SP ENERGY NETWORKS

Flexible Networks
for a Low Carbon Future

Future Roadmap for Improvement of HV & LV Network Modelling

Report No: 7640-08-R0

September 2015

DOCUMENT HISTORY AND STATUS

CONFIDENTIALITY (Confidential or not confidential):	Confidential
Project No.:	7640
Project Name:	Flexible Networks
Author:	Sarah Weatherhead and Charlotte Higgins
Issued by:	TNEI Services Ltd

Revision	Date issued	Reviewed by	Approved by	Date Approved	Revision Type
D0	11/08/2014	CEH	CEH	11/08/2014	First draft
R0	29/09/2015	CEH	CEH	29/09/2015	First release

Quality Assurance
TNEI is registered with Ocean Certification Limited (Certificate Number C145013 Q) as compliant with International Standard EN ISO 9001:2008. All work conducted by TNEI, its subsidiary companies and its subcontractors is carried out in accordance with in-house procedures and documentation.

Disclaimer
THE CONTENTS OF THIS DOCUMENT ARE FOR THE CONFIDENTIAL USE OF ONLY THOSE PERSONS TO WHOM IT IS INTENDED, AND MAY NOT BE REPRODUCED OR CIRCULATED IN WHOLE OR IN PART.

TNEI Services Ltd

Bainbridge House 86 – 90 London Road **Manchester** M1 2PW Tel: +44 (0) 161 233 4800 Fax: +44 (0) 161 233 4801	Milburn House Dean Street **Newcastle Upon Tyne** NE1 1LE Tel: +44 (0) 191 211 1400 Fax: +44 (0) 191 211 1432	Queens House 19 St Vincent Place **Glasgow** G1 2DT United Kingdom Tel : 0141 428 3184	Chester House 76-86 Chertsey Road **Woking** Surrey GU21 5BJ United Kingdom

CONTENTS

Executive Summary

To facilitate a future flexible network, improved network planning tools and processes will be required including more efficient and accurate network modelling of the HV and LV networks. As low carbon technology such as PV, electric vehicles, heat pumps and energy storage connect to the distribution network and with the growth of demand side response and generation ancillary services, a network modelling approach that reflects a more dynamic, controllable distribution network will develop. Also, smart solutions such as dynamic network thermal ratings, dynamic load shifting and voltage regulation will require detailed network modelling to most effectively assess their feasibility. As more detailed HV and LV network monitoring data becomes available over the RIIO-ED1 period, there should be a clear strategy for incorporating this into the existing modelling process to enhance understanding and response to both specific and wider HV and LV network characteristics, behaviours and trends.

Network modelling at HV and LV can be time-consuming, and modelling large parts of the network, particularly at LV, would be prohibitively expensive. Also, there is limited availability of load data for model verification and in some cases asset data such as cable ratings can be missing at LV, increasing uncertainty. A more techno-economic approach is to model in detail, representative areas of the network approaching capacity and the application of smart solutions, including verification with monitoring data, and use the learning to develop key metrics, validate more simplistic tools and adapt policy.

As part of this work, the input of key SPEN stakeholders was obtained to both understand current modelling tools and processes as well as to identify potential areas for future modelling improvements.

Improved network model build of the HV and LV networks

The efficiency of HV and LV network model build can be improved through increased automation to enable a detailed and accurate representation of the network and facilitate rapid update for network changes. A script was developed and tested to convert SPEN GIS data to an IPSA model for an 11kV network. A robust modelling approach for LV networks was also developed and tested based on manual trace of a background map, this approach is suitable for LV network modelling in small volumes.

These HV and LV network model build approaches were applied to the Flexible Networks trial sites. Results from verification of models are very encouraging however there are further refinements that are in development to reduce manual network correction post-conversion for the HV network model and to include a self-validation toolkit. Also, particularly at LV, there was found to be some missing asset data in GIS which reduces the accuracy of the models.

Whilst we envisage that HV networks are likely to be modelled for much of the distribution network in future to more full quantify the impact of LCT uptake and improve any network solution selection, LV networks will only be modelled in specific cases where network constraints have been identified along with high LCT uptake and/or rapid load growth. In parallel with LV network monitoring, learning from modelling and verification of these LV networks will address site-specific issues and inform simple LV network planning tools and "rules-of-thumb" as well as future policy. It will also enhance the understanding of, quantification and mitigation of uncertainties at this network level. We explore this further in "Flexible Networks Improved Characterisation of PV Capacity at LV".

Future improved business database linkages will support more automated network model definition such as asset ratings data and switching points.

Improved Characterisation of Network Load

SPEN modelling assumptions for representation of LV loads at ground mounted and pole mounted secondary substations were found to be broadly reasonable. These are as follows;

- For ground mounted substations, 80% of the MDI data value.
- For pole mounted substations, 20% of the transformer rating.

However, our analysis suggests that some further consideration of the secondary substation load type e.g. farming, schools, shops, and typical profile (particularly for larger industrial, commercial and other point loads) should improve network model peak loading assumptions and in some cases, identify additional network headroom. The impact of future LCT uptake on network thermal loading and voltage characteristics will depend on the existing load profile rather than just the maximum load. Consideration of load type changes e.g. domestic residence converting into doctors surgery, should also inform network modelling.

HV loads should be based on half-hourly settlement metering data at the timestamp of peak feeder or network loading, where possible. Typical profiles at peak network loading should be analysed for variability. This will ensure that the HV load magnitude at peak loading and profile is being more robustly considered in assessing the thermal and voltage capacity of the network.

SPEN modelling assumptions for power factor of demand loads (pf = 0.98) were found to be generally valid although analysis of measurements suggests that a value of 0.97 may be more appropriate. HV imbalance at high loading was found to be generally negligible therefore the current assumption of balanced phases at HV is reasonable for assessing maximum load conditions. However, there can be significant imbalance at LV based on our extensive analysis of LV feeder phase imbalance. This is more prevalent for rural loads or mixed loads (domestic, industrial and commercial) where there is less diversity. Thus, the existing modelling assumption of balanced LV loading is not valid although it is recognised that this is countered to an extent by the use of conservative estimates of loads.

A representative minimum domestic demand profile has been developed based on number of customers on an LV feeder and number of customers on a secondary substation. The application of this to characterise minimum daytime demand along with use of site-specific solar irradiance data from a nearby weather station to define PV generation maximum output should enable identification of additional generation capacity headroom.

A more probabilistic approach to defining suitable network load cases to understand the impact of future load changes such as LCT uptake will better define the network risk profile. This should reflect the increasingly dynamic nature of the distribution network with connection of LCTs, demand side management and energy storage.

Integration of LV Monitoring Data into Modelling

Increased network monitoring will support analysis of the specific networks being monitored as well as further verification of general load assumptions described above for application to the wider network. This includes the definition of generic load profiles with and without LCT uptake to assess demand and generation connections in LV network areas with limited or no monitoring.

A number of prototype analysis tools have been developed as part of Flexible Networks that utilise network monitoring data to help network planners better understand the characteristics of the HV and LV network and identify and test suitable smart solutions for increasing capacity headroom. A pilot study has also been undertaken with IBM as part of Flexible Networks to develop a Distribution Grid Analytics tool. This study utilised GIS data, NMS network configuration data, co-ordinates of monitoring locations and monitoring data to enable identification of thermally overloaded substations, voltages outside of statutory limits, and phase imbalance, from analysis of the monitoring data.

Customer Benefits

Improved HV and LV network modelling will give network planners a better understanding of the behaviour of the network and the likely impact of new demand and generation. This should lead to;

- More optimal identification, design and prioritisation of network reinforcement solutions, leading to generally more efficient network design and operation, ultimately reducing customer bills.
- Faster assessment of embedded generation connections.
- Greater assurance in compliance with network quality and security of supply standards and fewer CIs and CMLs due to circuit overloads at LV.
- Ability to confidently deploy and manage smart solutions such as flexible network control, automated voltage regulation, active network management etc.

Glossary

CI	Customer Interruption
CML	Customer Minutes Lost
DNO	Distribution Network Operator
ER P2/6	Engineering Recommendation P2/6 - the standard for distribution network planning
EV	Electric Vehicles
GIS	Geographic Information System
HP	Heat Pumps
HV	High Voltage
LCT	Low Carbon Technology
LCNF	Low Carbon Network Fund
LV	Low Voltage
MDI	Maximum Demand Indicator monitoring device
NMS	Network Management System
PV	Photovoltaics
SCADA	Supervisory Control and Data Acquisition (communications and control equipment)
SPD	SP Distribution (network license area)
SPEN	SP Energy Networks (network operating company)
SPM	SP Manweb (network license area)

1 Learning Outcomes

We have identified opportunities to improve HV and LV network modelling to achieve the following;

- Reduced network model uncertainty through;
    - increased model build automation enabling more detailed and accurate representation of the network and facilitating rapid updates
    - better quantification and mitigation of uncertainties such as missing asset data and link box connection configuration
    - Greater ease of integration of network load measurements from secondary substations
- Improved representation of network loading through;
    - Verification and improvement of typical SPEN assumptions for modelling of HV and LV loads in power systems models
    - Consideration of secondary substation load type and associated profile e.g. farming, industrial, commercial
    - Verification of SPEN assumptions for LV load power factor
    - Characterisation of typical levels of HV and LV phase imbalance and correlation to network types. Identification of significant levels of LV imbalance.
    - Development of a generic minimum domestic demand profile to improve identification of additional generation capacity headroom.
- Strategy for reduced reliance on measured data through improved characterisation of LV loads, thus reducing future monitoring costs and improving network quality and security.

1.1 Improved Modelling of HV and LV Networks

Network modelling is used in a range of business functions including asset management, network planning, connections and network operations for outage planning for example.

HV network models exist for the urban meshed SPM network and some of the rural networks whilst in SPD HV network modelling is only carried out on a case-by-case basis for assessment of generation connections. The LV network is generally modelled using simplified probabilistic tools such as Windebut or Excel spreadsheet tools. Network modelling can be time-consuming and there can be uncertainty regarding asset characteristics particularly at LV. There are also challenges with database linkages such as manual update of the current network configuration from the NMS into power systems models. Broad assumptions regarding LV load models, phase imbalance and power factor are made for networks that can have varying load types and topology.

The uptake of low carbon technology such as EV, HP and PV as well as smart solutions including demand side management and energy storage drives a need for faster and more accurate network modelling processes. For example, a flexible network control scheme to release capacity headroom will require a detailed understanding of the power flows and voltage profile on the 11kV network at different times of day. Likewise, network planners faced with clusters of domestic PV will require a robust approach and reliable data and assumptions on which to model the potential voltage rise and thermal implications at LV.

In this context, moving from a simple deterministic two load case analysis (maximum demand/minimum generation, minimum demand/maximum generation) is required to better understand network behaviour and the associated risk profile under a range of load conditions. A more efficient modelling approach will help to facilitate this and enable network capacity headroom to be better utilised.

1.2 Improved Integration of Monitoring Data in Modelling

There has typically been very limited monitoring on the HV and LV networks. Network monitoring data at HV and LV, where available will support the enhancement of loading assumptions including maximum loads, minimum daytime loads (for PV generation connection assessment) and load profile assumptions.

This can be applied to improving the management of specific networks to maximise capacity headroom as well as helping to develop support tools for more simplified analysis in areas of the network with similar characteristics without requiring detailed monitoring.

1.3 Potential Benefits

1.3.1 Network Planning

- More accurate characterisation and modelling of the HV and LV network and improved understanding of uncertainties
- Enhanced network reinforcement identification, prioritisation and proposal design
- More accurate and rapid assessment of capacity for new connections

1.3.2 Asset Management

- Better understanding of asset loading throughout its operational lifetime, thus facilitating the improved utilisation of remaining life

1.3.3 Network Operation

- Improved understanding of network behaviour at HV and LV will inform strategies for planned and unplanned outages

- Better characterisation of individual network risk profiles

2 Experimental Design

A future 11kV and LV network modelling approach has been proposed which aims to improve modelling efficiency and accuracy in order to release additional network headroom capacity, and enhance network planning decision-making whilst also reducing network uncertainty and risk.

The following considerations were made in developing improved modelling approaches in order to ensure robust learning outcomes;

Improved Network Model Build

- Improving automation of the HV and LV model-building process including linkage with key business databases to reduce potential for manual error.
- Improving representation of missing asset parameter data which can be significant particularly at LV.
- Identifying current challenges to efficient and accurate modelling and possible approaches to overcome these.
- Techno-economic assessment of the proposed approach at HV and LV and identification of when modelling should be utilised.

Improved Characterisation of Network Load

Existing assumptions for secondary substation and HV customer loads used in HV network modelling were tested in order to identify any areas for improvement, based on detailed measured data. This included;

- Assessment of load assumptions at peak demand for a range of secondary substation types.
- Assessment of load and generation assumptions at maximum PV generation/minimum demand.
- Assessment of assumptions for phase imbalance at HV and LV.
- Assessment of power factor assumptions at HV and LV.

Modelled voltage profile based on current load guidelines used by SPEN was also compared with measured data.

The three Flexible Networks trial sites were assessed; these contain a range of representative load types and network characteristics.

3 Improved Network Model Build

Network modelling is an important activity in a number of DNO business areas; asset management, network design and planning, network operations and connections.

The process of network modelling can be divided into;

- **Building the network model**: defining the physical network of overhead lines, cables, transformers, fuses, switching points etc. in a power systems software or manually, along with corresponding asset ratings, connectivity, and network loads.
- **Load modelling**: defining network demand and generation under a range of scenarios (e.g. maximum demand/minimum generation, minimum demand/maximum generation) based on monitoring data if available or standard network planning 'rules of thumb' with local network knowledge. This is considered in detail in Section 5.

Figure 3-1 provides an illustration of the current state of 11kV and LV network modelling in SPEN and how this may develop in the future as an improved characterisation of network behaviour is required at these voltage levels. Some degree of automation will definitely be required in future in order to manage significantly more network modelling than is currently undertaken.

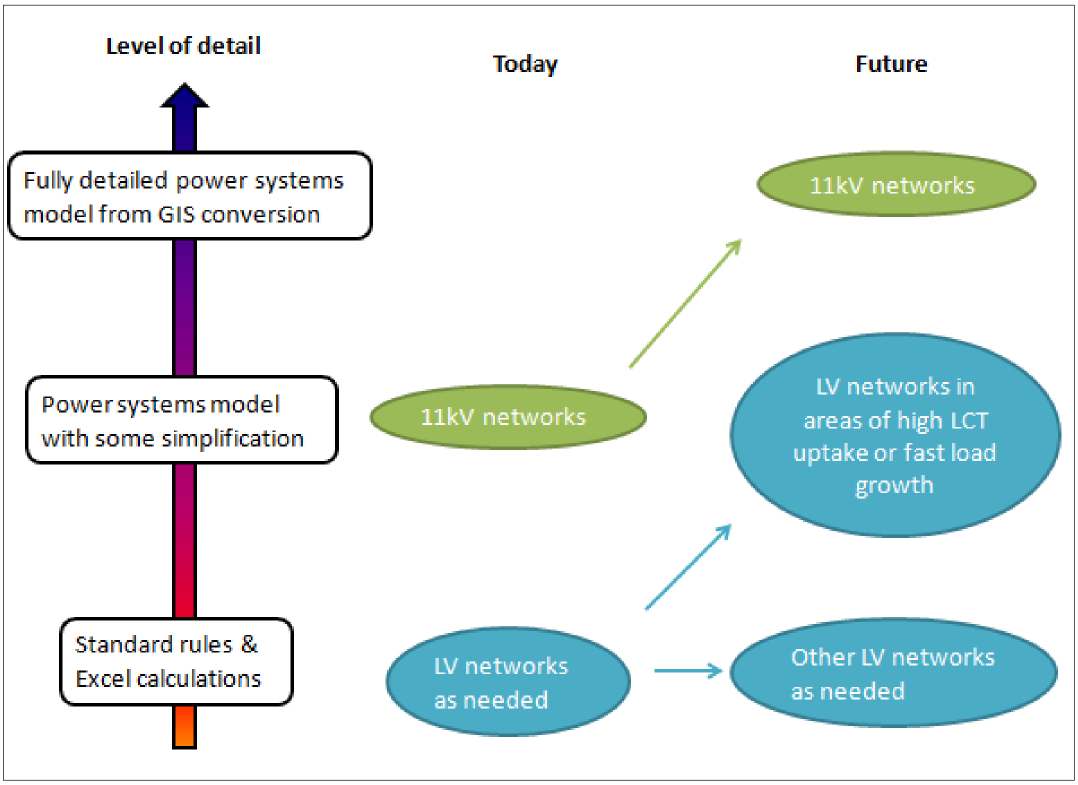

Figure 3-1 Level of detail required in network model build

3.1 HV Network Models

3.1.1 Current Approach

11kV network planners in SPM develop network models, incorporating the primary substations, HV feeders and secondary substations. Models have already been built for large parts of the SPM 11kV urban network. This is due to the meshed configuration of the urban network that can result in more complex load flows compared to radial networks. Models for the 11kV rural network are less common as the network is typically radial.

In order to build the network models, conductor connectivity, length, type and cross-sectional area can be exported from the GIS system. A separate cable database provides the linkage between cable type and size, and rating. The main SPEN asset database contains transformer ratings and impedance data for primary and secondary substation transformers (impedance data is generally only available for ground-mounted substations although pole mounted substations will generally have lower loading so the impedance data accuracy is not so critical). The main asset database is directly linked to the NMS database but not to the GIS database. Standard designation of asset ratings are also documented in SPEN policy ESDD-02-007 “Equipment Ratings and Assessment of EHV/HV Systems” as informed by manufacturers data.

Network configuration is then verified by comparing to the NMS system, which will contain the most up-to-date configuration of the network.

In SPD, due to their simpler, radial nature, 11kV networks are only modelled on a case-by-case basis for generation connection applications.

These HV network models are then used to analyse network behaviour at peak demand and generation loading, typically under contingency (i.e. N-1) conditions, to ensure that the network complies with ER P2/6 security requirements as well as not exceeding statutory voltage limits.

Challenges relating to the current network build process at HV include;

- The HV networks are extensive and model build and verification can be time-consuming.
- A verification process is required each time an existing 11kV model is reused, because there is no unified or automated process to keep models up-to-date. The network areas most likely to require reinforcement are updated each year, but it is not considered cost-effective to regularly maintain all the 11kV models as they are not used frequently enough.
- There are several conductor ratings databases that exist for various power systems software and currently no linkage with GIS or NMS. The main asset database is currently not linked to GIS.
- Some HV network models may be simplified and aggregate a number of similar and nearby secondary substation loads to speed up model build. This is typically done for overhead networks with small pole mounted

secondary substations. This can lead to increased uncertainty in feeder voltage drop.

- Information on the tap settings of the secondary substation transformers is not typically recorded and assumed to be set to nominal (i.e. the standard setting)
- In the GIS database, conductor material and/or cross-sectional area is not always available for HV and LV feeders so modellers assume values based on their experience. The GIS database was searched to identify the percentage of HV overhead lines and cables missing cross-sectional area data. In SPM, this was the case for 17% of overhead lines and 14% of underground cables, in SPD, this was 36% of overhead lines and 12% of underground cables. In SPM, 25% of LV cables are missing a value for cross-sectional area. Note that there is often additional information available in archived databases, which can be viewed using Arcview GIS, but which has not been transferred into the GIS database. A similar situation is expected for other DNOs.

3.1.2 Network Model Build Automation

As part of Flexible Networks, a GIS conversion script was developed to trial automation of network model build at HV and LV. This was tested for the three trial network areas. The advantages of this approach are:

- Creation of a detailed network model with no aggregation of loads required, thus preserving the full network topology.
- Less potential for manual data input errors.
- More rapid model build and ease of network model refresh if the network configuration changes.
- Greater ease of integration of network load measurements from secondary substations.

The GIS database contains details of conductor cross-sectional area and material type however not corresponding ratings. SPEN conductor ratings for standard overhead line and cable types were incorporated during network model build via a separate lookup table. Generic assumptions were made where conductor details were not available in GIS, future work could be undertaken to refine assumptions further through development of a smarter algorithm.

The network models created through the conversion process were reviewed for accuracy. This has provided the following key learning points (for both HV and LV network models) that will be used to refine the conversion process further in future:

- The conversion script was bespoke to suit the format of the GIS database output for SPEN e.g. data column numbers. Other UK DNOs are likely to have different GIS database output formats so the script would need to be adapted although this is relatively straightforward.

- The GIS database stores the location of assets as X and Y coordinates but not connectivity and it can be challenging to design the conversion algorithm to capture connectivity accurately. In some cases, connectivity is not represented well at tee-points where three or more overhead lines or cables connect and at switching points. This is typically due to very short cable lengths defined in GIS that are less than the minimum global deadband defined for matching conductor ends, and/or conductor ends that are slightly outside the global deadband. These issues require some manual error identification and correction. At LV, this can be very extensive and time-consuming.
- The GIS database does not contain information on normally open network points, this information is only available from the NMS. Network open points were manually added, however automation of this process may be possible based on network configuration files exported from the NMS database. This is being considered as a future development for the GIS conversion script developed for IPSA as part of Flexible Networks.
- The minimum global deadband for matching conductor ends was difficult to optimise for LV networks due to varying lengths of LV cable end proximity and some short LV cable sections particularly close to secondary substations.
- Configuration of LV feeder link boxes is sometimes not recorded when it has been changed.
- Cable or overhead line sections were sometimes defined several times in the GIS database. This resulted in instances of multiple circuit sections in the network model and thus, incorrect circuit impedances.

3.1.3 Enhanced Automation

A further enhancement to automation of network model build will be to incorporate automated conversion of network configuration data from the NMS. Network configuration data will be provided by NMS and circuit length and impedance data from GIS, or by using standard assumptions where data is missing.

A pilot study was undertaken with IBM as part of Flexible Networks to develop a Distribution Grid Analytics tool. This utilised GIS data, NMS network configuration data, co-ordinates of monitoring locations and monitoring data. The current network topology was then visualised through an overlay on Google Maps and analytic tools implemented to enable identification of thermally overloaded substations, voltages outside of statutory limits, and phase imbalance, from analysis of the monitoring data. However, the Distribution Grid Analytics tool does not have power systems modelling capabilities.

3.1.4 Roadmap for Future

3.1.4.1 Improved database linkages

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

To progress towards this, there is currently an internal SPEN Future Cities team project with IBM to develop a "system of insight" that collates and databases useful corporate information such as council future development plans to inform network load index and connections.

A Distribution Grid Analytics tool similar to that discussed in section 3.1.3 may also be integrated with the Smart infrastructure data management system in future.

3.1.4.2 Reduced network model uncertainty

An intelligent algorithm could be developed to determine and apply suitable conductor ratings where data is missing, for example by considering the standard conductor types for the network area, and the ratings of surrounding assets. It is likely to be more easily applied in SPM, which as a meshed network tends to have more standard conductor sizing. In SPD, conductor sizes and thus ratings, often taper in size towards the ends of the feeder depending on backfeeding arrangements. Adjacent conductor section ratings would be required for the algorithm to work best.

The algorithm would alert the modeller when conductor ratings assumptions have been made to help quantify the level of modelling uncertainty and could be set to a 'worst likely case' or 'most realistic case', depending on the aims of the modelling. This could be difficult if there are areas of the network where a lot of data is missing. The level of risk associated with the cable rating assumption would need to be quantified at a general level. The algorithm will need to reflect the specific network design philosophy of the DNO.

Further developments are being explored for the GIS conversion script to develop a more robust approach for automated network modelling.

3.2 LV Network Models

3.2.1 Current Approach

LV network constraints are often identified by customers when the voltage is approaching the statutory limits. Network problems can also be identified by the local operation staff who flag up such problems as blowing fuses due to high loads or areas where the network cannot be secured under outage conditions as anticipated.

Network investigations are then completed to assess network performance in more detail and to confirm the network arrangement. Where a potential reinforcement requirement is identified, an appropriate network solution is then found to resolve the issue.

The LV network is typically modelled in less detail than at HV, using probabilistic tools and 'rules-of-thumb' to avoid exceeding statutory voltage limits and minimise CIs and CMLs. This is due to network security requirements for the LV network being less stringent than at HV and the large LV network volumes. Maximum demands recorded on secondary transformers are available but the only way to obtain LV feeder loads is to do direct measurement at the secondary substation. Time restraints normally restrict the amount of useful information to be obtained by this method and it is not captured in the load database system.

Networks are designed based on rules found in ENA engineering recommendations[1] and SPEN policy "Framework for design and planning for low voltage housing developments underground network installations and associated, new, HV/LV distribution substations" ESDD-02-012. For assessment of new connections, the designer relies on network maps and making estimates of the demands to the existing properties connected, the circuit demands and resulting voltage to establish if the new connection can be accepted and/or any reinforcement is required.

3.2.2 Improved Network Build Methodology

It is expected that in future, LV networks will need to be modelled in more detail than currently. However, this will be on a case-by-case basis or to provide more generic learning to develop improved 'rules-of-thumb' for simplified network analysis.

As part of Flexible Networks, we have developed a robust approach to modelling LV networks efficiently and rapidly whilst minimising uncertainty.

The GIS conversion process was applied to LV network data extracted from the GIS database however this resulted in a model that required a lot of manual correction of connectivity.

A more efficient process has been developed that involves the following steps;

- Manually trace an image of the LV network in IPSA using the facility to include a map of the network from Arcview/GIS in the background.
- Manually add loads along LV feeders (these are typically aggregated circa 3-4 houses or more) and cable data from GIS.
- Include SPEN cable rating database in IPSA.

[1] G81 – The Electricity Association publication titled: Framework for design and planning, materials specification and installation and record for low voltage housing developments underground network installations and associated, new, HV/LV distribution substations.

This method is suitable for modelling LV networks in low volumes. We would anticipate that LV networks will only be modelled to this level of detail if there is a specific issue to analyse, such as the impact of extensive LCT clustering, and where learning outcomes can inform network planning strategies for the wider LV network.

3.2.3 Roadmap for Future

LV network modelling will be needed in some areas in the future to assess the effects of clusters of PV generation at LV, EV charging, and significant load change, and the impact of smart solutions such as flexible network control, voltage control, voltage regulators, LV meshing and energy storage. A more detailed but cost-effective LV network modelling approach should improve network management and optimise connections and reinforcement strategy.

The approach described in the SPEN RIIO-ED1 LCT Network Monitoring Strategy as summarised in Appendix D is to identify areas of the LV network with high LCT growth and pro-actively deploy monitoring to these areas. The strategy proposes a method for identifying LCT hotspots on the network (as illustrated in Figure 3-2) to give an indication of areas where LV monitoring and modelling should be considered. This will depend on the techno-economic case, initially LV modelling may be undertaken in a few areas and the learning used to improve the 'rules of thumb' used in planning and operation for other, similar LV networks.

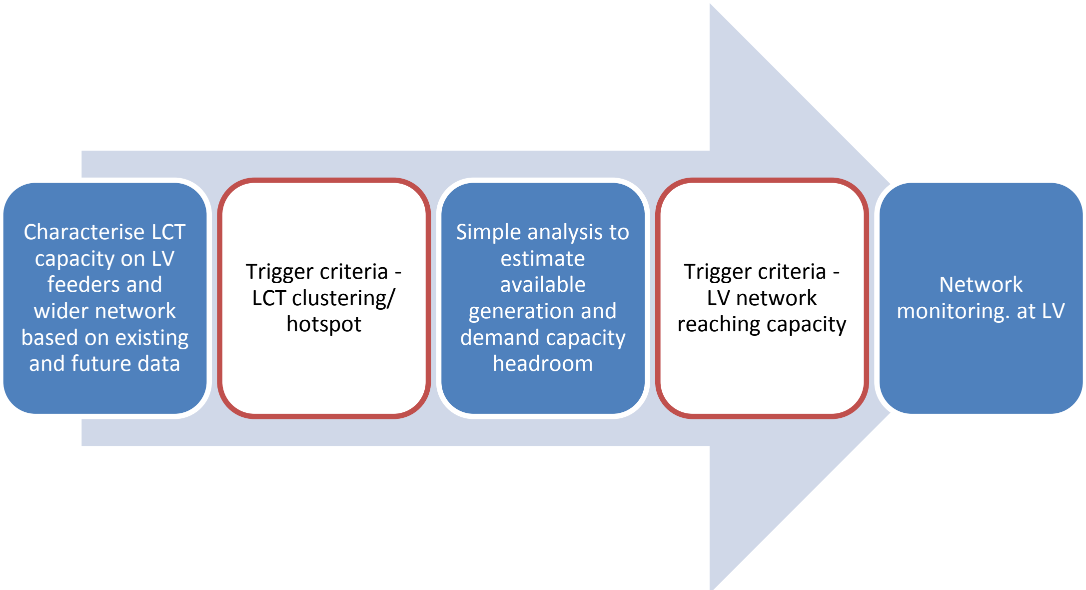

Figure 3-2 Overview of LCT network monitoring strategy

The SPEN GIS system already holds both connectivity information and asset data, so by executing a trace from a secondary substation, it is possible to extract information about each of the feeders supplied by this substation. A trace on a single feeder will determine:

- Length of the feeder

- Cable type for each section

In addition to this, it is proposed that small changes could be made to allow the following information to be returned on a per feeder basis:

- Number of customers connected along the feeder
- Number and capacity of G83 or G59 generation connected

This is currently a fairly time-consuming process per feeder (order of minutes) so some algorithm refinement would be required. As discussed in Section 3.1, a further algorithm can also be developed to handle cases where cable data is missing in GIS.

Figure 3-3 below shows a trace along part of an LV feeder with 12 customers connected, and 7 distributed G83 generators, totalling 11.2kW of installed PV (based on a capacity of 1.6kW per PV installation). The feeder information can then be fed into a simplified LV network modelling tool to determine whether the generation loading is broadly acceptable.

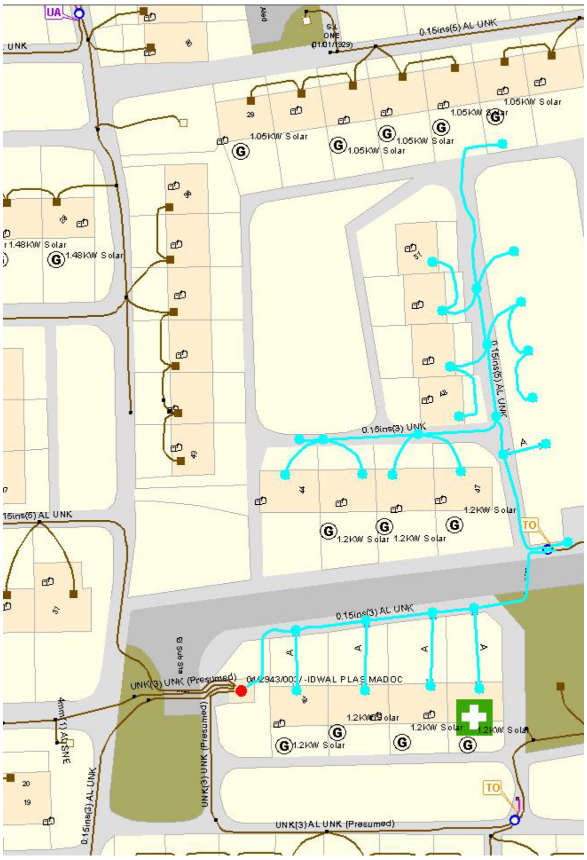

Figure 3-3 Trace on an LV feeder (supplied by Idwal Plas Madoc secondary substation)

Currently, normally open points are shown in the GIS database system. It is anticipated that the location of new control points would also be defined in the GIS database. Switch states are currently recorded in a paper log, this could be automated in future via a snapshot of network topology in NMS for the HV network when the switch is made or via an electronic log for the LV network.

4 Improved Characterisation of Network Load

To analyse an LV or HV network group, the load profile of the group must be determined based on available data.

For SPEN, the loading information available at HV is as follows;

- Current and voltage on primary transformers
- Yellow phase current on 11kV feeders

Loading information available at LV is as follows;

- Ground-mounted secondary transformer loading based on MDI data is available from the main asset database. MDI data is generally read six-monthly with total maximum loading and corresponding total three phase current measurements (no timestamp is recorded).
- No timestamp is recorded for the maximum demands and they are not necessarily concurrent i.e. the sum of these demands would exceed the recorded primary transformer maximum demands. A correction factor is applied.

4.1 Improved LV Load Characterisation

4.1.1 Current Approach

Currently on the SPEN network, MDI data is available for the majority of HV/LV ground mounted secondary substations. Pole mounted secondary substations do not have MDIs installed.

For HV feeders, half hourly yellow phase current data at the primary substation is obtained from the PI database.

Maximum Demand/Minimum Generation

The HV network is typically modelled for maximum demand/minimum generation conditions to ensure compliance with ER P2/6 – Security of Supply. Secondary substation loads are defined as follows;

- For ground mounted substations, the initial load value is set to 80% of the MDI data value (where available).
- For pole mounted substations, the initial load value is set to 20% of the transformer rating.
- HV connected loads are generally assumed to be at the maximum stated connection capacity, or some fraction of this based on the engineer’s judgement.
- A diversity factor is then applied to the secondary substation demands. This can be implemented as a global factor applied to all the secondary demands to reduce their combined total to match the recorded primary

transformer maximum demand and or on sections of the network to also reflect the recorded feeder maximum currents.

- For meshed networks the process is more complex and can require multiple iterations.

The primary transformer maximum loadings and corresponding 11kV feeder currents are sourced from the PI database.

Minimum Demand/Maximum Generation

In SPD, 11kV networks are modelled to understand the impact of generation connections rather than load growth. The load database is used to find the 11kV feeder minimum demand. Secondary substations are then initialised as follows:

- For ground mounted substations, the minimum load is assumed to be 10% of the transformer rating.
- Pole mounted substations are generally assumed to have zero loading.
- A diversity factor is applied to scale the secondary substation demands to the total minimum loading on the HV feeder.
- If there is already generation connected, it is assumed to be generating at 100% its rated capacity.

Alternatively, a system minimum load scaling factor of 39% in SPM[2] and 35% in SPD[3] can be used for high level system studies, based on maximum load. However, in reality, minimum demand varies between substations depending on specific load and customer characteristics.

When modelling the impact of PV generation on LV networks, internal guidelines recommend that a minimum demand value of 200W per property is used to include a factor of safety in assessments.

Challenges

Current challenges associated with LV load modelling assumptions include;

- Actual secondary substation loading at maximum and minimum demand may differ from assumptions. Assessment of the magnitude and materiality of this is included in Section 4.1.2. The impact on voltage profile is also explored through a test case.
- Point loads i.e. single point loads such as pumps that switch on and off, are difficult to characterise. The standard assumption is that, at the time of maximum HV feeder demand, the load will be at 80% of the MDI reading. However, this is inaccurate for point loads, which may be at 100% or 0% or a discrete value in between. It is recommended that point

[2] SP Manweb Long Term Development Statement 2013

[3] SP Distribution Long Term Development Statement 2013

loads are modelled as 100% of maximum demand when modelling for maximum demand conditions and a zero load when modelling for minimum demand conditions (unless there is a known seasonal pattern).

- Generation is assumed to be at 100% rated capacity, as this represents the worst case. However, this could result in an overly pessimistic estimation for wind and solar embedded generation. For example, for the LV network studied in Flexible Networks "Improved Characterisation of PV Capacity at LV", the maximum PV generation over a 10 minute averaged period was found to generally be 90% of the rated PV capacity (based on our PV resource assessment model which correlates irradiance with PV generation output). If generation does reach total rated capacity, it may only achieve it for a very short period or periods of the year.
- Characterisation of demand and generation phase imbalance, this is explored in Section 4.3 and in detail in the "Flexible Networks HV and LV Phase Imbalance" report and "Flexible Networks Improved Characterisation of PV Capacity at LV report".

4.1.2 LV Load Analysis

Detailed monitoring was installed on a number of ground mounted and pole mounted secondary substations for Flexible Networks. This has been used to verify the standard modelling assumptions regarding secondary substation loads, phase imbalance and power factor at maximum demand.

The loading as a percentage of MDI at the time of maximum HV feeder loading is shown in Figure 4-1 for a representative sample of secondary substations on St Andrews Feeder 25 and in Figure 4-2 for a representative sample of substations on Whitchurch Feeder 4. These indicate that an assumption of 80% of MDI is reasonable for ground mounted secondary substations although there is some variance. Full details of results are provided in Appendix C. This is also explored in further detail in "Technical Note on Investigation of Diversity in Secondary Substation Load" which concluded that:

- The level of diversity depends on the number of secondary substations considered for a given feeder. Short feeders with few substations are generally less diverse,
- Long urban/rural feeders appear to show more diversity of load, although this is difficult to fully characterise in the light of the limited monitoring of small rural secondary substations,
- For urban feeders, aggregate peak load is generally in the range 75% to 90% of the sum of the individual peak loads.
- For longer urban/rural figures a figure below 70% appears appropriate.

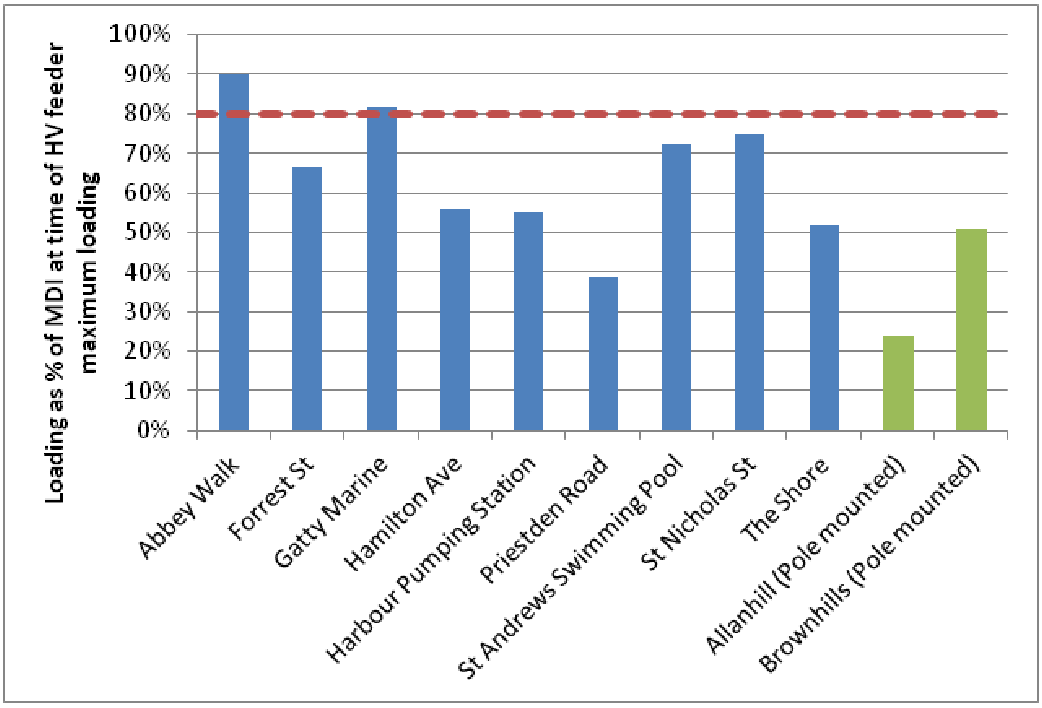

Figure 4-1 Loading of secondary substations on St Andrews feeder 25 at maximum HV feeder loading (05/12/2013 16:30)

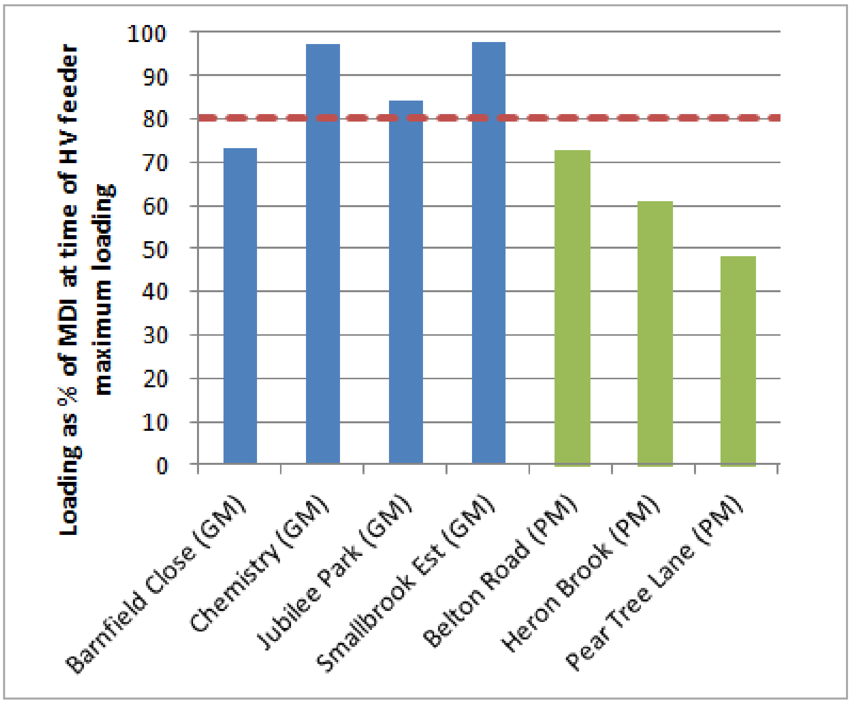

Figure 4-2 Loading of secondary substations on Whitchurch Feeder 4 at maximum HV feeder loading (07/01/2014 17:30)

Allanhill and Brownhills on St Andrews feeder 25 are pole mounted substations, with a transformer rating 200kVA. At the time of maximum HV feeder loading;

- Allanhill had a load of 26kVA i.e. 13% of transformer rating
- Brownhills had a load of 37kVA i.e. 18% of transformer rating

It is understood that the monitor calibration at Abbey Walk and Brownhills secondary substations may be suspect. This was taken into consideration when evaluating LV load assumptions.

Belton Road, Heron Brook and Pear Tree Lane on Whitchurch feeder 4 are pole mounted substations with transformer ratings of 100kVA, 200kVA and 100kVA respectively. At the time of maximum HV feeder loading:

- Belton Road had a load of 90kVA i.e. 90% of transformer rating
- Heron Brook had a load of 46kVA i.e. 23% of transformer rating
- Pear Tree Lane had a load of 17kVA i.e. 17% of transformer rating

This suggests that an assumption of 20% of transformer rating is generally reasonable for representing the loading of pole mounted transformers at maximum HV feeder loading, but there will be exceptions. This should be verified with a larger data sample. The analysis also suggested that the load at Belton Road exceeded the transformer rating at its time of maximum loading, 25/12/13 at 9:10am, with a load of 123kVA.

Figure 4-3 and Figure 4-4 explore how the loading of a number of ground mounted secondary substations varies on six highly loaded winter evenings in 2013. Detailed results for St Andrews feeder 25 and Whitchurch feeder 4 are given in Appendix C. It should be noted that Harbour Pumping Station is an industrial point load that can sometimes be close to zero at teatime peak. Point loads are not very well captured using an assumption of percentage of MDI for loading.

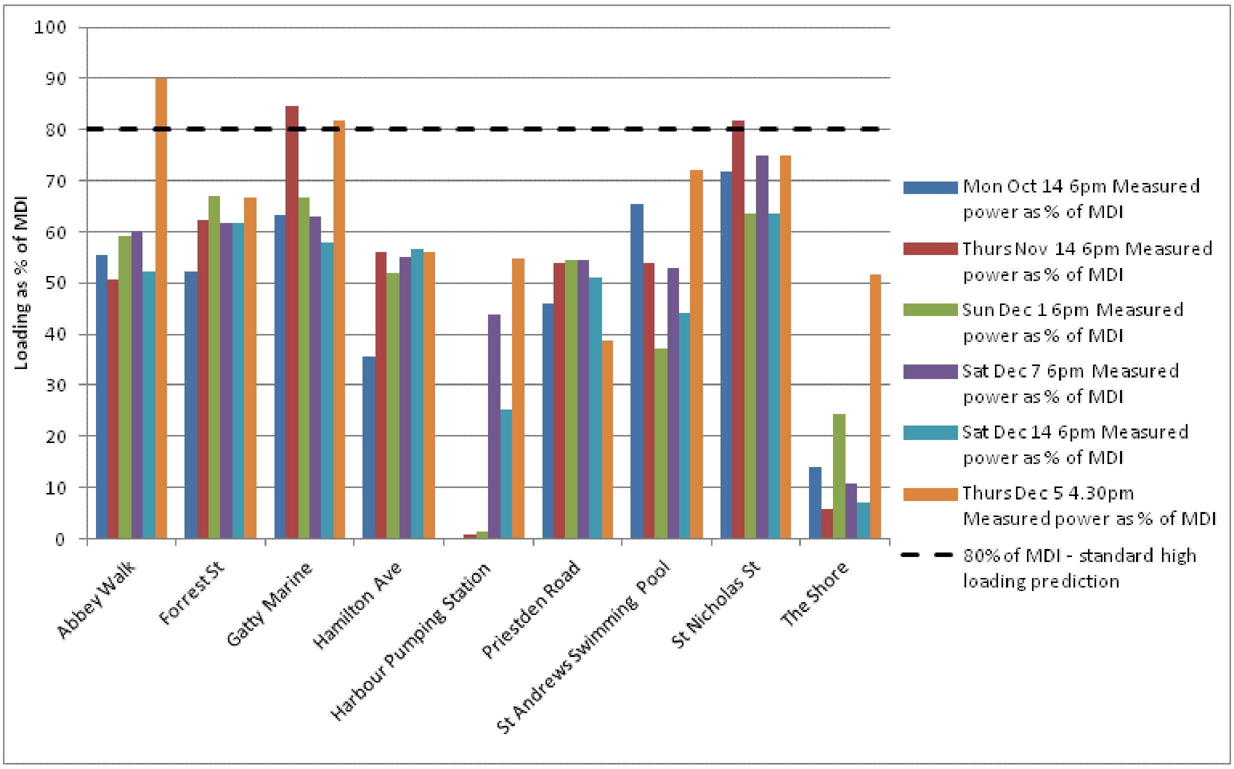

Figure 4-3 Comparison of St Andrews feeder 25 secondary substation loading as a percentage of MDI at selected peak times and at maximum HV feeder loading (05/12/2013 16:30)

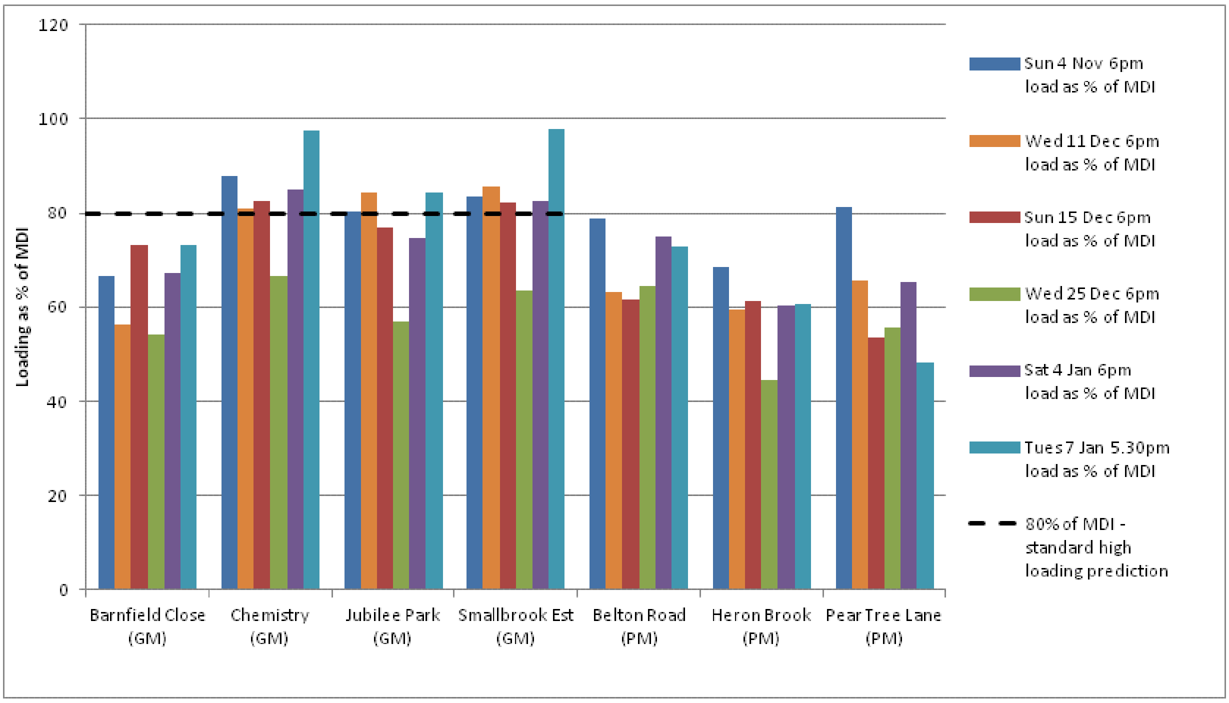

Figure 4-4 Comparison of Whitchurch feeder 4 secondary substation loading as a percentage of MDI at selected peak times and at maximum HV feeder loading (07/01/2014 17:30)

The load type for the secondary substations contained within the sample was characterised, based on a review of geographic maps of the areas supplied by each substation. This is shown in Table 5-1 and Table 5-2.

Table 4-1 Load type for secondary substations on St Andrews Feeder 25

Secondary substation	Load type
Abbey Walk	residential, schools, medical
Allanhill (pole-mounted)	farm
Brownhills (pole-mounted)	farm, residential
Forrest St	residential
Gatty Marine	industrial, university
Hamilton Ave	residential
Harbour Pumping Station	Industrial, pumping
Priestden Road	residential
St Andrews Swimming Pool	residential, leisure
St Nicholas St	residential
The Shore	Residential, industrial (pumping station?), commercial

Table 4-2 Load type for secondary substations on Whitchurch Feeder 4

Secondary substation	Load type
Barnfield Close	Residential
Chemistry	Residential
Jubilee Park	Residential
Smallbrook Est	Residential
Belton Road (PM)	Mixed
Heron Brook (PM)	Residential (rural)
Pear Tree Lane (PM)	Residential

Load type characterisation of the secondary substations helps to understand the differences in Figure 4-3. Residential loads tend to have less variability in loading at peak HV feeder loading times, likely due to large numbers of similar customers, thus less load diversity. This suggests that some consideration of the load type and typical profile (particularly for larger I&C and point loads) should improve network model loading assumptions in the absence of detailed measured data.

For example, at 6pm a commercial or industrial load may significantly reduce or on a Sunday evening, a leisure centre may be closed. Understanding these behaviours will be very useful for assessing the impact of future LCT uptake on load profile and thus network thermal load and voltage characteristics and also, exploring opportunities for dynamic load shifting to increase network group capacity. A probabilistic approach could be applied to quantify the network impact over a feasible range of high or low loading conditions. Consideration of load type changes e.g. domestic residence converting into doctors surgery, should also inform network modelling.

Load behaviour is generally very similar for the secondary substations of Whitchurch feeder 4, as shown in Figure 4-4. These substations have predominantly residential load types. There is no visible loading dependency on weekends and weekdays, this could be because people are generally at home and commercial businesses are closed at 6pm on weekdays and on the weekend.

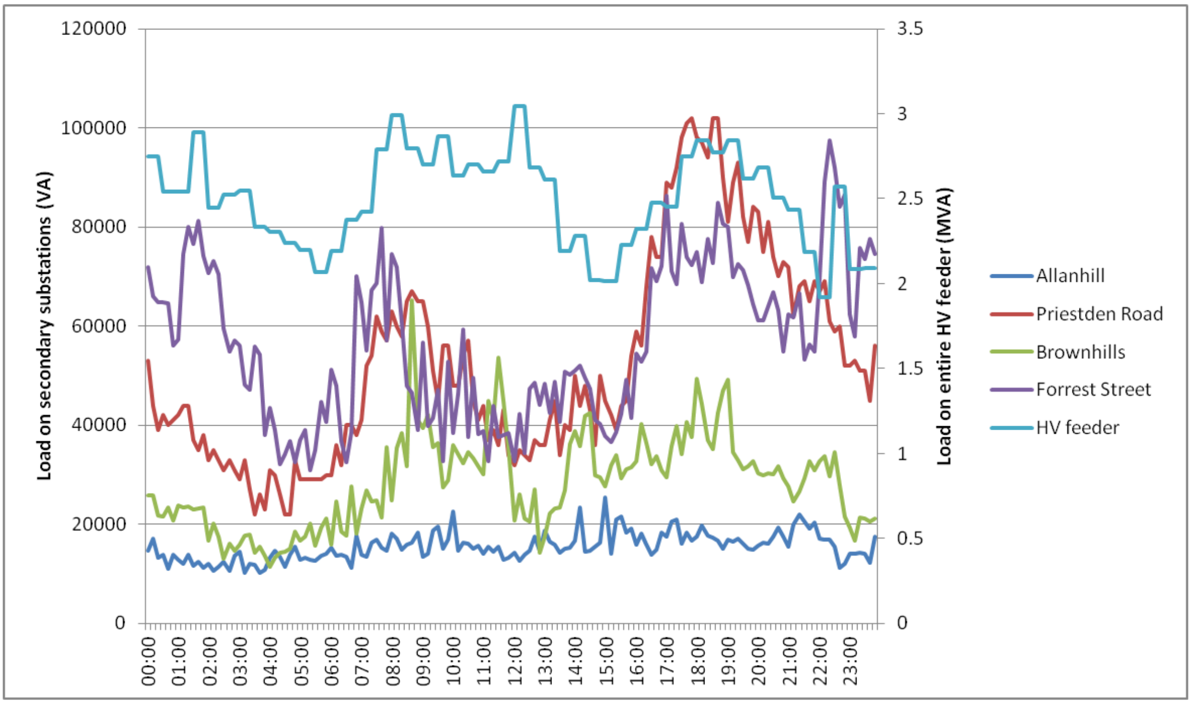

Figure 4-5 Daily load profile for St Andrews feeder 25 and monitored secondary substations on highly loaded day (Thursday November 14th 2013)

The daily load profile for several ground mounted and pole mounted secondary substations and St Andrews feeder 25 is shown in Figure 4-6 for a high loaded day. It can be seen that the pole mounted secondary substations that supply farms (Allanhill and Brownhills) tend to have a less variable load profile compared to residential areas such as Forrest Street and Priestden Road which generally display a more typical domestic customer load profile shape, increasing in the morning and peaking around teatime (6pm).

It is also worth noting that the shape of the early morning winter load profile for the HV feeder does not follow a more typical domestic load profile (as shown in Figure 4-7) where demand would generally be at a minimum. This indicates a mixed load profile, as supported by our assessment of secondary substation load types, with some economy 7 heating during the night. The load profiles for Forrest Street and Priestden Road in the early morning also show evidence of economy 7 heating.

The other St Andrews HV feeders display more typical daily load profiles as shown in Figure 4-6. Differences in load patterns between feeders within the same network group or for adjacent network groups can provide opportunities for dynamic load shifting.

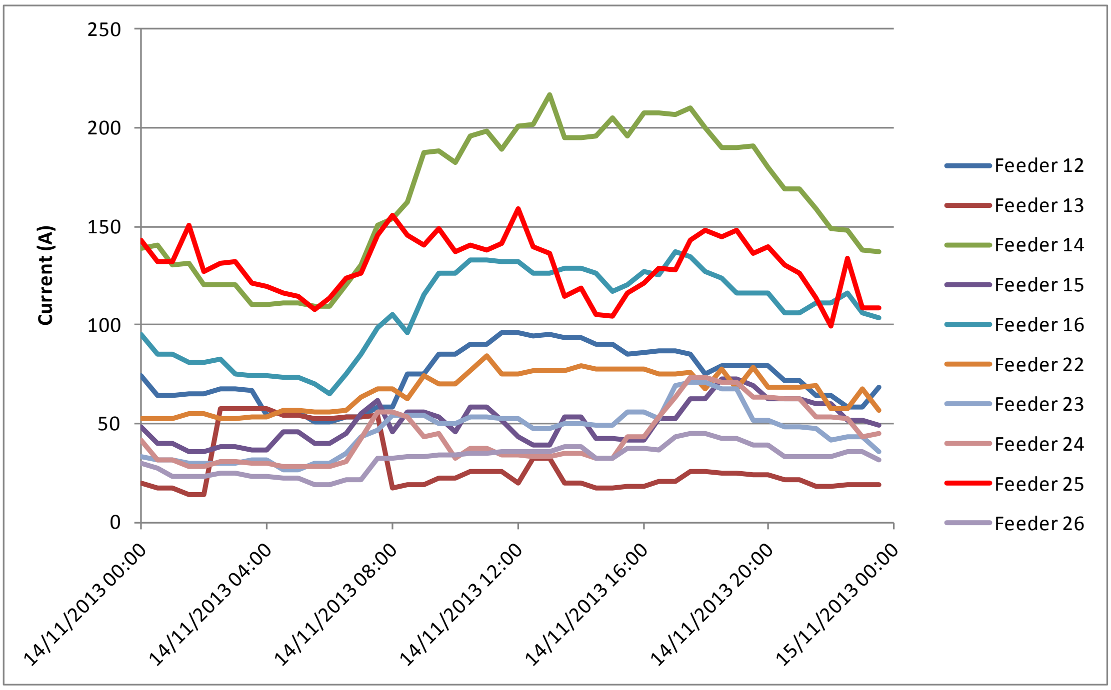

Figure 4-6 Daily load profile for St Andrews HV Feeders on highly loaded day (Thursday November 14th 2013)

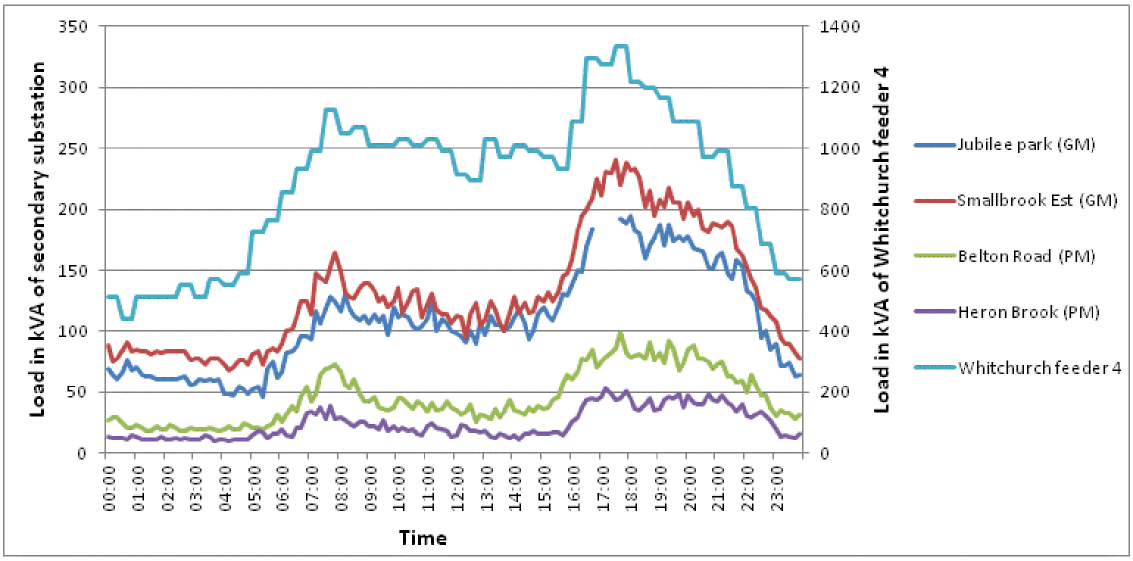

Figure 4-7 Daily load profile for Whitchurch feeder 4 and selected secondary substations on highly loaded day (Wed December 11th 2013)

Similarly, the daily load profile for selected substations on Whitchurch feeder 4 for a highly loaded day is shown in Figure 5-6. It can be seen that for the Whitchurch feeder, where nearly all substation loads are identified as residential, there is a strong correlation between loading patterns. This suggests that in network areas with less diversity in load types, such as for Whitchurch HV feeder 4, secondary substation daily load profiles can be predicted fairly well based on a the HV feeder daily load profile. This approach would not be suitable for an area with high diversity in load types, such as St Andrews feeder 25.

Further analysis with a larger sample size of substations should be carried out in future to verify the analysis findings.

4.1.2.1 LV Feeder Loading Assumptions

For LV network models, peak loads are typically modelled based on After Diversity Maximum Demand (ADMD) values depending on the housing stock e.g. semi-detached, terraced, or industrial/commercial properties with corresponding appropriate load profile assumptions. These load assumptions were not tested in this analysis as monitoring was not installed on individual properties and a large population size would be required for statistical validity.

4.1.3 Embedded Generation Connections

The rise in PV connections at LV brings new challenges for network modelling. Network constraints for PV occur at times of minimum summer daytime demand and maximum PV generation. The typical network constraint is voltage rise along the feeders. Thermal constraints on cables should also be considered, particularly if network voltage reduction has allowed large volumes of PV to connect.

Currently, network models and spreadsheet tools are analysed for minimum demand and maximum generation to assess the impact of new 11kV generation connections and in areas of high clustering of PV generation at LV.

Minimum load usually occurs at summer weekends in the early hours of the morning. However, maximum PV generation is close to midday, so network modelling should use minimum demand during daylight hours to avoid overly conservative voltage profiles.

As part of Flexible Networks, detailed analysis was carried out on LV feeder monitoring data in areas of high PV uptake to improve the characterisation of embedded generation on the LV network and corresponding voltage profiles[4].

A generic minimum demand profile was defined based on measured secondary substation LV feeder data (for LV feeders with no PV connected) in June and July 2014 and normalised in per unit based on the number of LV domestic customers, as shown in Figure 4-8. The average daily peak demand for the summer was calculated to be approximately 555 W per customer. This profile was validated for 28 LV feeders with predominantly residential customers. Minimum demand during the day was found to be lower during weekdays rather than weekends for residential properties. This approach will now be applied to other LV feeders with similar load characteristics but limited or no monitoring, to assess new PV connections.

It can be seen from the generic minimum demand profile that the load scaling factor during daytime minimum demand is around 50% to 60%. Thus, a summer minimum demand value per property of 300W should be appropriate. This also indicates that the system minimum load scaling factors of 39% in SPM and 35% for SPD (reported in Section 4.1.1) are broadly reasonable albeit slightly high. For example, 555W divided by 2000W After Diversity Maximum Demand is 28%.

[4] TNEI Services Limited, "Flexible Networks Improved Characterisation of PV Capacity at LV", September 2015.

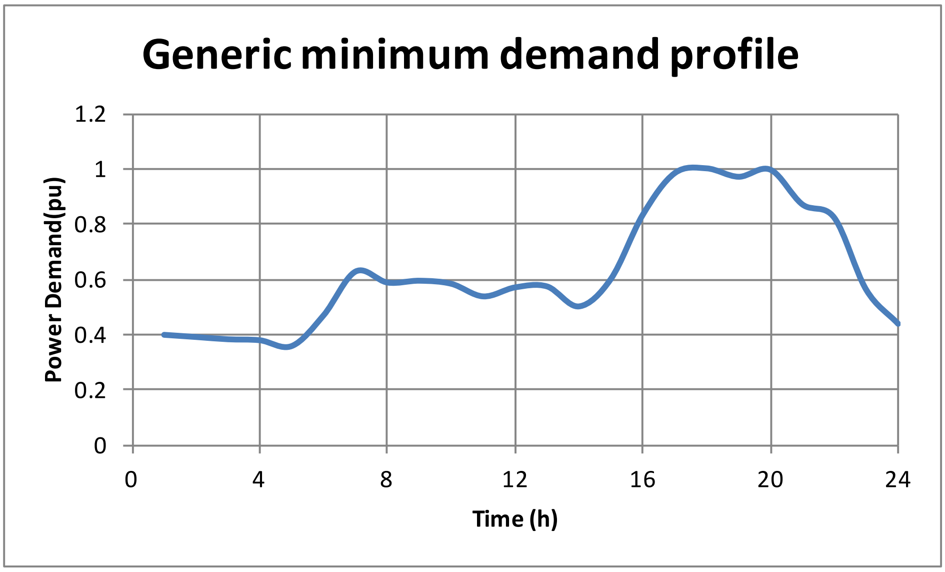

Figure 4-8 Generic weekday minimum demand profile for a residential LV feeder

For the LV network areas studied in Ruabon the maximum PV generation was generally found to be 90% of the rated PV capacity, based on 10 minute average measured solar irradiance data. This was validated through comparison of modelled and measured load flows. The impact of PV diversity e.g. varying roof pitch and direction is thought to be a second order effect when compared to consideration of the actual measured solar irradiance on PV generation output. Solar irradiance data from a nearby weather station will improve characterisation of maximum PV generation output compared to assuming PV rated capacity.

There are also concerns regarding the actual amount of PV connected to the LV network across the UK. Although installers have an obligation to notify the DNO of small-scale G83 (less than 3.68kW) PV installations, this is often not done. SPEN has compared the PV recorded on its GIS system with the government installations register (used for the Feed-in-Tariff program) and found that only 48% of the installed PV has been registered with SPEN. Recommendations are provided in the SPEN RIIO-ED1 business plan to address this. This may account for some of the limited variance found between modelled and measured LV feeder load profiles for the Ruabon LV network.

4.1.4 LV Network Templates

Western Power Distributions' Low Carbon Network Fund Tier 2 LV Network Templates project has developed a method of estimating load and voltage profiles for secondary substations, providing much more detail than MDIs but at less expense than installing monitoring stations across the whole network. The method is reported to estimate the load profile of a substation with circa 80% level of accuracy. It is anticipated that the tool will be extended as levels of low carbon technologies on the network increase.

Monitored substation data was used to group substations, leading to ten typical clusters of substations that captured a range of load types including industrial, commercial and domestic (residential), urban and rural.

The LV Network Templates tool can be applied to provide improved assumptions of proportional load at peak demand based on typical load profile. This should better capture the time-varying characteristics of different load types. There is ongoing work with SPEN to incorporate learning outcomes from this project into network planning practice.

4.2 Improved HV Load Characterisation

Currently, for HV network modelling at peak demand, HV connected loads are generally assumed to be at the maximum stated connection capacity, or some fraction of this based on the engineer's judgement. Stated connection capacity may be higher than actual consumption due to consideration that has been made for future expansion plans for a factory for example or to provide reasonable headroom for load variability. New 11kV loads/ generators are connected across three phases, previously connected loads/generators may only be single or two phase.

Half-hourly settlement metering data for HV connected customers can be requested on a case-by-case basis from SPEN's Distribution Use of System Admin group. This provides readings in kWh for half hourly periods for active power import and reactive power import and export. This data can be interrogated to provide the half hourly average load for the time of peak loading on the feeder or primary network group under analysis. Ideally, this data would be directly available to all network planners with some level of automation to extract and populate a power systems model. However, this may be difficult to implement due to the confidential nature of this customer data that requires a more formal request process.

For new connections, the new load maximum demand might occur at a different time than the feeder maximum demand. Although analysis is usually based on maximum loads and is does not take into account the daily load profile, the network planning engineer can take load profiles into consideration if they have enough information to evidence this. This would particularly be considered if the network is approaching thermal and/or voltage capacity.

4.3 Improved Voltage Representation

It is important to correctly represent the voltage set-point at the primary and secondary substations in network models in order to accurately model the voltage profile at HV and LV. The nominal primary network voltage for SPM and SPD is defined by SPEN policy. Primary transformer 11kV voltage can be obtained from the load database or alternatively the NMS SCADA system. Characterisation of voltage at peak load and more generally for high and low loading periods will improve accuracy of network modelling, understanding of network characteristics and behaviour and selection of network solutions when required.

Information on the tap settings of the secondary substation transformers is not always recorded and assumed to be set to nominal. Tap settings can be confirmed by site visit. This information should also be captured in future either during routine maintenance or for LV networks identified as approaching demand or generation capacity as it will help assessment of voltage solutions.

4.4 Improved Phase Imbalance Characterisation

4.4.1 HV

The HV network is generally assumed to have minimal phase imbalance due to the increased load diversity on the HV network compared to the LV network. At SPEN primary substations, current is measured on all HV feeders but typically only for the yellow phase.

HV feeder imbalance is likely to increase towards the ends of the feeders; this is where flexible network control schemes might be implemented in future to enable soft meshing of adjacent HV networks. High levels of phase imbalance may lead to adverse circulating currents during switching operations so are important to quantify.

Measurements of HV phase currents along feeders are being collected and analysed as part of the Flexible Networks project and are reported in "Report on Assessment of Load Unbalance in HV Feeders" (SP/LCNF-FN/TR/2014-005). The analysis has shown that HV imbalance is small in comparison to imbalance in LV feeders, and may be concentrated towards the end of the HV feeders in the St Andrews test area.

4.4.2 LV

It is standard practice in DNO LV network design to assume that phases are balanced or to apply a generic assumption. There is often no information on which customer is connected to which phase. Detailed analysis of LV feeder phase monitoring data as reported in "7640-07 Flexible Networks HV and LV Phase Imbalance" has revealed significant phase imbalance on some LV feeders as shown in Figure 4-9, particularly on feeders with a mixture of residential, industrial and commercial loads and rural feeders.

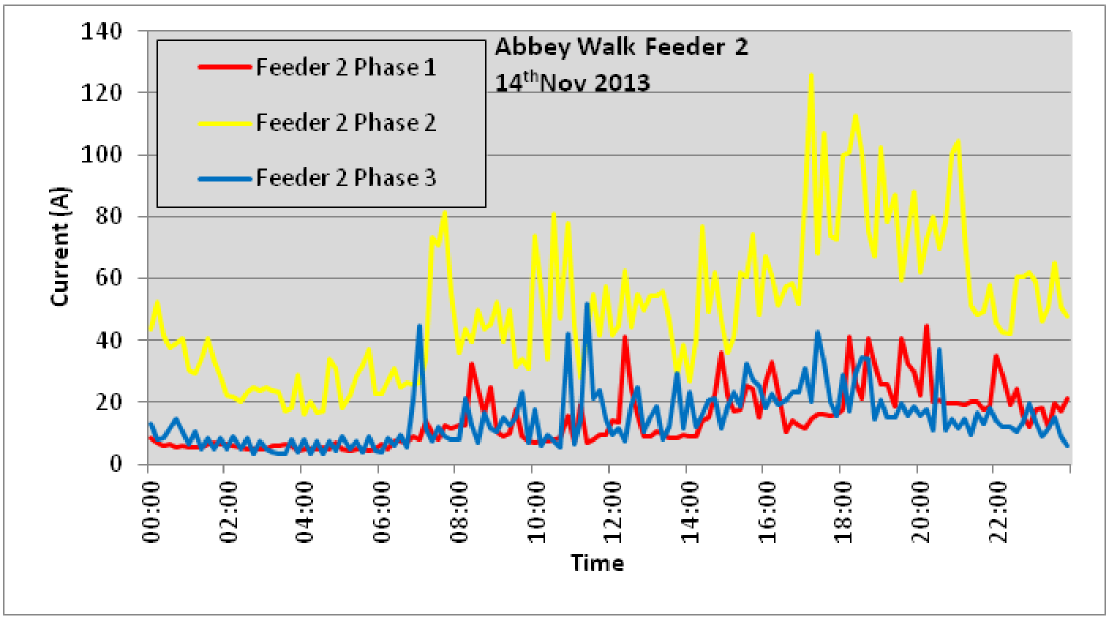

Figure 4-9 Abbey Walk LV Feeder 2

Secondary substation MDIs indicate the current on each phase (summated across all feeders) at the secondary substation at total peak loading. However, phase imbalance on the secondary substation MDI is not representative of phase imbalance on individual LV feeders. This is particularly the case for secondary substations with five LV ways out, the standard ground mounted substation configuration.

LV phase imbalance should be considered in the future through robust methods of analysis and extrapolation that do not require extensive monitoring due to the scale of the LV network (i.e. methods based on monitoring on a limited subset of LV feeders). The report "7640-07 Flexible Networks HV and LV Phase Imbalance" provides further details of the methodology developed for analysis of the LV feeders monitored for Flexible Networks and results with discussion of future applicability. For example, network planners should include a suitable margin to allow for any phase imbalance based on network type.

Network monitoring to be deployed in RIIO-ED1 will enable some further analysis and characterisation of LV phase imbalance however there are network data linkage and data uncertainty challenges to be overcome to enable full automation of this analysis.

The capability to model phase imbalance is already available in some power systems software packages and is being developed in others. This will help to understand the sensitivity of phase imbalance for voltage drop/rise and other network parameters.

4.5 Power Factor

Usual SPEN network modelling practice is to assume a power factor of 0.98 to model reactive power import for LV loads. The following power factor metrics were calculated for LV distributors monitored for Flexible Networks (a total of 391) throughout the measurement period; mean, median and standard deviation of power factor during the daytime (0800-1600), the night time and over 24 hours. A number of LV feeders were then discounted from further analysis due to likely measurement errors, leaving a total of 202 LV feeders.

A power factor assumption of 0.98 was found to be close to the median power factor for 202 LV feeders (median of medians = 0.97) however there were a few outliers that had a median power factor of down to 0.21.

Outcomes from ENW's First Tier Low Carbon Networks Fund Project "Low Voltage Network Solutions" resulted in a change to the default power factor assumption from 0.95 to 0.98 in the company's existing 'Load Allocation' algorithm for estimating load across the whole secondary network. This was based on LV monitoring at 200 distribution substations in the ENW network licence area.

The uptake of embedded PV generation can have a significant impact on real time real and reactive feeder power flows and thus, power factor. Figure 5-10 shows the current and the power factor for a high irradiance day on Ash Grove, an LV feeder with high PV uptake. However, when looking across a long measurement period, whilst there is a visible difference, there does not appear to be a strong influence of embedded PV generation on median day time power factor at least not at the uptake levels in the Ruabon network.

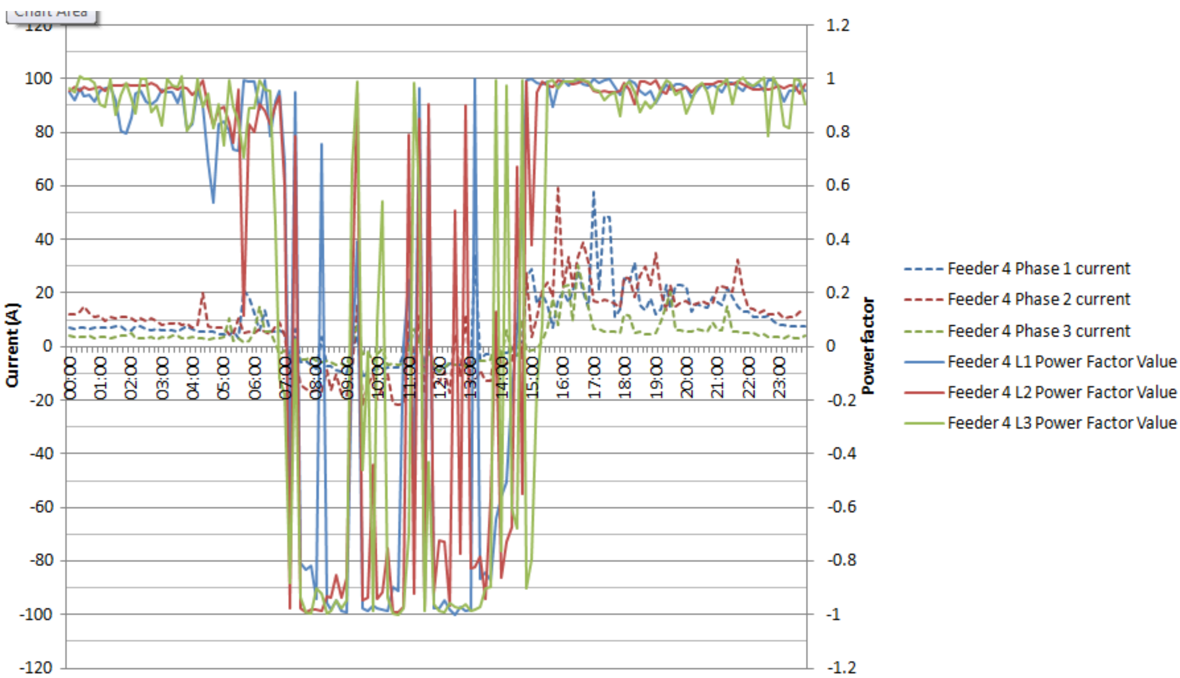

Figure 4-10- Current and power factor for Ash Grove LV feeder (Plas Madoc) with high PV uptake on a high irradiance day (June 23rd 2014)

SSE also found that connected PV has a visible impact on real power and power factor in their LCNF Tier 1 Project "Demonstrating the Benefits of Monitoring LV

Networks with embedded PV Panels and EV Charging Point". Embedded PV does not provide reactive power support at present and so this must be provided by the grid.

For network modelling, we recommend that the power factor for demand load should be set to 0.98 and for PV generation set to 1 or the appropriate reactive power range of the PV inverters. This will ensure that reactive power and power factor characteristics are appropriately reproduced in the modelled load profiles.

4.6 Modelling for Smart Network Solutions

An increasing driver for network modelling will be the need to assess the feasibility of a potential smart network solution. As traditional network solutions are replaced by or combined with more innovative solutions and increasing network automation and intelligence, modelling will be critical to understand the performance and controllability of the solution, both for network planners and control engineers.

Innovative network solutions that may require modelling include;

- Dynamic thermal ratings
- Dynamic network meshing
- Automated voltage control e.g. at primary substations or series voltage regulators
- Energy storage and Var control
- Generation constraint management algorithms
- Fault current limiters and active management algorithms
- Demand side management

For future LV network operation incorporating active network management, the LV feeder length may change dynamically depending on the required network topology so this would need to be considered for network modelling.

4.7 Test Case – Optimal 11kV Voltage Regulator Location

Detailed power systems modelling and comparison to measured load and voltage data has been carried out to identify the optimal location for a series voltage regulator. The voltage regulator will resolve voltage drop issues under backfeeding at peak loading conditions. The trial site is one of the circuits connecting the St Andrews HV network to the Anstruther HV network group as shown in Figure 4-11. This will enable load to be flexibly transferred between St Andrews and Anstruther, in order to increase the capacity headroom at St Andrews.

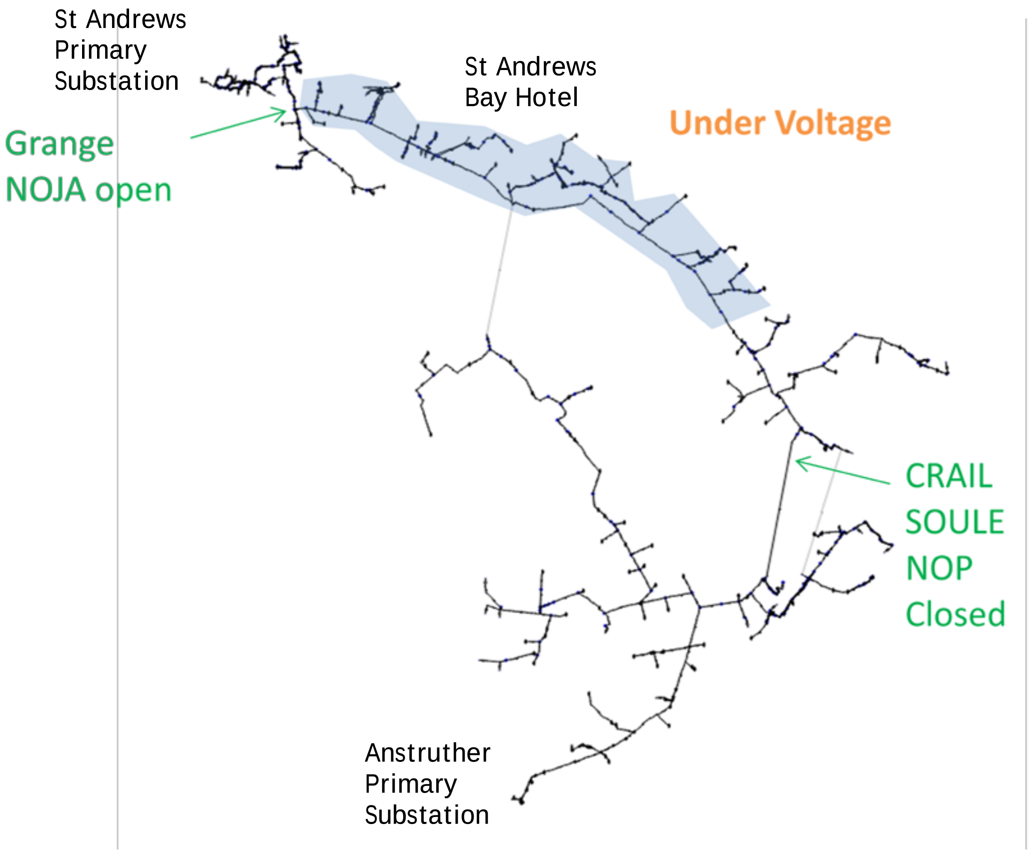

Figure 4-11 Anstruther feeder 12 backfeeding part of St Andrews feeder 25 at peak loading conditions (areas of the network outside voltage statutory limits shown in blue)

4.7.1 Secondary substation loading methodology

The peak loading at each secondary substation was determined based on common SPEN practice for 11kV network modelling (ground mounted substation load based on MDI loading, pole mounted substation load based on percentage of transformer rating). Loads were then scaled to match the corresponding total HV feeder currents at Anstruther and St Andrews as recorded by PI.

Secondary substation loads were then compared to measured data from monitors installed as part of the Flexible Networks project, at several peak loading timestamps. Some loads were adjusted to better represent the actual measured load for the timestamp under consideration, followed by minimal rescaling of other secondary substation loads to match the HV feeder currents.

The methodology used can be summarised as follows:

- Extract MDI data for ground mounted substations from SPEN SAP database.
- Determine ground mounted and pole mounted secondary substation loads based on common SPEN network modelling practice.
- A representative load based on settlement metering data from the previous year was used for the HV load connected to St Andrews feeder 25 as settlement metering data for the timestamps analysed was not

available at the time of analysis. This represents approximately 15% of the total feeder load.

- Refine loads to match the corresponding HV feeder currents (assuming a primary substation voltage of 1.01pu for St Andrews and Anstruther EHV/HV transformers).
- Use measured data from network monitoring implemented as part of Flexible Networks to refine substation loads.
- Validate loading assumptions by comparison of calculated and measured circuit voltage profiles. Validation of the load modelling assumptions was undertaken for two timestamps; 6th March & 9th March 18.30, both with good monitoring data availability, and a tea time peak demand that is generally representative of high loading conditions.

4.7.2 Comparison of voltage profile

A load flow was undertaken on the network model and the voltage profile down the feeder on both the 11kV and the LV side of each secondary transformer was recorded. This was then compared to the measured voltages on the LV side of each transformer at the same timestamp.

As the voltage on the LV side of the secondary substation is recorded for all three LV phases, the average measured LV voltage was calculated for comparison with the network model. The measured LV phase voltage was found to vary between phases by up to 3% for the timestamps assessed although for most secondary transformers it was within 1% so this assumption is deemed to be reasonable. Secondary substation voltage was not measured at 11kV.

Figure 4-12 shows a comparison between the modelled voltage profile at LV and 11kV and the measured LV voltages for a high loading timestamp in December 2041. This was based on a primary substation voltage of 11.0kV from pre-existing busbar monitoring. Secondary transformer (11/0.415kV) tap settings were also adjusted from nominal in some cases to improve match of the voltage profile although most of these tap settings have not been confirmed.

Possible reasons for deviation from measured voltage profile values include:

- Many secondary substations (pole-mounted and ground-mounted) are not fitted with monitors. Assumptions are therefore made for these loads. However actual loads are likely to vary from assumed loads at any measurement timestamp. This is confirmed by comparison of modelled loads to measured loads from secondary substations monitored as part of the Flexible Networks project above (although loads are broadly comparable). Also, any intermittent point loads (such as large pumps at waste water treatment works) that are not monitored, or which are monitored but operate intermittently at a frequency greater than the measurement resolution, may also introduce discrepancies. These will produce corresponding deviations when comparing modelled LV voltages to measured voltages.

- Secondary transformer tap settings may not be set to nominal.
- Calibration of monitors may be incorrect.
- The voltage recorded by the GridKey device at Harbour Pumping Station is higher than that at the primary substation; this is likely to be indicative of an error in the monitoring equipment due to the proximity of Harbour Pumping Station to the primary.

Aside from the CHP generator at the St Andrews Bay Hotel, there is no other generation thought to be connected to feeder 25.

Overall, our network model validation assessment has highlighted the challenges involved in accurately modelling an HV feeder voltage profile. This analysis suggests that the use of strategically located monitoring at LV and HV is preferable when detailed voltage characterisation of a feeder and secondary substation/s is required.

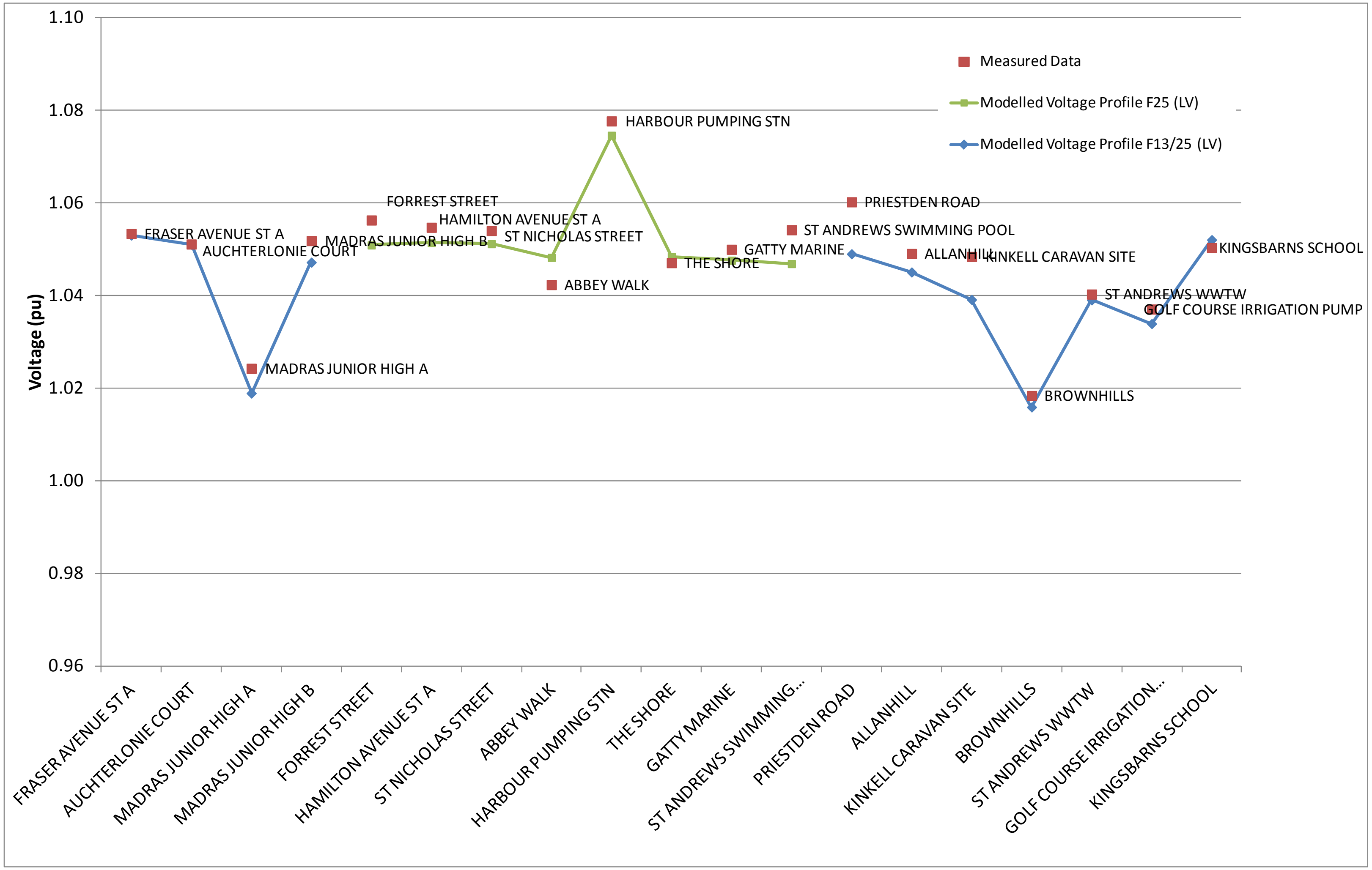

Figure 4-12 Voltage Profile along St Andrews Feeder 25 on 18th December 2014 17.30 – comparison between modelled results and network monitoring

4.8 Roadmap for Future Load Characterisation

Our assessment of load modelling assumptions based on comparison with measured secondary substation transformer and LV feeder monitoring data has produced the following findings;

- Current LV load assumptions for HV modelling (that at the time of highest HV feeder loading, ground mounted substations are loaded at approximately 80% of MDI reading and pole mounted transformers are loaded at approximately 20% of transformer rating) are generally acceptable however could benefit from further refinement based on more detailed assessment of secondary substation load type e.g. industrial, commercial, farming, and corresponding daily profile. This will be useful for understanding the impact of future LCT uptake on network thermal loading and voltage and identification of potential smart network solutions.
- HV loads should be based on settlement metering data where possible to fully consider the influence of the HV load profile and typical characteristics on network peak (and minimum) loading.
- In network areas with little diversity in load type, secondary substation daily load profiles can be represented by the HV feeder daily load profile with reasonable confidence.
- When assessing new PV connections, monitoring data analysis provides generic minimum demand profiles for LV feeders with domestic loads. The use of daytime minimum demand is key to improving assessment of embedded PV impact rather than use of minimum demand based on system minimum load scaling factors. Consideration of local solar irradiance from a nearby weather station to characterise distribution of actual maximum PV generation output should also improve network modelling of embedded PV and identification of additional generation capacity headroom.
- HV imbalance at high loading was found to be generally negligible therefore the assumption of balanced phases at HV is reasonable for assessing maximum load conditions.
- There can be significant imbalance at LV which is more prevalent for rural loads or mixed loads (domestic, industrial and commercial) where there is less diversity. Future characterisation of LV phase imbalance based on classification and correlation of LV feeder load demographics for a wider dataset e.g. all monitored Flexible Networks LV feeders, with LV feeder imbalance will provide more evidenced guidance for phase imbalance assumptions.
- Power factor assumptions for demand of 0.98, as used by SPEN network planners were found to be broadly reasonable however a value of 0.97 may be more appropriate.

- As LCT uptake, energy storage and a more active approach to network management are adopted, HV and LV network modelling including load case definition e.g. maximum demand/minimum generation, will benefit from a more probabilistic approach. For example, to characterise the impact of EV charging profiles and PV generation on a winter daily load profile. This also applies to the modelling of innovative network solutions such as dynamic load shifting and demand side management. Whilst it is not feasible to analyse a whole years worth of data, key load cases should be identified to develop a risk profile of approaching or exceeding thermal or voltage limits. These may include analysis of seasonal average daily load profiles for winter, summer and spring as well as load cases that include the maximum, minimum and the 90th, 95th and 98th percentile demand and generation for example.

4.8.1 Increased Network Monitoring

The RIIO-ED1 Business Plan allows for an additional LV monitoring on circa 5% of the SPEN network during the RIIO-ED1 regulatory period. This will be in areas identified with high LCT clustering resulting in constrained networks. Related to this, SPEN propose to install “smart” MDIs as part of the LV switchboard asset replacement program. Although a smart MDI device does not yet exist as a commercially available product, it is envisaged that it will become available during the ED1 period and will be similar in form, function and cost to currently available poly-phase smart meters. The value of smart MDI data to assessment of LV feeder capacity can be explored further as it is deployed as part of the LV switchboard asset replacement programme.

Increased network monitoring will support analysis of the specific networks being monitored as well as further verification of general load assumptions for application to the wider network, as shown in Figure 4-13.

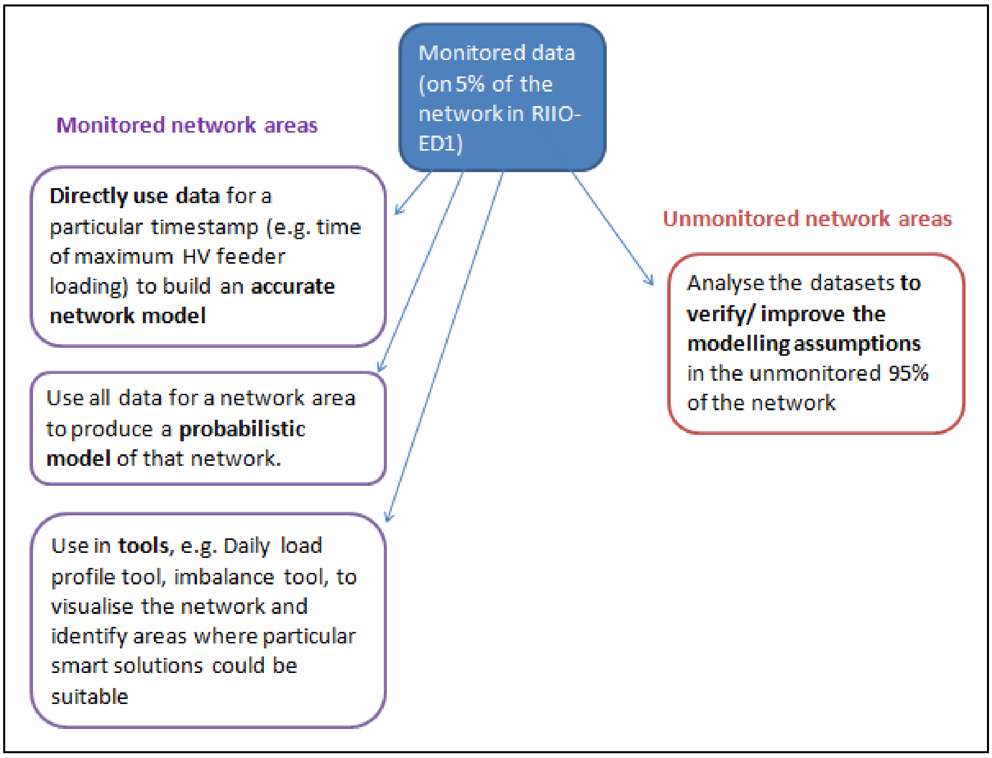

Figure 4-13 How LV monitored data will improve network modelling

Load profiles for high and low loading can be directly used to assess how robust the network is to demand and generation connections, and most appropriate network solutions for reinforcement.

A number of analysis methodologies and associated prototype tools have been developed as part of Flexible Networks to help network planners visualise characteristics of the HV and LV network and identify potential smart solutions for increasing capacity headroom. For example, load duration curves enable a rapid assessment of the peak loading characteristics of network assets. An LV imbalance analysis tool provides key metrics on LV feeder imbalance compared to cable ratings and identifies potential benefits of redistributing customers between phases. These will provide guidance for future refinement of the graphical interface for the data acquisition platform to provide improved visualisation of transformer loading and feeder loading.

5 Cost Benefit Analysis

In order to deliver a cost-effective network modelling approach, an HV or LV network should first be identified as approaching capacity through a simpler automated assessment such as aggregation of current LV or HV demand or generation compared to cable and/or transformer ratings. Such an approach is described in the RIIO-ED1 LCT Network Monitoring Strategy. Following this, more detailed network modelling may be justified. If the network is found to be constrained through network modelling then there is a strong case for monitoring followed by network model validation and modelling of suitable network solutions.

The benefits to be gained from improved HV and LV network modelling that incorporates more extensive HV and LV monitoring leading to improved characterisation of the network are;

- Increased accuracy of network models and thus, better understanding of network behaviour.
- Greater confidence in feasibility and potential benefits available from smart solutions such as dynamic load shifting, voltage regulation, active network management etc.
- Improved network reinforcement identification, prioritisation and management.
- Improved approach to assessment of the impact of embedded generation connections and solution identification.
- Greater assurance of compliance with statutory voltage limits and thus, quality of supply to HV and LV networks.

These can be complex to quantify as an economic value so are presented in a more qualitatively in the cost-benefit analysis in Table 5-1.

Table 5-1 Cost-Benefit Analysis

Existing Modelling Approach	Future Approach	Potential Capacity Headroom Gain	Cost	Benefit
Network Build				
HV Network Build	Increased automation for more efficient and accurate network model build	Depends on specific HV network	Marginal (reduction in model build time but increase in complexity)	Improved understanding of network behaviour and enhanced network planning decision-making. Improved modelling of smart network solutions.
LV networks modelled using probabilistic tools and 'rules-of-thumb'	LV Networks modelled in detail on exception in areas of high LCT uptake and/or where approaching capacity Model to understand wider LV network behaviour	Depends on specific LV network but may also facilitate verification and improvement of 'rules of thumb' for wider network	Approx. £1000-2000 per LV network area	Improved understanding of specific and wider network behaviour and enhanced network planning decision-making. Improved modelling of smart network solutions.
HV Load				
HV connected loads are generally assumed to be at the maximum stated connection capacity, or some fraction of this based on the engineer's judgement.	HV load characteristics at network peak and minimum load based on analysis of settlement metering data	Potentially improved voltage profile if the HV load is located some distance along the HV feeder	Approx. £100 per HV load	Improved understanding of specific and wider network behaviour and enhanced network planning decision-making. Improved modelling of smart network solutions.

Existing Modelling Approach	Future Approach	Potential Capacity Headroom Gain	Cost	Benefit
LV Load				
Standard SPEN LV Load Assumptions at Peak HV Feeder Loading Assume peak load occurs around tea-time	More detailed assessment of secondary substation load type and anticipated corresponding daily profile to understand impact of future LCT uptake and network solutions.	For example, if peak loading typically occurs during the day due to commercial loads, schools etc this may allow greater connection of residential EVs. This would need to be assessed on a HV/LV network specific basis. Estimated 10-20% in some cases although this suggests that at tea-time peak, other LV loads are greater in order to match total HV feeder load.	Order of £1000 per HV network	Improved understanding of network behaviour and enhanced network planning decision-making. Deferment of LV Cable Uprating or Overlaying at £50-75k, for example.
Power Factor				
Pf of 0.98	Pf of 0.97	No gain		
LV Phase Imbalance				
Assume balanced with conservative assumptions on demand	Use LV feeder monitoring to identify phase imbalance for LV networks approaching capacity and rebalance customers	20-30%	£3,500 + cost of rebalancing 3-5 customers (£500-2000 per customer)	Deferment of LV Cable Uprating or Overlaying at £50-75k
PV Characterisation				
Minimum demand of approximately 200W per domestic property Assume PV at rated capacity	Generic minimum demand profiles for LV feeders with domestic loads. Consideration of local solar irradiance	>30%	Marginal	Enables more generation to connect and defers generation related reinforcement e.g. New LV Cable at £50-75k

6 Future Work

Development of the future roadmap for HV and LV network modelling has highlighted some areas of further work that are beyond the scope of Flexible Networks but would provide significant additional value.

6.1 Network Model Build

In order to improve future network model build, the following recommendations for further work are made:

- Further development of automated model build techniques to reduce manual correction post-conversion from GIS data which is being progressed as part of Flexible Networks.
- An intelligent algorithm to apply a rule set for missing overhead line and cable ratings based on adjacent and standard asset specifications.
- Improved business database linkages to support more automated network model definition including ratings data, switching points and the identity of LV feeders. This could be linked to outcomes from the Distribution Grid Analytics pilot project.

6.2 Network Load Assumptions

Existing assumptions for LV network loads have been broadly verified, and a more detailed understanding of the effect of customer type on peak load and load profile has been gained. This has implications for the effects of future LCT uptake on the network. Further analysis with a larger sample size of substations should be carried out in future to verify analysis findings, incorporating results from WPD's LV Network Templates analysis tool. In addition:

- In future, it would be useful to integrate some automated or semi-automated classification of load type per secondary substation or LV feeder via the GIS database. Numbers of customer in each Elexon class is commonly available for some substations but not in GIS.
- The sensitivity of secondary substation load profiles for particular customer mixes e.g. commercial/residential, to LCT uptake could be explored through analysis of monitoring data. In future, uptake and diversity in EV load (domestic, commercial) may alter the time of existing demand peaks.
- The voltage profile can be challenging to reproduce in detail through network modelling due to individual secondary substation transient load patterns, tap settings etc. Secondary substation tap settings should be captured in future either during routine maintenance or installation of monitoring where applicable. Future measurements of voltage along HV feeders will also support the validation of network modelling of voltage profile.

- Development of general guidelines and network planning margins for LV phase imbalance should be developed based on more detailed correlation of LV feeder load types with imbalance. The capability to model phase imbalance is already available in some power systems software packages and is being developed in others. This can be used to characterise the sensitivity of voltage drop/rise and other network parameters to phase imbalance.

6.3 Network Monitoring

To date, a cost-effective approach to monitoring pole-mounted secondary substations has not been identified although it would be of value and is being explored.

7 References

Energy Networks Association, Engineering Recommendation P2/6 Security of Supply, July 2006

SP Power Systems Limited, Framework for design and planning for low voltage housing developments underground network installations and associated, new, HV/LV distribution substations, ESDD-02-012 Issue No.2

TNEI, University of Strathclyde, 7640-07 Flexible Networks HV and LV Phase Imbalance, 2014.

TNEI, 7640-10 Flexible Networks Improved Characterisation of PV Capacity at LV, 2014.

TNEI, 7640-11 Flexible Networks Identification of candidate LV feeders for phase rebalancing, 2014.

TNEI, University of Strathclyde, SP Energy Networks, Flexible Networks Work Package 1_1 Report, 2014.

TNEI, 7640-01 Flexible Networks Series Voltage Regulator Modelling, 2014.

University of Strathclyde, "Technical Note on Investigation of Diversity in Secondary Substation Load", February 2015.

Appendix A – Background

A.1 Flexible Networks for a Low Carbon Future

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

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

Solutions are needed that can:

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

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

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

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

Figure A-1 Trial Area Location Map

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

A.2 Improved Planning Tools

The existing best practice for distribution network LV and 11kV network modelling is based on a limited set of network measurements e.g. ground mounted secondary substation maximum demand recorded every six months, HV yellow phase feeder current. This does not provide information on the dynamic interactions of the various system states over the course of a year of operation.

The level of operating state uncertainty necessitated a number of assumptions for network modelling which have some inherent safety margins built in to minimise the risk of overloading equipment or failing to keep voltages within statutory limits. Also, existing load connections, i.e. customers, have generally been considered to be stable, i.e. load profiles and demand of existing connections do not change appreciably over time. At present, most load changes on the network are due to new connections, rather than changes to existing connections.

In the future, it is likely that customer consumption patterns could change radically, creating a significant impact on the distribution network over a short period of time. These changes could be localised and high-density due to rollout of electric vehicle charging points for example. This will necessitate an improved knowledge and characterisation of the distribution network particularly at 11kV and LV. The ability to model the behaviour of the existing network with a higher level of accuracy but without extensive additional monitoring will enable more robust exploration of the impact envelope of future load changes. This should lead to selection and design of the appropriate techno-economic response.

Also, the capability to more efficiently and accurately build HV and LV network models through increased automation and business database linkages will be valuable for more detailed assessment and planning for network areas experiencing rapid LCT uptake and likely to become constrained in future.

Appendix B – Selected Network Group Details

St Andrews

St Andrews is a large town in the rural location of Fife, Scotland, with a population of approximately 17,000. St Andrews is a tourist area and is also home to the well-known St Andrews University. The primary network group of St Andrews consists of 2 33/11kV primary transformers of 12/24MVA rating that supply the 11kV distribution network. The two transformers are located at St Andrews Primary Substation and operate in parallel. The 11kV circuits from this primary substation are operated radially but with the facility to be interconnected to neighbouring networks following a system outage.

Ruabon

Ruabon is a small village located in the borough of Wrexham, Wales, with a population of approximately 2500. The Ruabon 33/11kV system consists of one 10MVA 33/11kV primary transformer which supplies the 11kV distribution network. The 11kV circuits from this primary substation are operated radially but with the facility to be interconnected to neighbouring networks supplied from Llangollen, Johnstown, Monsanto and Maelor Creamery following a system outage.

Whitchurch

Whitchurch is a market town in Shropshire with a population of approximately 9000. The 33/11kV system, in Whitchurch, consists of three 33/11kV primary transformers that supply the 11kV distribution network, Whitchurch, Liverpool Road and Yockings Gate.

Appendix C – Secondary Substation Loading Results

Maximum demand for each secondary substation assessed is tabulated below along with details of monitoring periods.

Table C-1 Details of Maximum Demand for St Andrews Feeder 25 Secondary Substations

Secondary Substation	Maximum demand (kVA)	Time of Max Demand	Date Ranges of Monitoring Data	No. of Datapoints
Abbey Walk	398	11/07/2013 12:00	10/7/13-27/12/13 and 1/1/14-9/1/14 and 11/1/14-18/1/14	26671
Allanhill (PM)	109	13/09/2013 16:30	12/9/2013-23/12/2013	14791
Brownhills (PM)	73	15/10/2013 08:50	8/9/2013 – 23/12/2013	15301
Forrest St	118	18/01/2014 18:20	25/6/2013 – 23/12/2013 and 11/1/14-18/1/14	27269
Gatty Marine	240	28/11/2013 14:50	25/6/13 – 23/12/13 and 2/1/14-9/1/14 and 11/1/14-18/1/14	28396
Hamilton Ave	50	07/12/2013 00:40	9/7/13-8/9/13 and 9/9/13-23/12/13 and 24/11/13-31/12/13 and1/1/14-18/1/14	27650
Harbour Pumping Station	162	20/05/2013 17:10	28/4/2013-16/7/2013 and 13/11/2013 - 23/12/2013 and 1/1/14-9/1/14 and 11/1/14-18/1/14	18121
Kinkell Caravan Site (PM)	56	13/07/2013 18:50	9/7/2013 – 24/7/2013	2752
Priestden Road	180	08/05/2013 17:10	28/4/13 – 4/7/13 and 8/7/13-25/8/13 and 27/8/13-23/12/13 and 1/1/14-9/1/14 and 11/1/14-18/1/14	32097
St Andrews Swimming Pool	203	07/11/2013 18:40	8/8/13 -23/12/13	19700
St Andrews WWTW	150	10/09/2013 13:00	24/7/2013 -12/9/2013	3374
St Nicholas St	68	06/12/2013 12:40	23/7/2013–23/12/2013	22130
St Nicholas WWTW	515	18/07/2013 16:00	22/4/13-21/5/13 and 1/7/13-24/7/13	7399
The Shore	70	19/11/2013 21:00	11/9/13-31/12/13 and 1/1/14-18/1/14	18534
St Andrews feeder 25	*3521*	*5/12/2013 16:30*	*1/6/13 – 18/1/14*	*11184*

Table C-2 Details of Maximum Demand for St Andrews Feeder 25 Secondary Substations on Selected Winter Days

Substation	Maximum demand (kVA)	Mon Oct 14 Power at 6pm		Thurs Nov 14 Power at 6pm		Sun Dec 1 Power at 6pm		Sat Dec 7 Power at 6pm		Sat Dec 14 Power at 6pm		Thurs Dec 5 Power at 4.30pm (HV feeder maximum)		Customer Demographics
		(kVA)	(% of MDI)	(kVA)	(% of MDI)	(kVA)	(% of MDI)	(kVA)	(% of MDI)	(kVA)	(% of MDI)	(kVA)	(% of MDI)	
Abbey Walk	398	221	55	202	51	236	59	240	60	208	52	358	90	residential, schools, medical
Allanhill (Pole mounted)	109	17	15	17	16	17	15	16	14	15	13	26	24	farm
Brownhills (Pole mounted)	73	46	63	49	68	29	39	24	33	31	43	37	51	farm, residential
Forrest St	118	62	52	73	62	79	67	73	62	73	62	79	67	residential
Gatty Marine	240	152	63	203	85	160	67	151	63	139	58	197	82	industrial, university
Hamilton Ave	50	18	35	28	56	26	52	28	55	28	57	28	56	residential
Harbour Pumping Station	162		0	1	1	2	1	71	44	41	25	89	55	pumping
Priestden Road	180	83	46	97	54	98	54	98	54	92	51	70	39	residential
St Andrews Swimming Pool	203	133	66	109	54	75	37	108	53	89	44	146	72	residential, leisure
St Nicholas St	68	49	72	56	82	43	64	51	75	43	64	51	75	residential
The Shore	70	10	14	4	6	17	24	8	11	5	7	36	52	residential
St Andrews feeder 25	*3521*	*2709*	*77*	*2845*	*81*	*2592*	*74*	*3002*	*85*	*2723*	*77*	*3521*	*100*	

Table C-3 Details of Maximum Demand for Whitchurch Feeder 4 Secondary Substations

Substation	Maximum demand (kVA)	Time of Max Demand	Date ranges of reports	No. of Datapoints
Barnfield Close	113	04/11/2013 17:30	16/7/13-31-12/13 and 1/1/14-24/1/14	27580
Chemistry	195	08/01/2014 18:00	16/7/13-31-12/13 and 1/1/14-24/1/14	27085
Jubilee Park	230	11/01/2014 17:20	16/7/13-11/10/13 and 18/10/13-31-12/13 and 1/1/14-24/1/14	25362
Smallbrook Est	271	24/11/2013 17:10	24/10/13-31/12/13 and 1/1/14-24/1/14	13012
Belton Road (PM)	123	25/12/2013 09:10	16/7/13-31-12/13 and 1/1/14-24/1/14	27784
Heron Brook (PM)	76	15/12/2013 17:00	7/8/13-31/12/13 and 1/1/14-24/1/14	24469
Pear Tree Lane (PM)	35	15/11/2013 19:40	7/8/13-31/12/13 and 1/1/14-24/1/14	24468
Belton Farm (GM HV customer)	765	07/01/2014 09:50	18/11/13-31/12/13 and 1/1/14-24/1/14	9517
Whitchurch Feeder 4	1448	07/01/2014 17:30	1/1/13 – 24/9/14	30384

Table C-4 Details of Maximum Demand for Whitchurch Feeder 4 Secondary Substations on Selected Winter Days

Substation	Maximum demand (kVA)	Sun 4 Nov 6pm load		Wed 11 Dec 6pm load		Sun 15 Dec 6pm load		Wed 25 Dec 6pm load		Sat 4 Jan 6pm load		Tues 7 Jan 5.30pm load (HV feeder maximum demand)		Customer Demographics
		(kVA)	(% of MDI)	(kVA)	(% of MDI)	(kVA)	(% of MDI)	(kVA)	(% of MDI)	(kVA)	(% of MDI)	(kVA)	(% of MDI)	
Barnfield Close (GM)	113	75	67	64	56	83	73	61	54	76	67	83	73	residential
Chemistry (GM)	195	171	88	158	81	161	83	130	67	166	85	190	97	residential
Jubilee Park (GM)	230	185	80	194	84	177	77	131	57	172	75	194	84	residential
Smallbrook Est (GM)	271	226	83	232	86	223	82	172	63	224	83	265	98	residential
Belton Road (PM)	123	97	79	78	63	76	62	79	64	93	75	90	73	mixed
Heron Brook (PM)	76	52	69	45	59	47	61	34	44	46	60	46	61	residential (rural)
Pear Tree Lane (PM)	35.857	29	81	24	66	19	54	20	56	24	66	17	48	residential
Whitchurch Feeder 4	***1448***	***1086***	***75***	***1220***	***84***	***1048***	***72***	***819***	***57***	***1048***	***72***	***1448***	***100***	

Appendix D – LCT Network Monitoring Strategy

A robust and cost-effective LCT monitoring strategy has been developed to support the SPEN RIIO-ED1 Business Plan submission[5]. This details our approach to proactively identifying, monitoring and responding to the future growth of low carbon technology (LCT) on the LV network.

SPEN's vision in the long term is to have wide scale visibility and more automated analysis of our low voltage network. As technology develops, this is likely to become economically viable and will be progressed when the investment required reaches a level that would provide best value to our customers.

LV monitoring is a key deliverable under the 'Visibility' dimension of the SPEN Smart Grid Strategy. The outputs of this monitoring strategy will also support the SPEN Load Related Strategy and improve general understanding of the current behaviour of the network.

Step 1: A common database for all network data

The GIS database system will provide the underlying architecture for automated analysis and reporting processes defined in the monitoring strategy. This will ultimately provide ease of data access, analysis and improved consistency of data across the business. We will integrate network monitoring data with other sources including smart metering.

Step 2: Early Identification of LCTs on the Network

LCT uptake will be identified through analysis of existing data sources such as LV connections data, primary and secondary substation data, and asset management data. This approach recognises that data sources may not be complete and that by linking and correlating multiple data sources, sensitivity to missing or uncertain data is reduced.

Analysis of uptake figures and loading trends on the network will enable identification of LCT hotspots on the distribution network down to the LV feeder level. This will include a simple, automated analysis of loading and voltage along the LV feeder where an LCT hotspot has been identified.

Step 3: Deployment of LV Monitoring on the Network

LV monitoring will be deployed to better understand LV feeder loading characteristics and trends due to LCT uptake and to optimise selection and deployment of network solutions.

The decision criteria for when and where to deploy LV network monitoring will be based on an improved understanding of LCT and LV network characteristics.

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

Learning outcomes from the SPEN Tier 2 LCNF Flexible Networks project and other innovation projects will be incorporated into the decision tool.

The impact on the HV network will be assessed based on an aggregation of LCT uptake on LV feeders, analysis of LV and HV monitoring data and detailed modelling where required. The scale of detailed modelling at HV is expected to be limited.

Step 4: Intervention Strategy

Monitoring the LV network in areas of rapid LCT growth will enable better quantification of remaining network capacity and optimisation of network solutions. Interventions to address thermal and/or voltage issues include:

- Primary substation voltage control in order to facilitate dynamic voltage settings.
- Installation of voltage regulators to manage resultant voltage legroom issues along HV feeders
- Dynamic thermal ratings
- Installation of additional transformer capacity
- Splitting of HV/LV feeders.

Domestic EV charging will require tariff led demand-side management to minimise the potential impact on the LV network.

Benefit to Customers

The key benefit to customers results from the overall improved network performance as a result of timely interventions and the optimal selection of reinforcement solutions. This will be reflected in:

- A reduction in customer complaints (e.g. voltage excursions)
- A reduction in customer interruptions (CIs)

In addition, improved procurement and installation strategy for future network solutions required and optimisation of selection of LV network solutions should deliver some cost efficiencies.

Strategy Implementation

SPEN are progressing the specification and prototyping of tools and processes to facilitate the LCT monitoring strategy. This includes input from key stakeholders across the business to ensure that required functionality is captured and alignment with existing tools/processes and tools in development.

Full details of our LCT Network Monitoring strategy are contained in a confidential Annex C6 – LCT Network Monitoring Strategy of SPEN's ED1 Business Plan.

Appendix E – Existing HV and LV Network Modelling

Network Modelling

HV network loading is compared to asset ratings to ensure compliance with Engineering Recommendation P2/6 – Security of Supply, typically during FCO contingency conditions on the 11kV networks, including 33/11kV transformers. This may be carried out to assess the impact of a new connection or to analyse a network reaching capacity through underlying load growth in more detail.

Seasonal loads for winter, summer and spring/autumn and the following network scenarios are assessed;

- Group Demand, corresponds to winter max demand (FCO)
- Summer/winter load ratio, to give summer max demand (SCO)

Database and tool mapping

Figure D-1 illustrates how various planning tools, databases and standards are linked within the network planning process. There is a degree of automation across some software tools however, this is not universal.

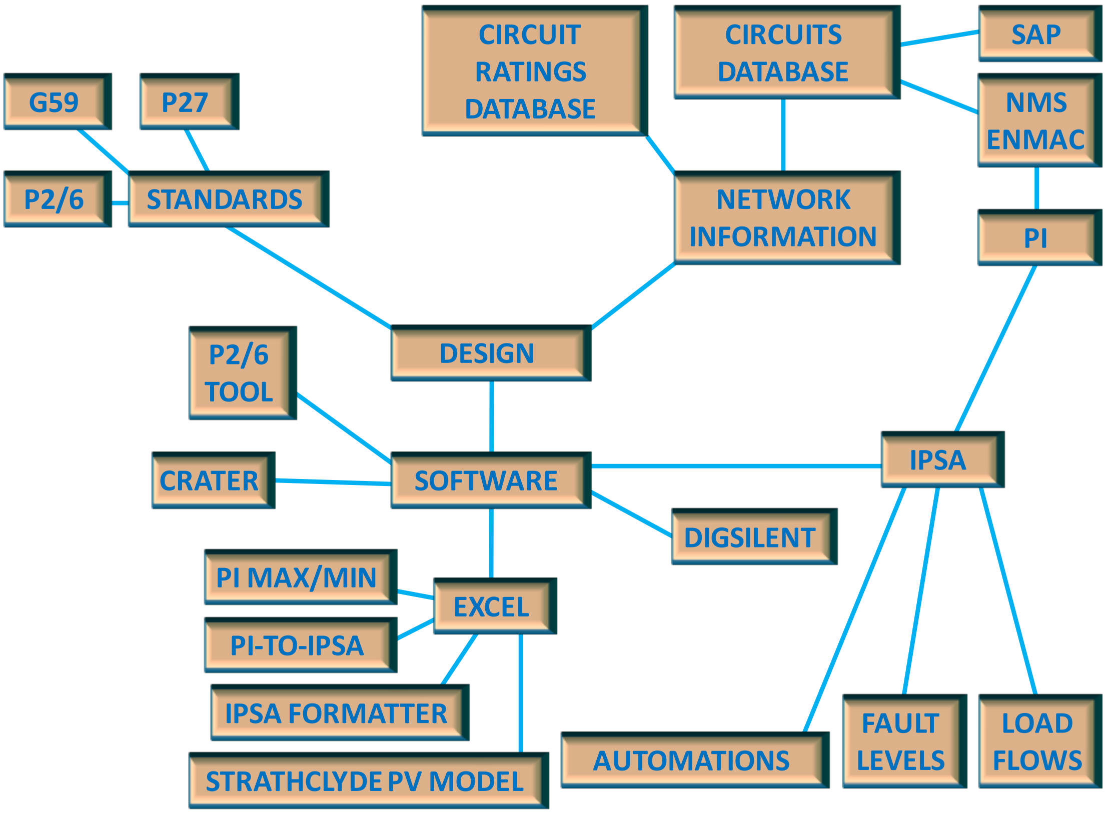

Figure D-1 Network planning - tool, database and standards mapping

Connection Studies

For assessment of connection of new loads or generation to the 11kV network, the characteristics of the new connection are first established as this may dictate where on the network the connection is to be made. Network investigations are then carried out to establish the available headroom. The initial investigation is analysis of load data using the Max/Min spreadsheet followed by the population of a power systems model using load data. Load flow analysis is then carried out to ascertain if the new connection can be accommodated and if required the minimum network reinforcement needed to enable the connection to be made.

When producing a network study to investigate the effect of a new connection, it is usual to extract demands from April of one year to March of the following year to include the winter season in one extract. This is usually done for the previous year and former years to investigate previous demand variations as part of the considerations when deciding the proposed new connection arrangement. Maximum demands are typically used directly, without any correction for temperature or network anomalies.

At LV the process is similar to HV but the tools available to the designer are not as robust. The maximum demands on the secondary transformers are available but the only way to obtain feeder loads is to do direct measurement at the secondary substation at the time of the investigation. Time restraints normally do not enable useful information to be obtained by this method. The designer has to rely on network maps and making estimates of the demands to the existing properties connected, the circuit demands and resulting voltage to establish if the new connection can be accepted and any reinforcement required.

Network Planning

Network planning includes network reinforcement identification and prioritisation activities.

HV Network

At the higher voltages, reinforcement is identified by several means. Firstly the annual review of the network identifies any areas which potentially will require reinforcement in the next few years by adding on estimated generic demand growth to the recorded maximum demand of the HV group. This also forms the basis of regulatory reporting for network reinforcement activities. Local knowledge through stakeholder engagement may result in this forecast being adjusted to match future load increase (or decrease) due to anticipated new connections (or closures). Areas of the HV network which will require reinforcement can also be flagged up by designers carrying out network investigations, e.g. designing new connections. This may identify problems adjacent to the network area being investigated which cannot be resolved as part of the proposal under consideration or the proposal does not proceed beyond the design stage.

Areas of network concern are also reported by the Network Control Centre and the local network operational staff. These are usually areas where the network is shown to be or anticipated to be stressed under outage conditions due to faults or planned outages, or a large number of customers cannot be restored until a fault is repaired.

When a potential reinforcement requirement is identified and initial investigations have been completed, each reinforcement request is ranked against a pre-approved set of criteria and added to the reinforcement programme for resolving at the appropriate time.

LV Network

At low voltage, the only reinforcement identified by available network data is the peak loading of secondary ground mounted transformers. Reports are generated which list the transformers which have a recorded value above a pre-set value i.e. 110% of rating. These values are confirmed by onsite investigations to confirm their accuracy and if the demands are likely to be repeated regularly before any design work is undertaken. This process may also involve the HV design section.

LV network constraints are often identified by customers when the voltage is approaching the statutory limits. Network investigations are then completed to assess network performance in more detail and to confirm the network arrangement. Where a potential reinforcement requirement is identified, an appropriate network solution is then found to resolve the issue.

Network problems can also be identified by the local operation staff who flag up such problems as blowing fuses due to high loads or areas where the network cannot be secured under outage conditions as anticipated. Following investigation if a reinforcement proposal is confirmed, a proposal is prepared.

Outage planning

The control engineer has access to real-time primary transformer loading and 11kV feeder currents with the current network running arrangement visible in the PowerOn network diagram.

For outage planning, primary substation data is used in several capacities;

- Outage planning – generally 1 to 4 weeks ahead based on historical and forecast demand profile and historical outages where available
- Outage management – generally now to 24 hours ahead based on historical and forecast demand profile and historical outages where available

The backfeed configuration for outage planning is typically done using the planner's experience of the network along with load data taken directly from the load database. Excel based tools are used to access and summate the load data.

Unplanned outages

In general, network reconfiguration for fault restoration due to unplanned outages will be selected based on experience and understanding of the network. Plans may be prepared (by operational planners) for specific situations of concern, and may be used once restoration is under way. These plans would typically be prepared for the peak load case; off-peak cases are dealt with from experience.

However, in the future impedance mapping may be implemented which would enable improved identification of the likely fault location.

Appendix F - LV Network Templates

Western Power Distributions' Low Carbon Network Fund Tier 2 LV Network Templates project has developed a method of estimating load and voltage profiles for secondary substations, providing much more detail than MDIs but at less expense than installing monitoring stations across the whole network. The method is reported to estimate the load profile of a substation with circa 80% level of accuracy. It is anticipated that the tool can be extended as levels of low carbon technologies on the network increase.

For development of the LV network templates, monitored substation data was used to group substations according to the daily patterns of real power delivered, leading to ten clusters of substations. Within a cluster, the daily demand pattern is similar. The clusters were:

1. High I&C Dominance
2. Modest Domestic Dominance (~60%) (Suburban)
3. Modest Domestic Dominance (~60%) (Urban)
4. High Domestic Dominance (~90%) (Modest Customer Size ~170)
5. High Domestic Dominance (~90%) (Low Customer Size ~70)
6. Very High I&C Dominance (~90%)
7. Modest Domestic Dominance (~60%) (Rural)
8. Industrial Flat
9. Domestic Economy 7 Dominance (~65%)
10. Lighting

Classification was based on an algorithm with the following input data.

- Number of customers in each Elexon class;
- estimated annual consumption for each Elexon Class,
- Transformer type;
- Transformer Rating;
- Percentage of industrial and commercial customers;
- Percentage half hourly metered load;
- Total length of HV feeder;
- Number of LV feeders; and
- Percentage of overhead lines at HV feeder,

The algorithm also calculated a probability to indicate how certain the choice was. A classification tool has been developed for DNOs, and the classification system has been validated with data from various DNOs. The tool predicts daily load profiles and voltage profiles for a substation, for each season and for weekdays and weekends, given the above inputs.