site,
800 kVA transformer, significant “possible hidden” load

Red, Yellow, Blue: Voltage; Orange: kW, Pale Orange: kW + generation (assumed to be running all the time); Black kVAr, Purple: power factor

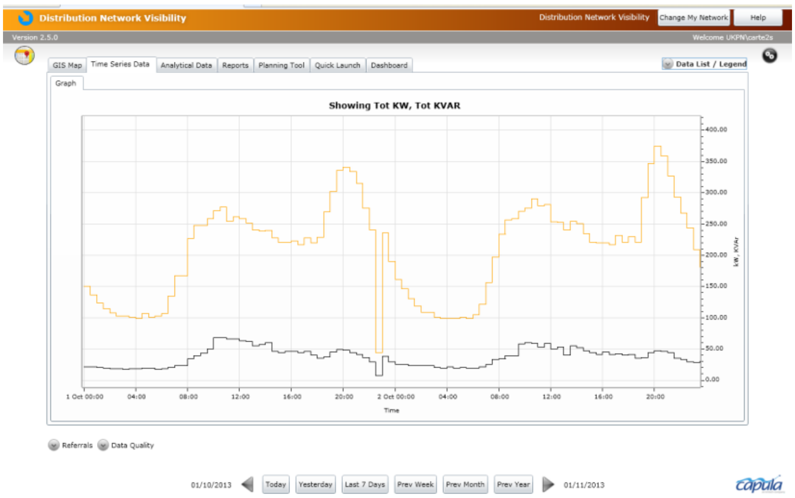


Figure F43: 220 kVA diesel generator, step change reduction in substation demand during generator test run

Orange: kW; Black kVAr

Benefit 4.2 Load analysis and growth profiling to improve planning process

Background
As the system migrates to a low carbon distribution network, it is expected that load profiles may change and be very different to those experienced today due to new generation, load types and controls, e.g. distributed generation, demand side management, electric space heating, electric vehicles and energy storage. Load profiles, particularly those with high ramp or fall rates, or those having a high harmonic content (associated with power electronics) are known to significantly affect the life and thermal rating of assets. Equipment failure can be associated with both low and rapidly falling load as much as with high and rapidly rising conditions. Understanding and acting on these aspects will have a major impact on asset lives and utilisations. Early identification of changes in load growth and demand patterns will enable optimisation of the use of the existing assets.
Functionalities Developed
<u>Planning tool</u> The DNV application enables the Planning Engineers to have fast visualisation of, and access to the feeder and secondary substation data needed to undertake system planning using DINIS. The planning tool displays 15 months of selected feeder data both on a feeder basis and the summed group load to enable visualisation of the annual load profile. The tool automatically selects the time of maximum demand and undertakes a load allocation using the feeder demands and the RTU measurements to determine the load on the non-monitored RTUs, and to prepare an excel file which can be uploaded into DINIS. The users have the option to choose a different demand time and to adjust the RTU loads, especially around HV supplies and non-monitored RTUs. <u>Load profiling</u> The visualisation provides the distribution planner with an overview of secondary substation load profiles and visibility of opportunities for load transfer between adjacent secondary substations. The variability of the profiles through seasonal and between weekdays and weekends can be observed both on the GIS pin display, in the load profile time series charts and reports. The DNV application also produces a transfer capacity report which considers the ability of each substations demand to be accommodated by each of the five nearest substations.
The Apparent Power (kVA) of the secondary substations with RTUs for 2010 and 2011 were analysed to establish a library of load profiles. The following load profiles are the results of clustering based on the k-mean analysis. An integer number known as "Load Type" is

allocated to each load profile which is stored in the application database as a Load Profile Library. Each actual secondary substation daily load profile is then analysed by the application and matched against the set of common load profiles in the library. The profiles can be visualised on a geographical map or obtained in a report. In this way, changes in usage patterns over time can be easily spotted.

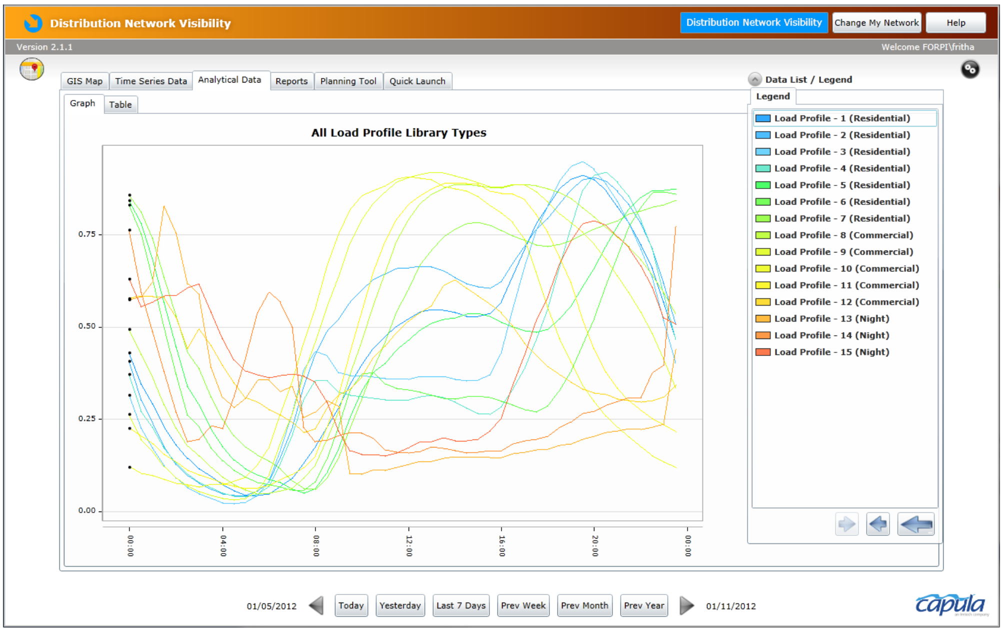


Figure F44: The Load Profile Library

It has been observed that load profiles can vary over time both with a difference between weekdays and weekends and with seasons. The GIS map visualisation provides an indication of the variability of the load profile over time as a colour band at the edge of the pin.

Load growth

A report of load growth can be produced for both primary and secondary substations. The report considers one year and five yearly summer and winter growth. The report details growth in respect of maximum demand and average demand. At present, due to data anomalies with 5 year old data, the average demand growth values are more stable than the values based on maximum demand.

Primary Substation MVA hrs at risk

A report can be obtained which assesses the primary substation MVA hours at risk report required for the annual Load Index submission. This uses the summer and winter firm capacities and the PI data to assess the number of hours the demand exceeds the firm capacity. The time series and analytical data can be used to further understand the substation demand with respect to time of day.

Benefits

Load Flow Studies are required for a variety of projects in the Distribution Planning department. Prior to use of the DNV application, the time taken to set up a basic load model for use in DINIS, prevented load flow analyses being viable for quick turnaround jobs especially those regulated by GSOPs. The visualisation allows planners to have early identification of localised load growth and changes in load patterns, as well as optimising the use of the existing assets by understanding the available transfer capacity between substations. With a full time series of load data available, it is expected the less expensive rebalance or transfer options will be adopted in a greater proportion of studies making better use of load diversity between adjacent items of plant and allow additional connections to be made. This may allow deferral of some HV feeder reinforcement schemes. The ability to view load duration curves and obtain the MVAh at risk for primary substations will save the Infrastructure Planners time analysing data.
Business process improvements
System modelling and load flow analysis is the only way to predict how the network should behave when additions or alterations are proposed. A major element of the time to run this analysis is the collection of correct load data and to populate the model. In the past, due to the time taken to assimilate and cleanse the data, there was a tendency to only run one model at the yearly peak. This did not take account of the different load distributions at seasonal peaks. The DNV application has provided an opportunity to undertake load flow analysis for certain short timescale projects where desirable. This will lead to better designs, better network operation and utilisation, less network stress, less CI & CML and better customer response. Consideration is given to the date and time of the demand to be analysed. Data then needs to be collected for that time for: • Feeder currents. • Secondary transformers MDs. • HV supplies MDs. Prior to DNV the information came from a variety of sources including; • PI data. • Asset management records of recorded data. • Metering records for half hourly customer loads. The DNV application allows: • Selection of feeders in a group. • Easy visualisation of annual load profile to select the appropriate date and time. • Automatic collection of time stamped data for the date / time specified. • Collection of annual demand data.

- Rationalisation and diversification of annual data to equate to feeder loads.
- Automatic preparation of an Excel file that can be read directly into DINIS.

Data	
RTU Data	Primary feeder data Secondary transformer kVA Load profiles
Other Data Sources	Primary substation firm capacities Distributed Generation records ONAN rating / age MDI readings Interconnected / Non interconnected status Planning referrals database
Data sampling	Half hourly averages
Monitoring location	Primary and Secondary Substations

Example: Load Analysis

The Planning Tool is used to specify Date/Time (Defaults to the maximum within the range).

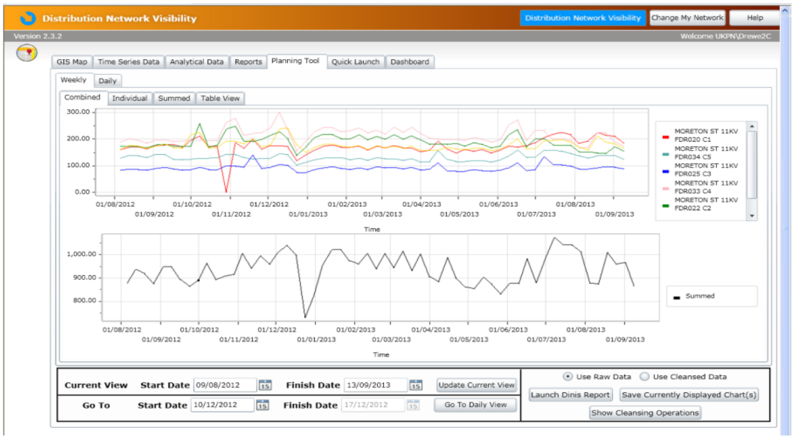


Figure F44: Feeder group 13 month view

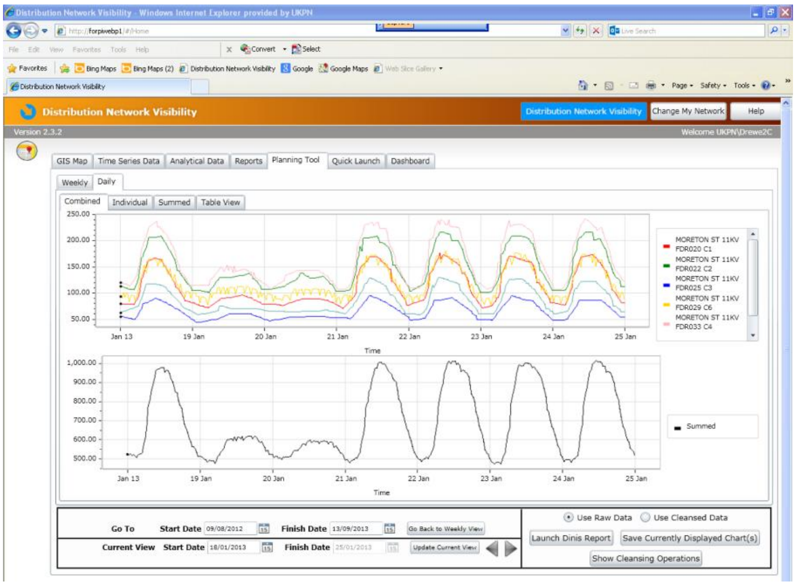


Figure F45: Feeder Group Weekly view

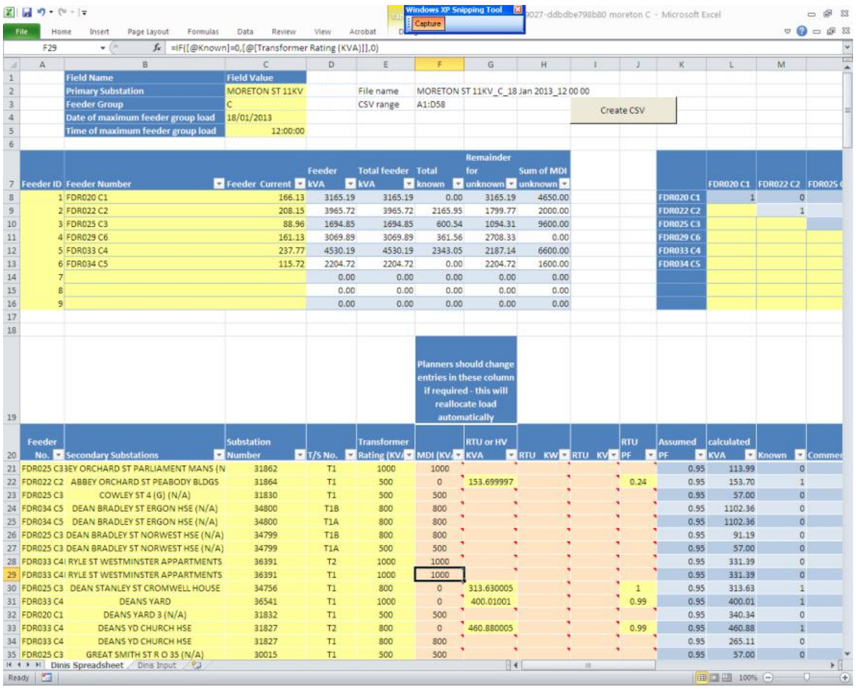


Figure F46: Excel spreadsheet to allow Planners to inspect and modify loads

Automatically generated by the DNV application

Example: Load Growth

The DNV application reports historical load growth over a period of five years and for the previous year at the primary and secondary levels. Analytical data enables plotting of average utilisation per week to visualise the growth.

These reports provide knowledge of areas on the network that are experiencing load growth and exceeding network limits. As heating and transport loads are picked up by the networks and load growth becomes significant, the tool will help Planning to better anticipate and address network problems.

All values are in MVA:

Substation Name	5 year average yearly growth (Summer)	5 year average yearly growth (Winter)	1 year growth (Summer)	1 year growth (Winter)
LEICESTER SQ 11kV	+0.76	+5.90	+1.53	+2.66
LITHOS RD A	-1.01	+0.64	+1.48	+2.35
CARNABY ST 11 kV	-5.90	-2.92	+1.46	+2.45
BLACKHORSE LANE	+1.24	+1.88	+1.42	+0.79

Table F6

The application can be used to report the load growth at the secondary substations associated with a primary e.g. Leicester Sq 11kV.

All values are in kVA

Substation Name	Trans rating	Previous Winter average utilisation	5 year average yearly growth (Summer)	5 year average yearly growth (Winter)	1 year growth (Summer)	1 year growth (Winter)
WHITEHALL PL	800	64%	+19.6	+37.4	+30.1	+79.2
VINE ST PICADILLY	800	15%	+8.0	+16.5	+16.66	+30.66
REGENT ST 18-20	800	28%	+16.6	+15.4	+12.04	-4.94
VILLIERS ST CHARING	800	64%	+19.5	+15.2	+79.4	+6.85

Table F7

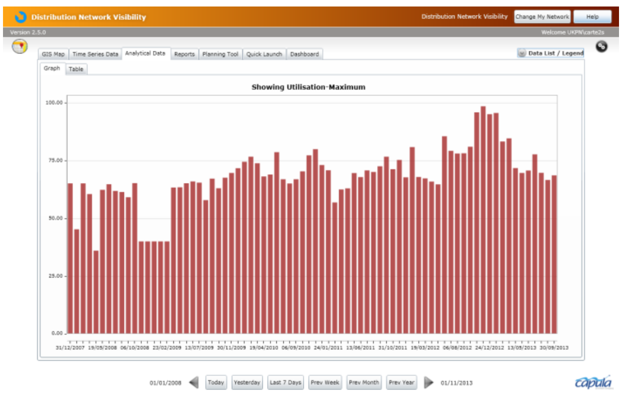


Figure F47: Whitehall Place load growth
(average maximum utilisation per period) 2008 – 2013

Example: MVA hours at risk

The primary substation summer and winter firm capacities are used together with the Primary substation PI data to determine the summer and winter MVA hours at risk. This can be visualised using the analytics tool (Figure F49).

Figure F48: Annual MVA profile

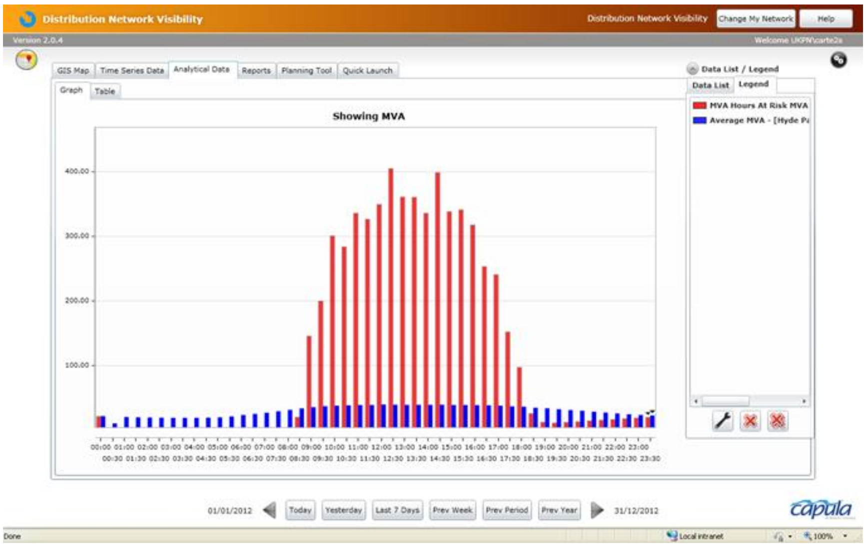


Figure F49: Time of day profiles
MVA hours at risk Red, Average MVA blue

Benefit 5.1 Secondary substation ventilation

Background
Ventilation of enclosed secondary substations must be considered in order to disperse heat from the transformer and other heat emitting plant or equipment. UKPN substations are designed to achieve this by using natural ventilation as far as possible, generating a cross flow of air over the transformer and other plant. Wherever possible, natural air flow to the outside of the building is used. Forced ventilation is only used where natural ventilation is not practicable or does not provide sufficient cooling to ensure the maximum room temperature does not exceed 40°C, when all transformers/plant are operating at nameplate rating. There are external heat inputs and cooling factors for substations from a wide variety of sources and these vary according both to the physical construction of substations and their time constants, as well as environmental conditions and the provision and condition of the ventilation itself. Transformers are operationally overloaded for short periods of time using traditional overload factors. Use of dynamic ratings may allow more operational flexibility and allow active health management.
Functionalities developed
The dashboard reports the number of substations where the temperature at the substation exceeds the set parameters. The substation temperature, data from the closest external weather station (Met Office) and the transformer utilisation are compared in a ventilation report which also reports: • Difference between average substation temperature and average weather station temperature: A large difference indicates insufficient ventilation whereas small difference shows a well-ventilated substation. • Correlation coefficient between the substation temperature and weather station temperature: A well ventilated substation has correlation coefficient close to unity whereas small correlation coefficient indicates inadequate ventilation. Time series and analytical charts can be used as well as the GIS map to further understand the substation ventilation. A model was developed to investigate the dynamic rating of transformers using the substation temperature, the ambient temperature and the transformer loading. The concept has been proven, but the functionality is not yet included in the DNV application.

Benefits	
The DNV application allows better management of secondary substation ventilation with the potential to save transformer asset life and prevent partial discharge in switchgear. Knowledge of which transformers may have undergone accelerated aging due to high loads and or temperatures which increase oil acidity, will help to prioritise transformers that require acidity and condition inspections. Asset management and operations can target substations for ventilation maintenance or improvement. Having knowledge of and using the dynamic rating of distribution transformers should provide information to enable improved operational and asset replacement decisions, and specifically to make greater use of existing assets whilst actively managing their health.	
Business process improvements	
The DNV application highlights transformers and other substation equipment which are operating in an environment above 40^{o}C, allowing operations to target substations for ventilation maintenance or improvement. Asset management traditionally use age and oil acidity as basis for transformer replacement. Having knowledge of and using the dynamic rating of distribution transformers should provide information to enable improved operational and asset replacement decisions and specifically to make greater use of existing assets whilst actively managing their health. Once fully trialled and implemented, the dynamic rating assessment should allow calculation of an indication of the remaining life of transformers, assessment of normal running and emergency system configurations and real-time management of on-going overload.	
Data	
RTU Data	Secondary ambient temperature kVA
Other Data Sources	Meteorological Office weather data Secondary substation asset data (ONAN rating, age)
Data sampling	Half hourly averages
Monitoring location	Secondary Substations
Case Study: Substation Ventilation	
The DNV application reported a secondary substation with consistently high temperatures during 12 months, with particularly high temperatures recorded in July	

2013.

(01/07/2012-01/07/2013):

Average	Maximum	Minimum
35.08°C	45.34°C	27.35°C

Table F8

Historical half hourly average Air Temperature and Utilisation data, London ambient temperature and rainfall from the DNV application were used to investigate the ventilation issue. Half hourly average substation temperature and utilisation for the past year shows high utilisation (80%) and substation temperature (more than 40^{0}C) in the summer.

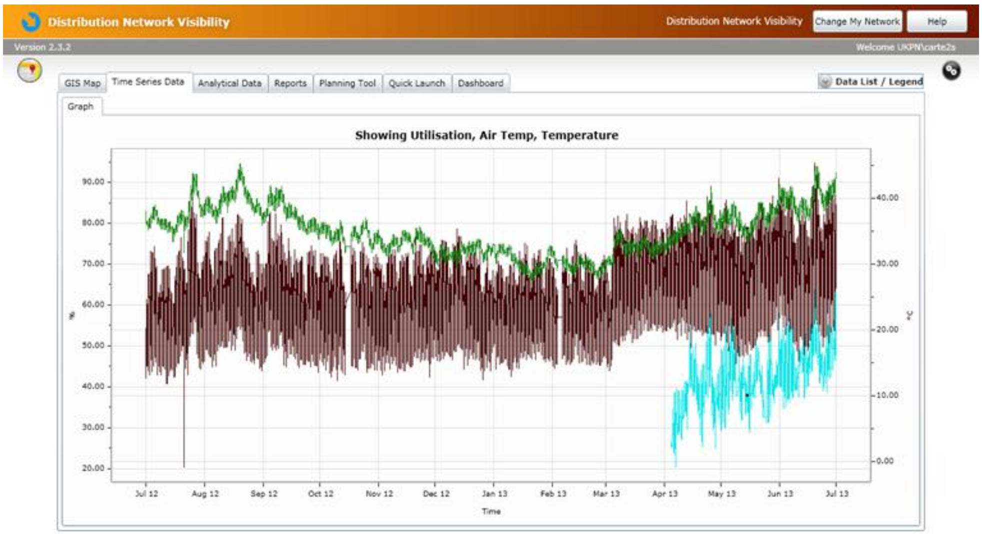


Figure F50: Substation Utilisation, Temperature and ambient temperature
Air Temp (Secondary Axis): Green; Utilisation (Primary Axis): Brown; Weather station Temp: Cyan

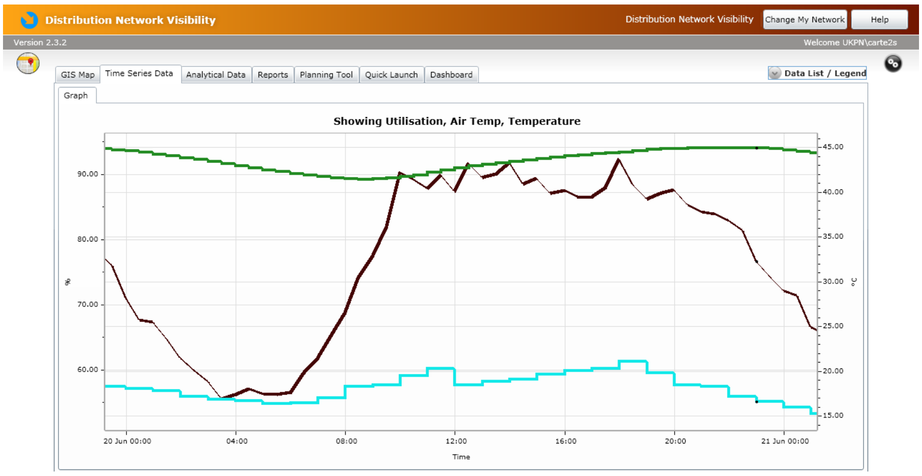


Figure F51: Typical weekday view of substation temperature and Utilisation

Substation Air Temp (Secondary Axis): Green; Utilisation (Primary Axis): Brown; External Weather station Temp: Cyan

The substation temperature dropped to around 30°C in July. This may have been caused by rainfall during July.

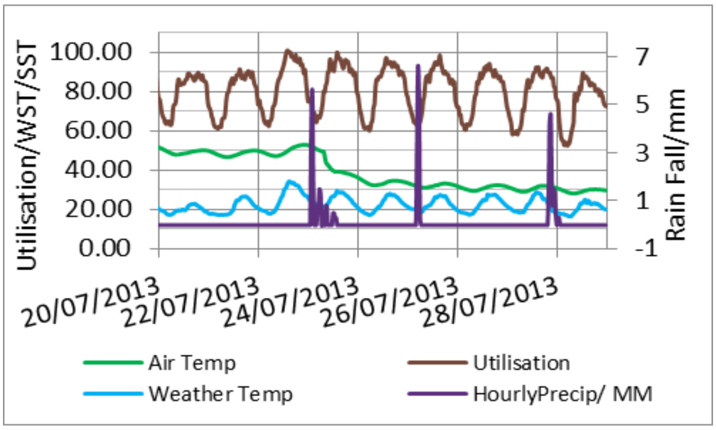


Figure F52: Chart showing sudden drop in substation temperature following precipitation

RH Axis: Substation Air Temp: Green; External Temp: Blue, Utilisation: Brown; LH Axis Rainfall: Purple

A site investigation revealed that the substation temperature had been adversely affected by the construction of the building above the substation. The transformer temperature had been further compromised by plastic sheeting covering the cooling fins and lower air paths blocked by rubbish. It is likely that the cooling of the substation due to heavy rainfall and evaporation cooling, accounts for the rapid drop in air temperature which occurred in July.

Without attention, the consistently high transformer temperature may have resulted in premature transformer failure. Clearing of air paths and removal of the transformer coverings and the cooling following rainfall has assisted the transformer ventilation and the business is reviewing the substation ventilation system.

Development Transformer Dynamic Rating

The present transformer overloading rules do not allow Control Engineers or Asset Management to quantify the impact of overloads on the life of a transformer. Presently a transformer in an interconnected area is normally loaded to a maximum of 80% can be operated at 160% for 3 hours in an emergency situation.

A model has been designed where the ageing rate of transformers is directly calculated from two RTU measurements: Air Temperature and Transformer Load.

There are a number of parameters impacting the hot spot temperature. Figure F53 below presents the main impacting factors.

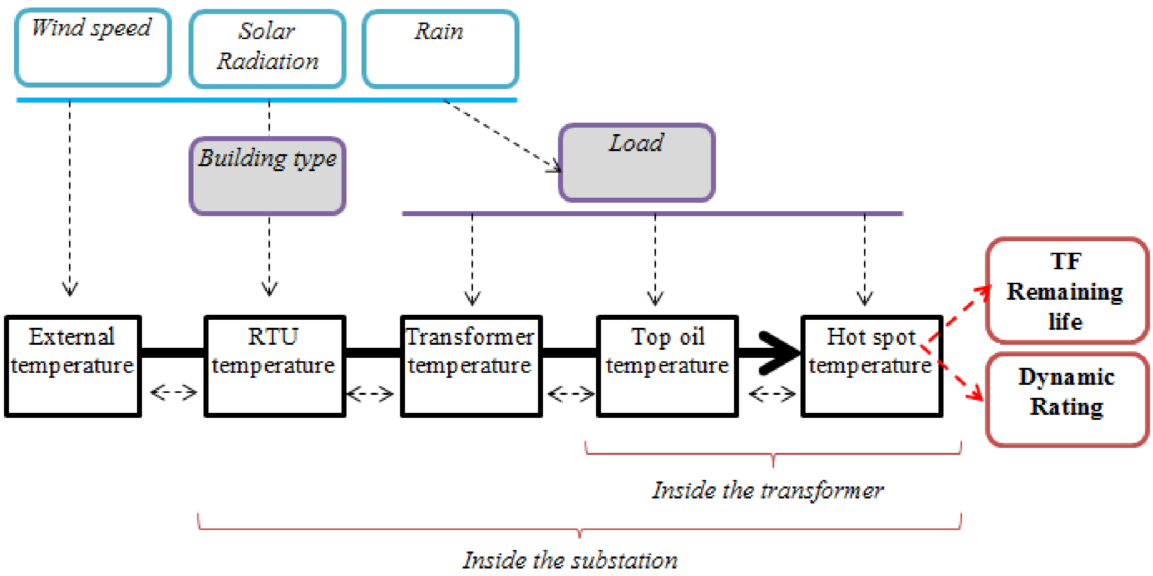


Figure F53

The aim was to find a solution applicable to the substations with RTUs by using the substation air temperature and utilisation data. In order to design and validate a model, temperature sensors were mounted on 10 different transformers in substations already equipped with RTU measurements. Regression analysis was used to determine a model for estimating the transformer temperature from substation air temperature, utilisation data, the building type and external weather parameters, such as solar radiation, wind speed and rainfall.

A methodology was defined to calculate the transformer hot spot temperature from the transformer temperature using a simplified steady-state version of a method developed by the IEEE.

If this hot spot temperature exceeds a critical limit (different for thermally upgraded and non-thermally upgraded transformers), the transformer ages faster than expected. A methodology was defined to calculate a transformer’s remaining life, based on hot spot temperatures historic data, and a set of guidelines were established to enable the overloading of a transformer for a period of time while making sure that its insulation life is under control.

Dynamic rating charts of a transformer

If a transformers initial load was K1 and it is then overloaded to K2, the model can determine how long the load can remain as high as K2 without compromising its life:

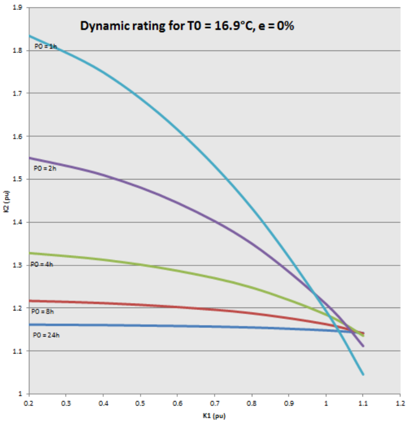


Figure F54

The dynamic emergency rating can be determined to indicate how much a transformer can be overload for 3 hours without compromising its life. This would be used with a load forecaster.

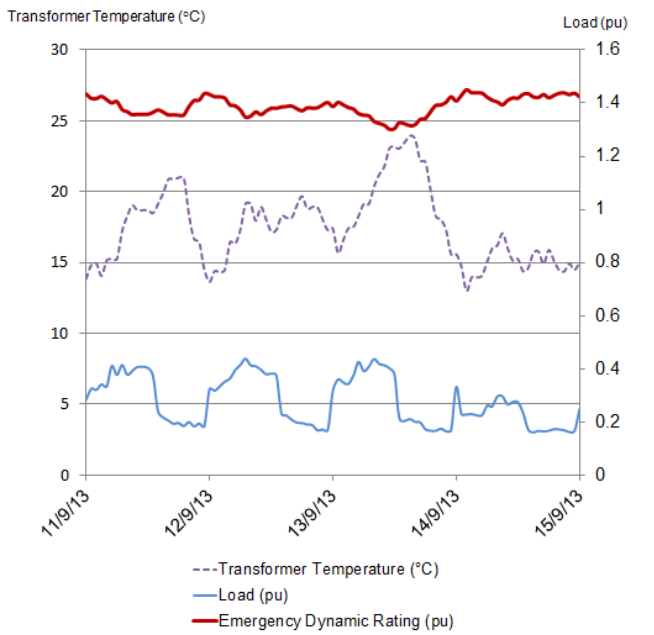


Figure F55

Historic loading and temperature data can be used to assess the remaining life of a transformer.

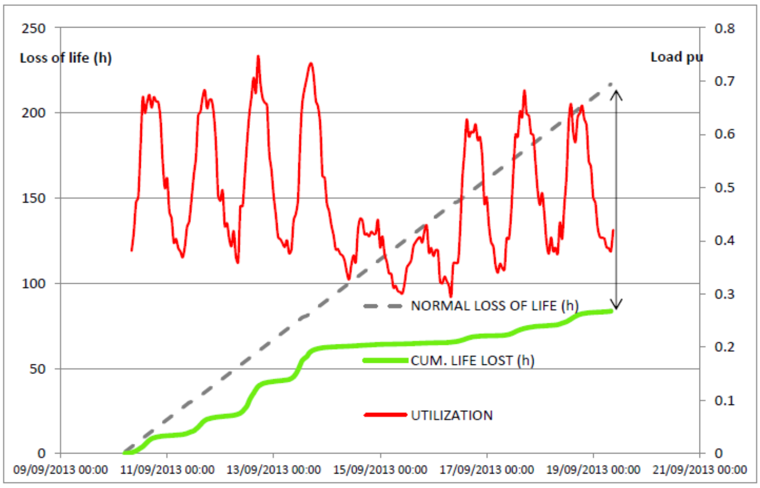


Figure F56: Assessment of loss of life of transformer

Grey line shows normal loss of life for constant load of 1 pu

Benefit 5.2 Visualisation of Primary Transformer

Background
Primary transformer tap change counts are read during major and minor substation inspections (counter driven by the motor box) and recorded into the asset database. Tap Change in Progress (TCIP) and Tap position indicator (TPI) readings are recorded into PI from the voltage control relay. There was a concern with both the quality of the PI data and with the accuracy of the tap change counts recorded in the database. There may be a difference between tapchanger counts recorded directly from the tapchanger counter, and those indicated on the voltage control relay as the former will indicate the actual number of taps completed, while the latter will also count any uncompleted tapping instructions. Uncompleted tapping instructions could result when the tapchanger has reached the extremity of its range or when the tapchanger has not mechanically operated in response to a tapping instruction. The present primary transformer status is shown on PowerOn (voltage, current, tap position). Control should be alerted to any abnormal operations from PowerOn. Maintenance of tap changers is time-based. This has been implemented by UK Power Networks so that the maintenance of tap changers can be aligned with the maintenance of other transformer components.
Functionalities developed
The DNV application compares the PI tap changer TCIP (tap change in progress) or TPI (tap position indicator) data with that recorded in the asset database from the tapchanger counter. This provides confidence in the data where they match. Reports of numbers of tap changers and the time of tap change operation can be obtained. The analytical tools can be used to display the number of tap changes each period over a year and to display the average voltage and or utilisation.
Benefits
Visualisation of a non-operating tap changer, or a tap changer behaving in a different way to others at the same substation could provide an opportunity to target maintenance resulting in prolonged life for tap changer, and possible reduction in catastrophic failures with significant safety implications.
Business process improvements
The comparison of the tapchanger counts recorded directly from the tapchanger counter and the PI data provides confidence in the data at some substations and highlights

substations where the data collection methods should be checked.

The DNV application allows reports of number of tap changers and time of tap change operation to be reviewed.

Data	
RTU Data	Primary Substation Tap Change data Primary Substation Load and Voltage
Other Data Sources	Asset database Substation tap changer counter
Data sampling	In accordance with PI excursion settings
Monitoring location	Primary Substations
Example Primary Transformer Taps	

The TCIP (tap change in progress) and TPI (tap position indicator) data returned to PI are not regarded with confidence by users. An investigation was undertaken into the tapchanger counts recorded directly from the tapchanger counter and those indicated on the voltage control relay recorded in PI. The former indicates the actual number of taps completed, while the later will also count any uncompleted tapping instructions. Comparisons between the average tapchanger counter data and the PI TCIP data show a strong correlation in some substations thus providing confidence in the PI data (Figure F57).

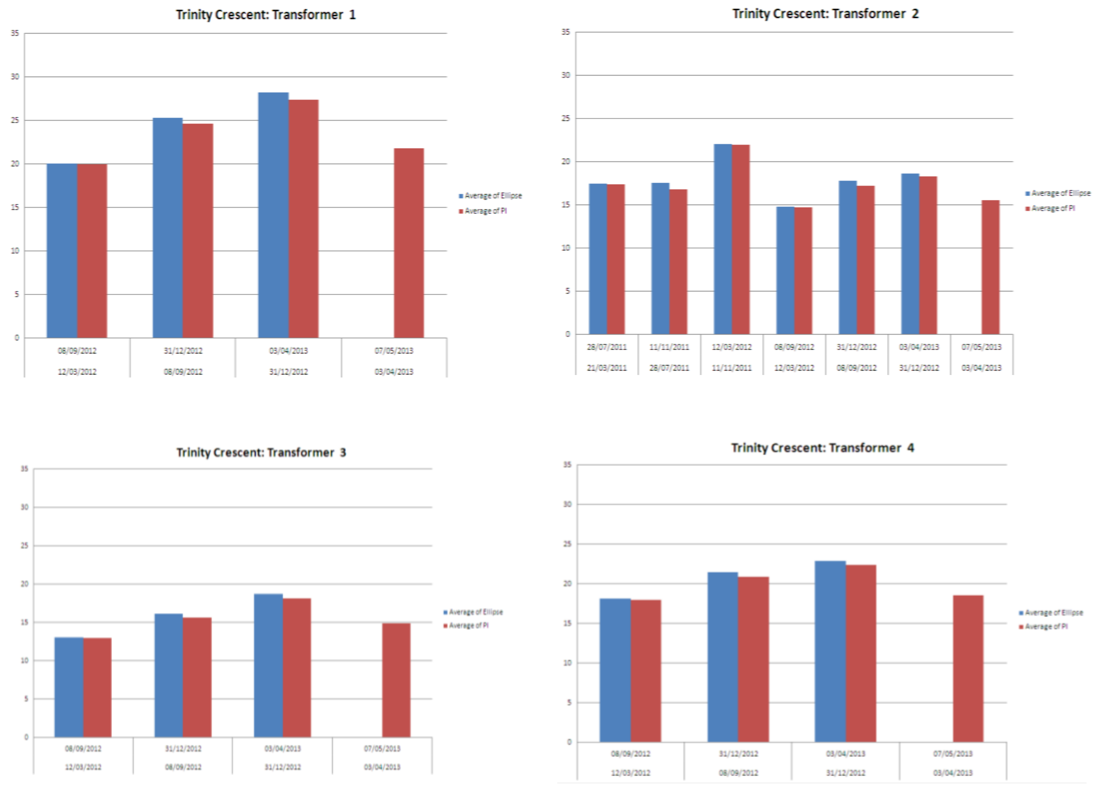


Figure F57: Comparison of asset database (Ellipse, blue bar chart) and PI data (red bar chart)
Average number of taps per day during each ellipse count period and average number of daily taps recorded in the PI TCIP data

For substations where there is a significant mismatch between PI data and the asset database tap change count data, there is an opportunity to inspect and maintain the voltage control relay and ensure that the tapchanger is not regularly reaching the extremity of its range, or not mechanically operating in response to a tapping instruction.

Having this information available could give an early indication of a potential problem. Such a case is apparent at Wandsworth Central A, where on Transformer 1, the average number of daily tapchanger counts has apparently doubled (figure F58).

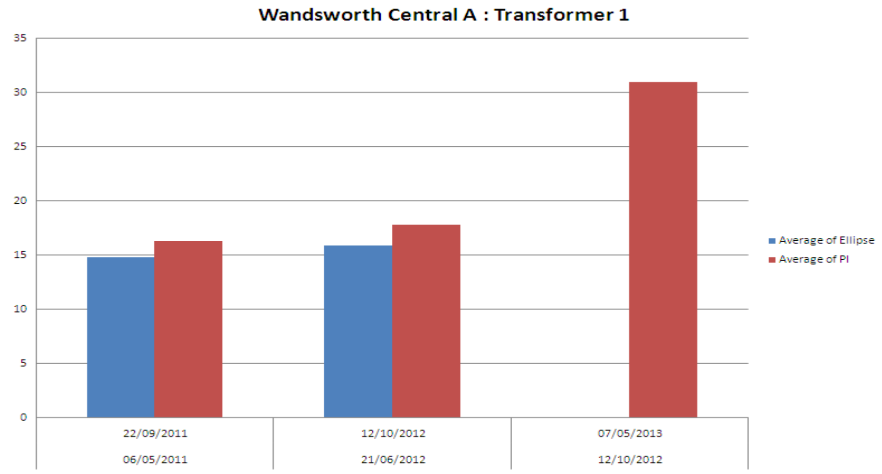


Figure F58: Increase in number of tap changer counts

The data can also be used to identify the actual week or day when tapchanger behaviour varied from the norm. Figure F59 shows how the number of weekly taps changed during a period and in particular how the increase in number of tap change operation dropped.

Figure F59: Number of tap change counts per week