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## Executive Summary

It is critical to develop improved network planning and operations tools and processes to facilitate a future flexible network and make best use of existing assets. These tools will provide a greater understanding of network behaviour and enable a more appropriate techno-economic response to load growth. Such tools will be supported by more detailed and focussed monitoring of the network that provides insights into underlying HV and LV network behaviour and trends. Network monitoring data has traditionally been deployed and analysed consistent with a fit and forget network. This will be inadequate as increasing amounts of low carbon technology including 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.

HV and LV feeder phase loading varies continuously as the contribution of individual customer demand and any embedded generation fluctuates throughout the course of the day. Ideally, customers and corresponding loads on an LV feeder will be relatively evenly distributed across the three phases. Where this is not the case, particularly when a high demand customer is connected to a single phase, there may be significant and persistent phase imbalance, resulting in reduced capacity headroom on the LV feeder. Also, losses can be much greater for an unbalanced feeder compared to a balanced feeder, because losses on each phase are proportional to the square of the current, thus reducing capacity headroom further. As LV load grows organically and through the uptake of low carbon technology, this will bring forward the requirement for reinforcement.

Extensive primary and secondary substation monitoring has been installed and analysed for three trial network sites for Flexible Networks. This provides an opportunity to improve the characterisation of imbalance on the HV and LV networks and better understand the scale of imbalance and corresponding impact on asset loading and customers.

In order to identify LV feeders that have material levels of phase imbalance where a network solution can be applied to rebalance the feeder, it is important to first understand the characteristics of phase imbalance. The definition and application of key metrics which efficiently identify problem LV feeders from analysis of large volumes of monitoring data is a crucial step towards more techno-economic LV network planning. This becomes part of a cost-efficient LV network planning strategy to detect and mitigate significant imbalance, help release capacity headroom and facilitate more efficient network investment.

Future monitoring on LV networks is most likely to be deployed in the case of identification of rapid uptake and clustering of LCT and/or reported network issues such as the operation of fuses or customer complaints. Understanding which types of LV network are more likely to experience phase imbalance due to customer types, loads and network characteristics is also important for planning of monitoring investment. In the longer term, smart meter technology may provide some data or metrics that will enhance or even replace detailed monitoring.

An assessment of technical, cost and practical challenges to integration of the LV phase imbalance analysis tool and network rebalancing solutions is also included.

### *New methodology for identifying feeders with significant phase imbalance*

We have developed and tested a simple methodology to characterise LV phase thermal imbalance from large volumes of monitoring data. Our approach comprises the following:

- Focus on assessment of the 100 highest phase loading times.
- Calculation of the mean ratio of the phase current to the average current for all three phases → **Magnitude of phase imbalance**.
- Calculation of the lowest and highest ratio of the phase current to the average current for all three phases → **Persistence of phase imbalance**.
- Maximum phase loading → **Potential capacity headroom release**.
- Visualisation of the top ten highest loaded phase events.

This allows LV feeders with significant phase imbalance to be identified and compared with cable thermal ratings. Feeders can then be ranked and prioritised for investigation of phase rebalancing to improve headroom.

**The simple methodology developed to identify LV feeders with significant imbalance could be built directly into the data acquisition system in future.**

Future enhancements may involve coding of this methodology directly into the monitoring data acquisition system for automated analysis on a monthly or annual basis. Alternatively, it could exist as a stand-alone software tool that runs as an annual report for all LV monitoring systems.

### *Improved characterisation of HV and LV imbalance*

High levels of thermal phase imbalance were found in areas of SPENs LV network. A total of 89 secondary substations with 233 LV feeders were analysed. Of these 233 feeders, 165 had a mean phase imbalance ratio of  $>1.3$  for the 100 highest loading points. The HV network in comparison had relatively low levels of phase imbalance.

**Installation of network monitoring at three trial sites within SPENs network found significant imbalance on many low voltage (LV) feeders, currently not visible to network planners.**

31 feeders associated with 10 secondary substations were analysed in more detail. Pole mounted substations were found to experience higher levels of phase imbalance as expected due to fewer customers and thus reduced load diversity.

Based on this dataset, residential feeders were found to be most balanced due to higher volumes of customers and similar load profiles. This is an important finding to better understand phase imbalance implications for the connection of PV and EV to domestic properties.

**Feeders with high volumes of residential load where volumes of future PV and EV will connect were found to be relatively well balanced.**

Feeders with a mixture of residential, industrial and commercial loads and rural feeders were more likely to be unbalanced. Secondary substation MDI data was found to not provide a reliable indication of LV feeder phase imbalance.

The increased LV network monitoring to be deployed in RIIO-ED1 will enable further analysis and characterisation of LV phase imbalance network-wide. We recommend more detailed local monitoring in constrained network areas and areas identified as having high LCT uptake, and particularly where rebalancing of feeders can be a cost-effective solution.

Development of standard assumptions for thermal phase imbalance for various customer types/networks is the preferred approach to incorporate LV phase imbalance findings into network planning practice in parallel with improved characterisation of load profiles for various load types. This should help to improve knowledge of available network capacity headroom without introducing significant additional complexity, risk or requiring extensive monitoring due to the scale of the LV network.

**Secondary substation MDI data does not provide a reliable indication of LV feeder phase imbalance.**

There are some network data linkage and data uncertainty challenges to be overcome to enable automation of this analysis. These include mapping of the LV feeder monitoring to the appropriate LV feeder representation in GIS and establishing the LV cable rating. The mapping issue could be resolved with a unique LV feeder identification ID that is applied during monitoring install and updated in GIS via a portable hand held device. Uncertainty relating to cable ratings could be addressed through the application of intelligent algorithms to estimate missing ratings.

#### ***Improved utilisation of network capacity headroom***

Phase imbalance can have a significant impact on capacity headroom and losses. Phase imbalance was found in particular on a number of rural and mixed load feeders i.e. residential, industrial and commercial. Rural feeders have the most potential for rebalancing if connected by overhead LV feeders. This is because it is possible to visually determine which phase each customer is connected to and relatively easy to move customers from one phase to another with no excavation required. However, in some areas there may be a long string of customers connected to a single-phase overhead line or the HV circuit may be a single phase spur line in which case rebalancing would not be possible.

For mixed load feeders, a large 3 phase connected customer may be easy to rebalance if they have a 3 phase distribution board and where it is feasible to shift some load between phases. These findings also suggest that for new connections on mixed and rural LV feeders in particular, capacity margins should be considered more carefully to allow for phase imbalance.

**Rural feeders are more likely to be unbalanced but have the most potential for cost-effective phase rebalancing.**

To improve modelling for connection of PV generation, we are also assessing generation LV phase imbalance during summer daytimes, this will be reported in "7640-10 Flexible Networks Improved Characterisation of PV Capacity at LV".

9% of LV feeders monitored were identified as suitable for rebalancing, with the potential to release more than 20% capacity headroom and high enough peak load (>100A) to be worthwhile rebalancing. Lower capacity release may not provide a reasonable cost-benefit case for rebalancing versus other network planning options for reinforcement and there is less likelihood of achieving in practice due to the stochastic nature of phase imbalance. 4% of LV feeders were considered to have the highest potential for rebalancing, because they had greater than 30% potential capacity headroom increase and loads >150A. Generalising, if approximately 10% of the LV network can be rebalanced to release a minimum of 20% capacity headroom then this indicates that phase rebalancing can provide an additional 2% of LV capacity headroom network wide. We recommend targeting phase re-balancing solutions to approximately 1% of the network containing the most imbalanced LV feeders approaching capacity at first.

**LV phase rebalancing may provide an additional 2% capacity headroom network wide**

There are some practical challenges to be considered. For example, for underground LV feeders, it can be relatively costly to rebalance customers compared to installing a new LV split feeder. However, this depends on the forecast future utilisation of a new LV feeder and whether the existing LV board has available space.

If there is a link box located along the LV feeder, jointing works can be undertaken to swap phase cores and provide some rebalancing. However, the rejoining procedure will result in loss of supply for several hours. For LV OHLs, it is more cost-effective to rebalance customer load connections compared to increasing circuit capacity by laying a new LV cable.

**To improve phase balance, it is most cost-effective to rebalance individual customer connections on LV OHLs and rejoin link boxes on LV cables**

## Glossary

ADMD	After Diversity Maximum Demand
EV	Electric Vehicles
HP	Heat pumps
LCNF	Low Carbon Network Fund
LCT	Low Carbon Technology e.g. PV, electric vehicles, heat pumps
MDI	Maximum Demand Indicator. Installed in ground mounted secondary substations to record maximum load.
PI	Process Instrumentation - SPEN's Network Monitoring Data Historian System
SSEPD	Scottish and Southern Energy Power Distribution
SPD	Scottish Power Distribution
SPEN	Scottish Power Energy Networks
SPM	Scottish Power Manweb
UKPN	UK Power Networks



# 1 Learning Outcomes

New analysis techniques and metrics have been developed for improved characterisation of imbalance on the HV and LV networks based on detailed monitoring data available from the Flexible Networks project. These achieve the following learning outcomes:

- Improved understanding of the scale of thermal (current) imbalance on SPEN HV and LV networks and impact on asset loading.
- Identification of cost-efficient network planning strategies to detect and mitigate significant current phase imbalance, helping to release capacity headroom.
- Development and application of internal stakeholder engagement strategies to understand challenges to future adoption of new analysis techniques into business-as-usual.

## 1.1 Improved characterisation of HV imbalance

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.

## 1.2 Improved characterisation of LV imbalance

SPENs LV network planning tools (as described in Appendix A) generally assume that LV phases are balanced i.e. that at any instant each phase carries the same current. However, at LV most customers are connected to a single phase, so in practice the loading will vary between phases. Phase imbalance can lead to one phase exceeding the thermal rating of the LV circuit cable and/or the voltage on the LV feeder being outside statutory voltage limits towards the end of the feeder. Phase imbalance also increases losses. Figure 1-1 illustrates phase imbalance for an LV feeder with mixed load.

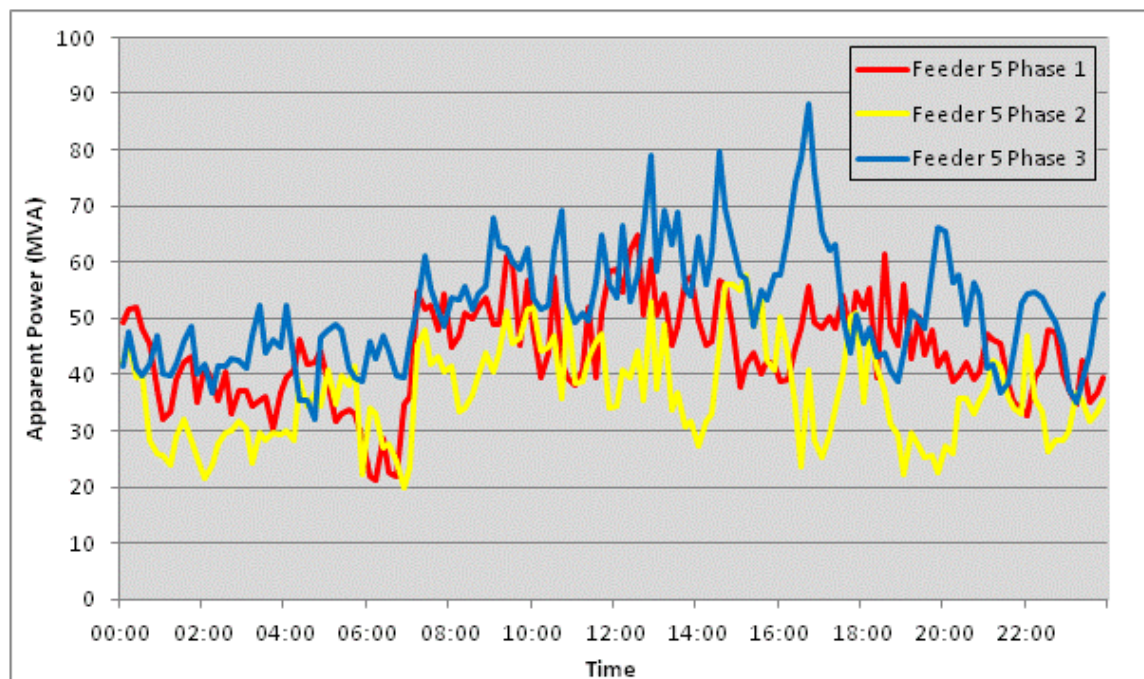


Figure 1-1 Phase imbalance for an LV feeder with mixed load  
(Abbey Walk Feeder 5, 14<sup>th</sup> December 2013)

In urban networks where there are many customers, phase imbalance is expected to be lower than in rural networks where less customers reduce load diversity.

As LCT connections increase the loading on the LV network, any clustering along with pre-existing phase imbalance may result in the feeder approaching capacity more rapidly. Also, phase imbalance will similarly apply to embedded generation connections and any assessment of how much PV generation can be connected to an LV network.

An improved approach to HV and LV load imbalance characterisation will enable a more efficient approach to network planning and reinforcement

## 1.3 Potential Benefits for DNOs

### 1.3.1 Network Planning

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

## 2 Background

### 2.1 Flexible Networks for a Low Carbon Future

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

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

Solutions are needed that can:

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

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

To ensure representative and replicable outputs, the project involves three carefully selected trial areas across SP Distribution and SP Manweb licence areas, covering various network topology and customer demographics: St Andrews in Scotland, Wrexham in Wales and Whitchurch in England, see Figure 2-1.

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



Figure 2-1 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.

## 2.2 Development of Improved Planning Tools

The existing best practice for distribution network LV and 11kV network design and operation is based on a “fit and forget” philosophy where there is only a limited set of representative network metrics available e.g. the magnitude of peak loading on a feeder or secondary substation, which generally does not provide information on the dynamic interactions of the various system states over the course of a year of operation. Short term capacity overloads or voltage excursions are typically identified by through customer feedback or investigations for new connections. Historically, it has been difficult to provide robust cost-benefit analysis in support of collection and analysis of time series data for large parts of the network.

The level of operating state uncertainty necessitated a number of assumptions which have inherent safety margins built in to minimise the risk of overloading equipment and keeping 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. Presently, 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 “clustered” rollout of electric vehicle charging points for example. This will necessitate an improved knowledge of the distribution network particularly at 11kV and LV and the ability to detect and extrapolate changes to implement the appropriate response.

A key aim of the Flexible Networks project is to develop more knowledge of the characteristics and behaviour of the existing network, identify additional capacity headroom available and better understand the likely impact of future network changes. It will develop cost-effective tools to improve network performance and investment, and to flag network changes and trends. A key aspect will be engaging with network operations and planning staff to understand their viewpoint and needs with the objective of obtaining their buy-in to implement changes in techniques and behaviour.

The outcomes will allow existing inherent design and operational safety margins for capacity to be reduced, without placing the system at risk, or degrading quality of supply to customers. It will also enable the development of techno-economic strategies for management of the future low carbon network that are effective and easy to implement. Although network monitoring and analysis is not in itself an innovative technique, the innovation in this work package is the core focus on improvement of the use of existing data across the business to create better knowledge and foresight of the changing environment.

At present, as with all DNOs, SPEN undertake an annual assessment that provides a ranked portfolio of network capacity issues. These then get prioritised based on value, criticality and deliverability. As distribution networks become more dynamic in nature, and the demand growth increases driven by low carbon technology adoption, network planners will need more sophisticated Decision Support tools.

### 2.3 Phase Imbalance

Unbalanced phase for LV feeders has been identified as a key issue for connection of low carbon technology. This study examines the existing levels of phase imbalance on the HV and LV networks through analysis of detailed monitoring data. It also investigates the incorporation of phase imbalance field data into the network planning process. The benefits of considering phase imbalance for assessment of network capacity headroom and reinforcement prioritisation and design are explored.

Two recent LCNF projects have considered phase imbalance at LV and this study builds upon their work by developing a methodology for analysis and characterisation of phase imbalance from high volumes of data, and by examining LV phase imbalance at a large number of secondary substations.

- SSEPD's LCN Fund Tier 1 project "Demonstrating the Benefits of Monitoring LV Networks with Embedded PV Panels and EV Charging Point" [1] monitored four secondary substations and found one phase loaded almost twice as highly as the other phases on a LV feeder at World's End Hill secondary substation. A similar level of imbalance was observed at the other substations. They calculated that if perfectly balanced, the feeder would have 2% lower losses. Balancing the feeder would increase the capacity headroom from 200A to 245A. Though it is not simple to move customers to a different phase on an underground network, they estimated that the cost of doing this would be lower than the cost of standard reinforcement work, at c. £14,000 vs c. £28,000.
- The application developed for UKPN's LCN Fund Tier 1 project "Distribution Network Visibility" [2] can be used to obtain a report of secondary substations with voltage unbalance or current unbalance above user-defined limits. In a case study, significant phase imbalance was found at a secondary substation. UKPN suggest that further monitoring at LV is worthwhile because it could inform actions such as phase balancing large 3-phase service loads, re-configuring link box open points, re-jointing single phase services or installing a phase balancer.

### 3 Experimental Design

An analysis technique has been developed to characterise phase imbalance for LV feeder monitoring data. This utilises LV monitoring data collected from mid-2013 at a number of secondary substations within the three Flexible Networks trial areas. In order to develop a fit-for-purpose analysis methodology that will enable the characterisation of LV imbalance to inform network planning processes for both SPEN and other UK DNOs, the following considerations were made;

- Requirement for efficient analysis of large volumes of monitoring data to output simple phase imbalance metrics that can be easily understood and directly comparable to circuit ratings. Data cleansing techniques previously developed by the Flexible Networks project can be applied prior to analysis.
- Characterisation of the impact of phase imbalance on LV network capacity headroom and network losses.
- Identification of correlation of phase imbalance levels on SPEN LV and HV networks with network type/features e.g. urban, rural. This will enable extrapolation of phase imbalance findings to the wider network to improve LV network planning practice and assessment of the impact of future LCT connections.
- Considerations for integration of LV network monitoring data analysis for thermal phase imbalance into future network planning processes and associated challenges.
- Cost-benefit analysis and practical considerations for deployment of phase re-balancing solutions.

This will ensure that the developed approach is robust and reproducible.



## 4 Improved Characterisation of phase imbalance

### 4.1 HV feeder phase imbalance methodology

The level of HV phase imbalance was characterised in two general ways:

- The difference in current (in amperes) between the most heavily loaded phase and the least heavily loaded phase. This will provide a measure of the risk of large circulating currents (leading to unwanted protection tripping) during reconfiguration.
- The relationship between the individual phase currents and the overall load. This provides an indication of the scope for rebalancing to reduce losses and increase capacity headroom. Two measures were considered:
  - The difference between the largest and smallest phase currents, as a percentage of the largest phase current
  - The ratio of each phase current to the average phase current. This is also the metric applied at LV, and is discussed further below.

The proportions of each season for which each phase was most and least heavily loaded were also calculated and visualised, to illustrate the likely effectiveness of rebalancing, and whether this would change seasonally.

A more detailed discussion of the HV imbalance characterisation methodology (including issues specific to mid-feeder NOJA measurements, which are considered to produce less reliable indications of imbalance as a result of the low volume of data and/or clustering in time) is given in the “Report on Assessment of Load Unbalance in HV Feeders” (SP/LCNF-FN/TR/2014-005).

### 4.2 Imbalance on ground mounted secondary substations

Phase currents are recorded on the secondary substation MDI at the time of total peak loading. These may not provide an indication of maximum LV feeder phase imbalance but do characterise the level of phase imbalance under high loading conditions at the HV/LV interface. Ground mounted secondary substations in SPD and SPM typically have between two to five LV feeders.

The level of phase imbalance on representative SPD and SPM ground mounted secondary substations was assessed from 2013/2014 MDI data. Data was available for a total of 10,528 substations. A phase imbalance factor was calculated for each phase based on the recorded phase current divided by the ideal balanced phase current (total current divided by 3).

Only 197 or 1.9% of ground mounted secondary substations were found to have a phase imbalance greater than a factor of 2 for one phase and 1765 or 16.8% of substations were found to have a phase imbalance greater than a factor of 1.3 for one phase. This suggests that at secondary substation level (with the aggregation of loading for all LV feeders), at least for ground mounted secondary substations, the level of phase imbalance is generally relatively low. Phase imbalance is expected to be higher for pole mounted secondary substations where there are



fewer customers connected so less diversity of load. However, MDIs are not installed for pole-mounted secondary substations due to space and access restrictions.

A total of 69 or 0.7% of ground mounted secondary substations were found to have MDI values recorded as 0. However, it is not clear in these cases whether the MDI device was not working or no load is connected.

### 4.3 LV feeder phase imbalance methodology

An LV phase imbalance methodology was developed to allow a network planner to easily interpret phase imbalance data on an LV feeder, assess the implications for network reinforcement and select the most economic network solution e.g. LV phase re-balancing.

From the three network trial sites (Whitchurch, St Andrews and Wrexham (Ruabon)), ten secondary substations were selected and monitoring data obtained from the data acquisition system. These represent a range of substation types, network trial sites and loads.

#### 4.3.1 LV imbalance analysis tool

An LV phase imbalance analysis tool was developed in Visual Basic to process LV feeder phase current data. The analysis tool has the following functional specifications;

- Ability to read and process large volumes of LV feeder monitoring data efficiently.
- Provides phase imbalance characterisation at the times of peak loading to enable assessment of thermal overload, voltage drop and losses.
  - Magnitude of phase imbalance
  - Persistence of phase imbalance
  - Maximum current loading for each phase for comparison with cable rating
- Provides a focus on the datapoints most likely to cause asset overloading, i.e the timestamps with maximum loading of a single phase.
- Provide a graphical output of phase imbalance results for ease of understanding.

#### 4.3.2 Phase imbalance metrics

Several phase imbalance metrics were devised to enable a simple characterisation of phase imbalance. These are based on the ratio of the phase current to the average current for all three phases. For example;

- Phases with a phase current to average current ratio  $>1$  have higher than average loading.

- Phases with phase current to average current ratio  $<1$  have lower than average loading.
- If all phases have phase current to average current ratios close to 1, the feeder is well balanced.

The analysis tool finds the 100 timestamps with highest loading of a single phase. The mean, lowest and highest ratio is then calculated. This provides an indication of the magnitude of the phase imbalance and whether it is persistent during peak loading periods or tends to vary across feeders. For example;

- If the mean ratio is much greater than 1 and the highest and lowest ratio are close to the mean ratio, this indicates persistent imbalance for that phase.
- If the mean ratio is somewhat greater than 1 and the highest and lowest ratio are above and below 1 respectively with a wide spread, this indicates that phase imbalance occurs intermittently on several phases.

This is illustrated further in the results below.

The number of timestamps can be adjusted by the operator however, a much larger number of timestamps (in the order of 10,000) results in the key metrics being influenced by phase imbalance characteristics at lower loading whereas we are interested in phase imbalance at high loading times. Four feeders were analysed and results indicated that phase imbalance characteristics and metrics did not change significantly based on 100, 500 and 1000 timestamps with the highest loading of a single phase. 100 timestamps correlates to around 16.5 hours or 0.2% of the time annually, 1000 timestamps correlates to 2% of the time.

#### 4.4 HV feeder imbalance results

Examination of primary substation feeder currents and mid-feeder HV currents measured by NOJAs suggests that HV imbalance is much lower than at the more imbalanced secondary substations and LV feeders. The analysis of HV imbalance is described in more detail in the “Report on Assessment of Load Unbalance in HV Feeders” (SP/LCNF-FN/TR/2014-005), a summary of the main findings is given here.

For the three test areas, the difference between the heaviest loaded phase and the lightest loaded phase was found to be less than 30A at maximum on any feeder, with some having a very low value of less than 10A. 1 shows the maximum unbalance current for the feeders in the St Andrews test area.

Table 4-1 Maximum unbalance (in A) and heaviest loaded phase for St Andrews area HV feeders

Primary Substation Feeder	Anstruther	Cupar	Leuchars	St Andrews
12	14 (B)	29 (A)	8 (B)	14 (C)
13	20 (B)	13 (B/C)	10 (A)	18 (C)
14	—	12 (B/C)	14 (B)	15 (A)
15	—	15 (A)	—	16 (B)
16	—	—	—	20 (C)
22	10 (C)	2 (—)	0 <sup>1</sup>	12 (C)
23	18 (A)	11 (B)	0 <sup>1</sup>	13 (B)
24	—	16 (B)	9 (C)	16 (C)
25	—	—	6 (A/C)	22 (B)
26	—	—	—	13 (C)

The pattern of imbalance over the year and through an average day was calculated for each feeder. In general, the magnitude of the imbalance was found to be greater when the load was highest (in the winter and at the daily demand peaks). According to this measure, imbalance was found to be similar in

<sup>1</sup> Leuchars feeders 22 and 23 were recorded as supplying zero current throughout the period of this study.

the three test areas. Maximum mid-feeder imbalance was found to be similar to that measured at the primary substation.

Figure 4-1 shows the seasonal pattern of imbalance for Whitchurch area feeders. In the graph, each column represents a season for one feeder; a group of four columns therefore shows changes across the year. In each column, the proportion of each colour shows the proportion of that season for which the phase represented by the colour is most heavily loaded. It can be seen that, for most feeders, the pattern is consistent across the year, and that there is a general pattern of one or two phases being predominantly the most heavily loaded throughout the year.

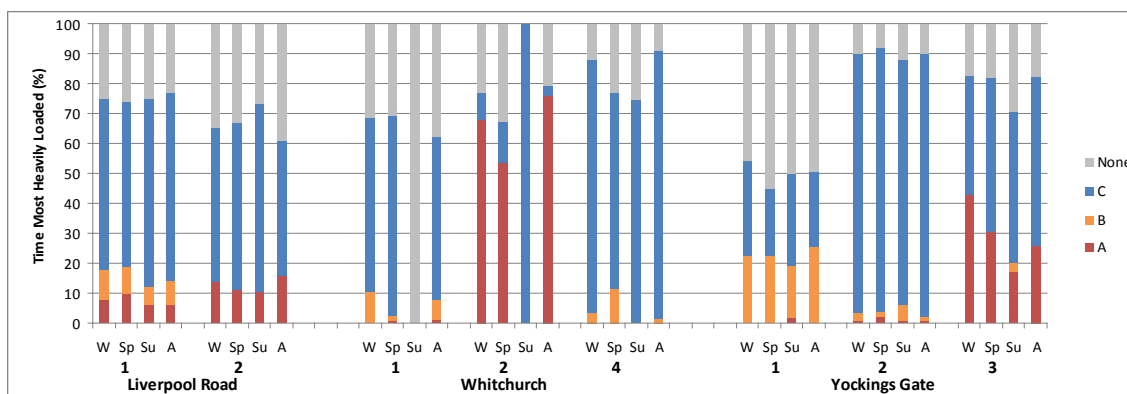


Figure 4-1 Demonstration of phase imbalance tool and results

Similar graphs were constructed to show the least heavily loaded feeder, and were found to be similar in terms of consistency between seasons, and there being one or two predominantly lightly loaded phases.

The two measures of the relationship between imbalance and overall load were found to give similar results: the results from method which is applied at LV are therefore summarised here, together with an example.

The least balanced HV feeder was found to be Liverpool Road Feeder 2. The range of ratios of phase current to mean current for this feeder were found to be as follows in Table 4-2.

Table 4-2 Summary of phase imbalance metrics for example HV feeder

	Mean ratio of phase current to average current	Highest ratio of phase current to average current	Lowest ratio of phase current to average current	Maximum current (A)
Phase A	1.112	1.412	0.857	90
Phase B	0.722	1.038	0.333	86
Phase C	1.166	1.5	0.857	93

The values in the “mean ratio” column were found to include the highest and lowest for any feeder phase in the St Andrews and Whitchurch test areas. Similarly, the “highest ratio” column included the largest value across all feeders, while the “lowest ratio” column includes the lowest value across all feeders. It can be seen from Figure 4-1 that phase B, which according to Table 4-2 is rather lightly loaded, is never the most heavily loaded phase on this feeder.

Liverpool Road feeder 2 was found to be the least well balanced HV feeder in the two test areas considered. Nevertheless, in comparison to the results presented in Table 4-3, the level of imbalance is small in relation to the most imbalanced LV feeders.

The same ratio metrics were calculated using data from NOJAs in the St Andrews test area. As previously noted, these results are considered less reliable than those for primary substations, but provide an indication that HV imbalance is no less at mid-feeder, and may be somewhat greater.

**Table 4-3 Summary of phase imbalance metrics for example HV feeder NOJA**

Location	Mean ratio of phase current to average current		Highest ratio of phase current to average current	Lowest ratio of phase current to average current
	Minimum	Maximum	Maximum	Minimum
Primary	0.904	1.085	1.191	0.375
NOJA	1.122	0.874	1.413	0.336

This suggests that HV rebalancing efforts, if required, would be most productive towards the end of the HV feeder. This result is perhaps to be expected, since NOJAs are placed in the overhead line network remote from the primary substation. It is known that imbalance in overhead line feeders can result from single-phase secondary substations being generally connected to the most accessible phases in the overhead line. Also, reduced customer numbers for overhead feeders reduces load diversity on individual phases.

## 4.5 LV feeder imbalance results

### 4.5.1 LV feeder analysis dataset

LV feeder phase current monitoring data from selected LV feeders from secondary substations located in the Ruabon and St Andrews network trial sites were analysed in detail. In St Andrews, 5 secondary substations with 14 corresponding LV feeders were assessed. In Ruabon, 5 secondary substations with corresponding

17 LV feeders were assessed. This enabled a comparative assessment of LV imbalance across a range of network characteristics.

Four pole mounted secondary substations were analysed: Allanhill and Brownhills in St Andrews and Plas Bennion and Afoeitha Road in Ruabon. The other secondary substations were ground mounted.

#### 4.5.2 Test case - Abbey Walk

An example of LV phase imbalance analysis is presented for Abbey Walk secondary substation, as shown in Figure 4-2 and located in the St Andrews HV network. The analysis was carried out for LV feeder phase monitoring data collected between the 10<sup>th</sup> July 2013 to 3<sup>rd</sup> May 2014, of which a total of 4 winter days were missing from the data.

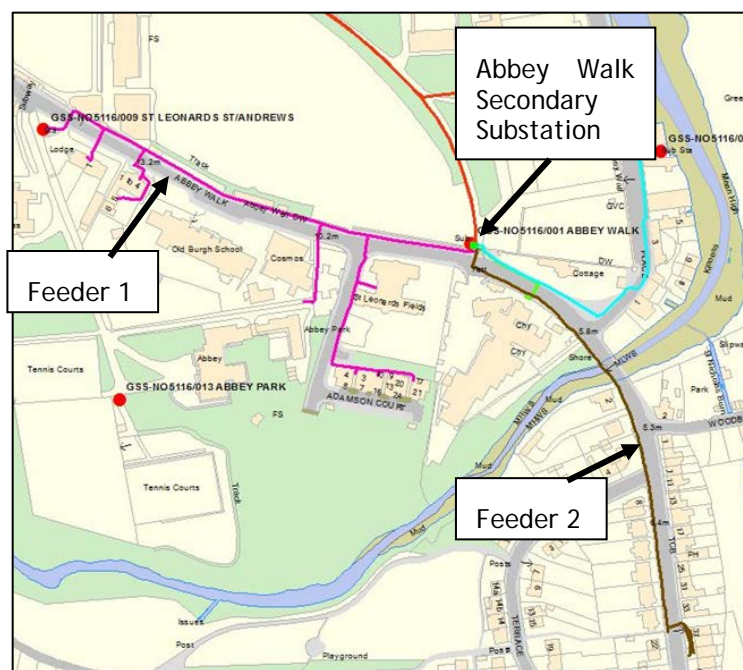


Figure 4-2 Map of Abbey Walk feeders

Key findings are shown in Figure 4-3. Feeder 1 is an example of a well balanced LV feeder as seen in the graph of high phase loading times. In general, the highest loaded phase varies and the mean ratio values are close to 1 for all phases. These properties are also reflected in the 14<sup>th</sup> November daily load profile. For comparison, daily load profiles for each phase are also shown, from Thursday 14<sup>th</sup> November 2013.

Feeder 2 is an example of an unbalanced LV feeder. The graph showing high loading times and the 14<sup>th</sup> November daily load profile both indicate that phase 2 is much more highly loaded than the other phases. For the 100 highest loading times, the ratio of phase 2 current to average current has a mean value of 2.33 (i.e. at these times phase 2 is more than twice as highly loaded as it would be if balanced). For the 100 highest loading times, the minimum ratio of phase 2 current to average current is 1.86, which shows that phase 2 was consistently much more highly loaded than the other phases. Hence feeder 2, if close to the

cable capacity, would be a good candidate for redistributing load between phases.  
Note that these feeders were chosen as a particularly clear example.

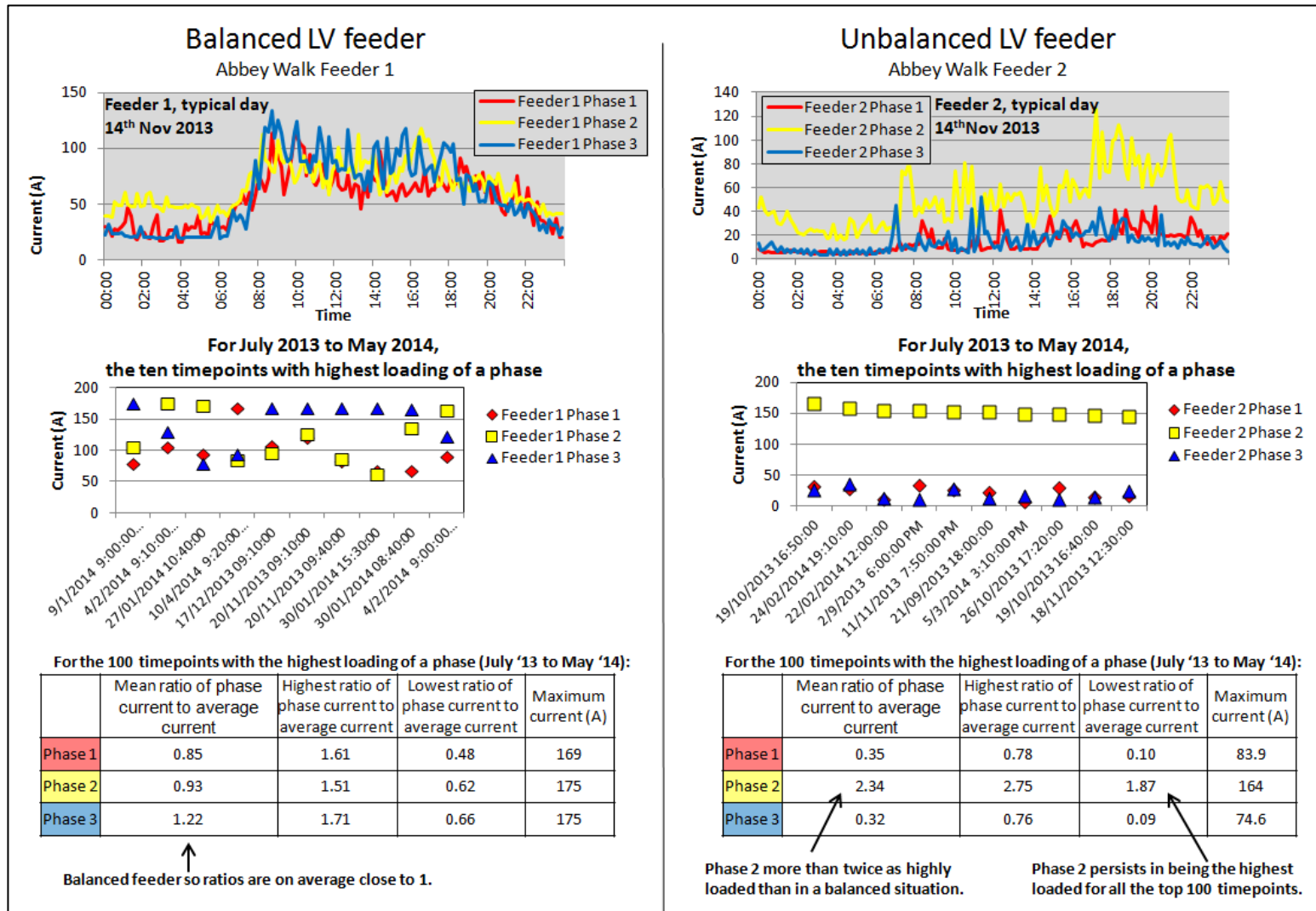


Figure 4-3 Demonstration of phase imbalance tool and results



### 4.5.3 Phase imbalance results

The mean ratio of phase current to average current (for 100 highest loading times) is shown below for the 14 feeders identified (among 31 assessed in detail) as having phase imbalance i.e. a particular phase was always loaded higher or lower than the mean. The highest loaded phase is shown in bold text.

Table 4-4 Results for unbalanced LV feeders

Substation	Feeder	Mean ratios		
		Red phase	Yellow phase	Blue phase
Abbey Walk	Feeder 2	0.350	<b>2.335</b>	0.315
	Feeder 3	0.016	0.329	<b>2.655</b>
	Feeder 5	0.909	0.911	<b>1.180</b>
Allanhill (PM*)	Feeder 1	1.064	0.818	<b>1.118</b>
St Nicholas St	Feeder 4	<b>1.966</b>	0.663	0.371
	Feeder 5	0.232	0.615	<b>2.153</b>
Afoneitha Road (PM)	Feeder 1	0.880	0.854	<b>1.266</b>
	Feeder 2	0.336	0.528	<b>2.136</b>
Bodlyn	Feeder 1	<b>1.645</b>	0.956	0.398
	Feeder 4	1.167	<b>1.821</b>	0.012
Cae Gabriel	Feeder 5	<b>1.508</b>	0.880	0.611
Plas Bennion (PM)	Feeder 1	0.511	0.430	<b>2.059</b>
Plas Madoc	Feeder 1	0.060	1.090	<b>1.849</b>
	Feeder 4	<b>1.869</b>	0.787	0.344

\*refers to pole mounted substation

### 4.6 LV feeder losses

Losses are greater for an unbalanced feeder compared to a balanced feeder, because losses on each phase are proportional to the square of the current. The equation for feeder losses is shown below where  $R_A$ ,  $R_B$ ,  $R_C$  refers to the cable resistance.

$$\text{Losses} = I_A^2 R_A + I_B^2 R_B + I_C^2 R_C$$

The worked example presented below gives the theoretical losses for a balanced feeder, and for a feeder with one phase loaded four times as much as the other two phases (or twice as much as the average).

Total feeder current: 300A

Balanced feeder:

$$\begin{aligned}\text{Losses} &= 100^2 R_{\text{phase}} + 100^2 R_{\text{phase}} + 100^2 R_{\text{phase}} \\ &= 10\,000 R_{\text{phase}} + 10\,000 R_{\text{phase}} + 10\,000 R_{\text{phase}} = 30\,000 R_{\text{phase}}\end{aligned}$$

Unbalanced feeder:

$$\begin{aligned}\text{Losses} &= 200^2 R_{\text{phase}} + 50^2 R_{\text{phase}} + 50^2 R_{\text{phase}} + I_{\text{neutral}}^2 * R_{\text{neutral}} \\ &= 40\,000 R_{\text{phase}} + 2\,500 R_{\text{phase}} + 2\,500 R_{\text{phase}} = 45\,000 R_{\text{phase}}\end{aligned}$$

(Note that  $R_{\text{phase}}$  = the resistance of each phase of the LV feeder)

A feeder with this level of imbalance incurs losses 1.5 times the losses of a balanced feeder.

For all LV feeders analysed (31), there were seven feeders where losses were greater than 1.5 times the balanced losses, due to phase imbalance at high loading times. LV feeder losses are in the order of 0.5% to 2% of the total feeder current.

This analysis does not include losses due to increased current on the neutral line which would act to increase losses further.

#### 4.7 Phase imbalance characteristics

The dependency of LV feeder phase imbalance was investigated in relation to secondary substation type (ground mounted or pole mounted), load type and network trial site. It is recognised that these features are linked in that a rural network is more likely to have a lower volume of customers connected and these will be connected via pole-mounted secondary substations with lower rated transformers.

**An unbalanced feeder is defined as phase imbalance that persists across the 100 highest phase loading events, for a particular phase**

Whilst the sample size was small (ten secondary substations), it was still possible to gain some useful learning from the analysis.

**Table 4-5 Results of comparative phase imbalance analysis**

	No. feeders with imbalance	Total no. of feeders (substations)
All feeders	14	31 (10)
Pole mounted substations	4	5 (4)
Ground mounted substations	10	26 (6)
Rural load	2	3
Residential load	5	16
Mixed load	7	12
St Andrews	6	14
Ruabon	8	17

#### 4.7.1 Substation type

There was found to be significantly more imbalance on LV feeders supplied by pole mounted secondary substations compared to LV feeders supplied by ground mounted secondary substations. Pole mounted substations tend to be in more rural locations with lower capacity transformers and fewer customers. Fewer customers reduces the diversity of load between phases.

For smaller pole mounted secondary substations, often only a single phase transformer is installed and a single phase line is run out to customers or there may have originally been a single phase transformer which has been replaced by a three phase transformer to accommodate a three phase customer such as a large farm or warehouse. In these cases, phase imbalance would directly impact on the HV feeder.

For the Flexible Networks secondary substation monitoring programme, only a few pole mounted secondary substations have been monitored and these have tended to be substations with larger transformers where it is possible to install the monitoring.

From a review of the monitoring data, it seems that customers are connected on all three phases for all four pole mounted secondary substations assessed.

#### 4.7.2 Load type

Based on a visual analysis of the ten selected secondary substations using GIS substations were divided into three different 'types';

- rural which supply farms or small clusters of rural buildings,
- residential which supply suburban residential areas,

- and 'mixed' which supply a mixed load of residential properties, shops, schools, leisure and medical facilities.

Results for phase imbalance are shown below;

- 5 out of 16 feeders from residential substations were unbalanced.
- 7 out of 12 feeders from mixed substations were unbalanced.
- 2 out of 3 feeders from rural substations were unbalanced.

This indicates that feeders in residential areas are least unbalanced which is likely due to residential customers with similar load profiles being at sufficient volumes to provide reasonable diversity of load across the phases.

The higher incidence of imbalance on mixed feeders is likely due to greater variation in load profile and lower customer volumes (larger, lumpier loads). Rural feeders also have lower customer volumes and possibly a few discrete larger loads e.g. farm, warehouses.

Further analysis on a larger sample size should help to verify this learning.

#### 4.7.3 MDI imbalance

Ground mounted secondary substations have Maximum Demand Indicators (MDIs) which are read on a six-monthly basis to report the maximum current recorded on each phase. However, the secondary substation MDI data does not provide a reliable indication of LV feeder phase imbalance for the following reasons;

- Loading on each feeder phase is aggregated at the secondary substation, which due to load diversity on various feeders may act to cancel out phase imbalance to an extent. Typically there are five ways out in a ground mounted secondary substation. For example, a number of the secondary substations had little MDI phase imbalance whilst having LV feeders that were unbalanced.
- The time of maximum phase imbalance on an LV feeder may not align with maximum demand on the secondary substation due to the various types of loads connected.

If the secondary substation only has a couple of LV feeders connected, any LV imbalance is more likely to be transferred to the HV network.

For Abbey Walk, which has 3 LV feeders with substantial imbalance, the imbalance for the secondary substation was analysed using the same method as for the LV feeders. In this example, the phase imbalance on the LV feeders is not reflected in the marginal phase imbalance for the secondary substation loading.

**Table 4-6 Comparison of secondary substation and corresponding LV feeder phase imbalance**

Substation	Feeder	Mean ratios		
		red phase	yellow phase	blue phase
Abbey Walk	Feeder 1	0.852	0.927	1.221
	Feeder 2	0.350	2.335	0.315
	Feeder 3	0.016	0.329	2.655
	Feeder 4	0.318	1.050	1.631
	Feeder 5	0.909	0.911	1.180
Abbey walk secondary substation		0.845	0.996	1.158
MDI readings		520A	580A	640A

#### 4.8 Summary of key findings

Ten secondary substations and associated LV feeders were analysed, representing a variety of substation types, network areas and loads. Significant imbalance was found on many of the LV feeders assessed; in one case for peak phase loading conditions, the load on one feeder phase was 2.7 times higher than it would be if fully balanced.

Key findings are as follows;

- 14 of the 31 LV feeders analysed show persistent phase imbalance. If this is replicated across the LV network, it indicates wide-spread phase imbalance.
- As expected, pole mounted substations generally indicate more phase imbalance than ground mounted substations most likely due to lower volumes of customers and thus less diversity.
- Preliminary results suggest that LV feeders supplying suburban residential areas are less likely to have phase imbalance compared to other network 'types' such as rural and mixed loads. This suggests that connection of future LCT such as EV and HP in residential areas may not be so constrained as existing levels of phase imbalance will be lower. This is also an important finding as phase re-balancing for residential areas is more challenging compared to re-balancing customers on rural overhead lines for example.
- Phase imbalance on the secondary substation MDI is not representative of phase imbalance on corresponding individual LV feeders.
- Phase imbalance can have a material effect on feeder losses thus further depleting capacity headroom. Phase imbalance increased losses to more than 1.5 times the losses of a balanced feeder, for 7 of the 31 LV feeders analysed.

- Graphical representations of phase imbalance are as important as numerical representations in providing a better understanding of network characteristics.
- Monitoring datasets can be large and computationally time-consuming to analyse, efficiency and identification of key metrics for characterisation of network behaviour is vital in development of an analysis tool.

## 5 LV network capacity

Analysis of LV feeder phase imbalance can be used to identify feeders approaching thermal overload as well as feeders likely to suffer from voltage drop issues. LV phase imbalance can significantly erode potential capacity headroom and lead to the requirement for early reinforcement. Phase rebalancing can defer this where there is a clear cost-benefit case.

In order to assess the remaining network capacity and inform the case for phase re-balancing, the maximum phase current is compared to the LV cable rating. LV cable type can be extracted from the SPEN GIS database to determine cable rating.

### 5.1 Methodology

A high level search algorithm has been developed and applied to identify LV feeders in the network trial sites with the greatest potential for capacity headroom increase by phase rebalancing. More generally, network capacity headroom gains at LV due to phase rebalancing are characterised.

The approach is described below;

- Take the mean ratio of phase loading to average feeder loading (over the 100 highest loading datapoints).
- If the mean ratio is above 1.3 for one of the phases, shortlist this feeder.
- Check that the feeder is persistently imbalanced towards the same phase (top 100 timestamps of phase loading all have the same highest loaded phase). This represents roughly the top 0.5% of timestamps of the October to March period.
- Estimate the percentage capacity headroom that could be released.

#### 5.1.1 Calculation of potential capacity headroom release

Thermal capacity headroom can be calculated as follows;

$$\text{Thermal capacity headroom} = \frac{(\text{Thermal Capacity} - \text{Thermal Loading})}{\text{Thermal Capacity}}$$

For an unbalanced system, this should be performed for the maximum loading of the highest loaded phase. The change in capacity headroom between the existing loading and rebalanced loading can then be calculated, to give the percentage headroom gain available.

However, data on the thermal capacity of LV feeders can be challenging to obtain, this is reviewed in detail below. Therefore for the purposes of this analysis, an alternative approach has been developed for estimating the potential headroom gain, as described below.

In applying the simplest solution to phase imbalance, we assume load would be redistributed from the highest loaded phase to the lowest loaded phase. The

maximum loading of the second highest loaded phase would then determine how close the feeder is to capacity as long as this value was more than the lowest loaded phase with redistributed load. This is encapsulated in the following equation:

$$\frac{\text{max. loading of highest loaded phase} - \text{max. loading of second highest loaded phase}}{\text{max. loading of highest loaded phase}}$$

This gives the percentage by which the existing maximum loading of a phase could be reduced by rebalancing phases. It has been postulated that, for an imbalanced feeder, the relative level of phase imbalance will remain similar as load increases towards the feeder capacity. Therefore, this percentage can also be used as a proxy for the capacity headroom increase that would be available through rebalancing when the feeder approaches capacity.

A worked example is provided below to illustrate.

### 5.1.2 Example: Plas Madoc Feeder 1

Load would be redistributed from phase 3 to phase 1. Therefore, the maximum phase loading of the feeder would now be 112.6A. The reduction in maximum loading of a phase is  $(125-112)/125 = 10\%$ . If we postulate that this relative level of phase imbalance will remain the same as load grows towards feeder capacity, a capacity headroom increase of 10% will also be available from phase rebalancing when the feeder approaches capacity.

Table 5-1 Plas Madoc Feeder 1 phase imbalance

	Maximum line loading (A)
Feeder 1 L1	26.750
Feeder 1 L2	112.620
Feeder 1 L3	125.500

It is noticeable in the Plas Madoc Feeder 1 example that more capacity headroom could potentially be released by moving load from both phase 2 and phase 3 to phase 1. This more complex approach to phase rebalancing has not been considered in this initial identification of candidate feeders. However if rebalancing is relatively straightforward, there may be a clear cost-benefit case for releasing more capacity through further phase rebalancing.



### 5.1.3 Limitations

For feeders where one phase is highly loaded and the other two phases are less loaded but at similar levels, it should be noted that the approach to calculating potential capacity headroom release as described above will result in an erroneous value. For example;

- Maximum potential capacity release if one phase is highly loaded and two phases are loaded close to 0 is 50%, where load is then shared equally between two phases. Compare this to 100% calculated using the approach above.
- Maximum potential capacity release if one phase is highly loaded and two phases are loaded close to 0 is 66.6%, where load is then shared equally between all three phases.

For these cases, the average potential capacity headroom release for the top 100 timestamps may be a more appropriate characterisation. This should then be compared to the potential capacity headroom calculated as per the example of Plas Madoc Feeder 1 and the lower value taken. To provide some context, the intention of this analysis is to develop efficient and robust methods of phase imbalance characterisation and identifying suitable candidates for rebalancing rather than precise values of potential capacity release for what is a stochastic phenomena.

## 5.2 Results

89 secondary substations with a total of 233 LV feeders were analysed, out of a total of 117 gridkey MCU monitored secondary substations for Flexible Networks. Subnet monitors used at other secondary substations did not have phase currents recorded. Of the gridkey monitored secondary substations that were not analysed, this was due to data unavailability or erroneous data. The analysis period was October 2013 to March 2014, chosen because the highest demands are usually found in the winter months.

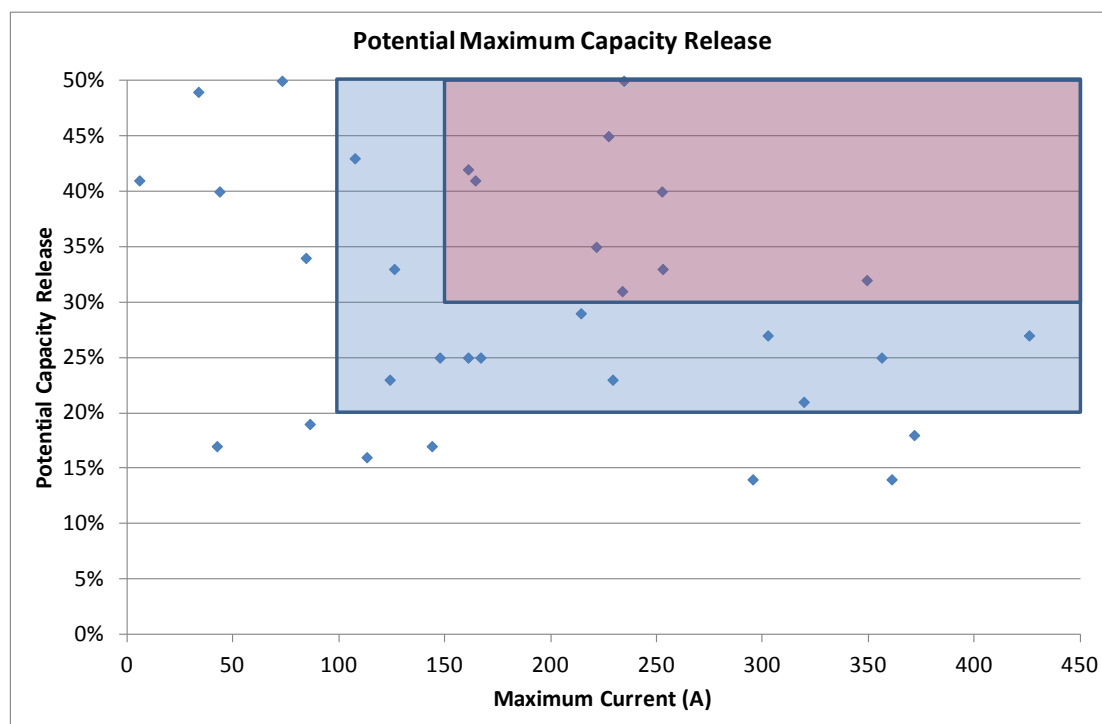


Figure 5-1 Distribution of persistently imbalanced feeders with mean ratio >1.3, by size of maximum load and by potential capacity release.

Of these 233 feeders, 165 had a mean phase imbalance ratio of >1.3 for the 100 highest loading points. Of these, 36 were persistently imbalanced towards the same phase over the top 100 loading points. Figure 5-1 shows these 36 feeders, in terms of their maximum loading and the potential headroom release. The highlighted areas show the feeders with most potential, as described in Table 5-2. From within this group of feeders, we highlight a subgroup of candidates for rebalancing, and a smaller group of the most promising candidates.

21 feeders were selected as candidate feeders for rebalancing, because they had greater than 20% potential capacity headroom increase and high enough loads (>100A) to be worthwhile rebalancing. These feeders are listed in Appendix B. Lower capacity release may not provide a reasonable cost-benefit case although this has not been assessed in detail. We have assumed that LV feeder ratings (at incomers to secondary substations) will generally be greater than 100-150A based on our experience of the SPD and SPM LV networks.

9 of these feeders were considered to have the highest potential for rebalancing, because they had greater than 30% potential capacity headroom increase and loads >150A. These feeders are listed in Table 5-3.

**Table 5-2 Number of candidate feeders for rebalancing identified**

Total number of feeders analysed	Feeders with >100A maximum loading, and >20% headroom increase available	Feeders with >150A maximum loading, and >30% headroom increase available
233	21	9

**Table 5-3 Feeders with highest potential for rebalancing**

Secondary Substation Feeder	Maximum Line Loading (A)	Potential Maximum Capacity Release
Gibson PI Feeder 1 L2	235	50%
Greenside Place s Feeder 1 L1	227	45%
Afoneitha Est No.1 Feeder 5 L2	161	42%
Abbey Walk Feeder 2 L2	164	41%
University Library Unit B-1 Feeder 3 L1	253	40%
The Elms Feeder 1 L3	222	35%
Afoneitha Road Feeder 2 L3	253	33%
South Castle St Unit B Feeder 1 L3	349	32%
Plas Bennion Feeder 1 L3	234	31%

It is important to note that in practice, it is not possible to achieve a perfectly balanced LV feeder, however for some feeders where imbalance is significant, improvements can be made through re-balancing as shown above.

### 5.2.1 Next Steps

The following steps are recommended for feeders identified above as good candidates for rebalancing:

- Use the phase imbalance analysis tool to assess imbalance over a larger number of timestamps, to verify that the phase balance persists over all or most high loading times.
- Check the ratings of the cable to calculate the actual capacity headroom increase available.
- Perform a cost-benefit analysis for the rebalancing.

### 5.2.2 Limitations

To keep analysis algorithm run times low for such large volumes of monitoring data, the method examines the 100 datapoints with the highest loading of a phase. This gives a very good indication of whether one phase is persistently more highly loaded than others. The 10 datapoints with the highest loading of a

phase are plotted by the analysis tool. However, once a substation has been identified as a candidate for rebalancing, a larger number of datapoints should be plotted to visualise phase imbalance.

In a few substations, some of the feeders appear to have negative loads. As this is occurring at high loading times in winter, these monitors may have been connected in reverse. In these situations, it can erroneously appear that a large headroom increase is available and it becomes obvious when looking at the data in more detail, which would be recommended in any case before undertaking rebalancing. There is also potential to refine the algorithm in future to exclude such cases if necessary.

### 5.3 Practical challenges

There are currently several challenges to more accurately analysing LV feeders to identify rebalancing opportunities. These are;

1. Linking LV feeder monitoring data recorded at secondary substations with the appropriate LV feeder in GIS
2. Determining LV cable rating

#### 5.3.1 Linkage between LV feeder monitoring and GIS

In SPEN GIS, the LV feeder at the secondary substation is labelled by fuse number. Fuse numbers do not generally correspond to the physical left-to-right position of the feeders in the substation.

In the Flexible Networks data acquisition system, LV feeders are labelled 1 to 5 which corresponds to the LV feeders running from left to right within the substation enclosure. In the substation enclosure, the feeders are each labelled with a description of their destination, e.g. street name. During monitoring installation, this label has been recorded. In most cases it is then possible to manually identify the feeders on a map (e.g. with the label "Ash Grove Hamden Arms LB), by comparing with the feeder topology in the GIS system. However, this is time consuming. Additionally, a few labels have no inscription, or an unhelpful inscription such as "UG cable 1" and "UG cable 2".

A further potential issue is that in a few cases cables may have been rejoined without update of the substation labels.

In Fife, Edinburgh and Borders for older secondary substations, the feeder order in the GND archive replicates the feeder left-to-right order in the substation. This will significantly accelerate matching LV monitoring data to the appropriate GIS feeders.

It is recommended that matching of monitored LV feeders to the GIS database is a key activity to be carried out during monitoring installation in future to improve efficiency of later analysis.

### 5.3.2 LV feeder rating

*Issue: No cable rating field in GIS*

Cable conductor material (e.g. Aluminium, Copper) and cross-sectional area can be queried for LV feeder sections in the GIS database. From this, cable or OHL ratings can be determined through reference to a ratings database (i.e. Equipment Ratings and Assessment of EHV/HV Systems ESDD-02-007 Issue No 4) however, this is a separate manual task.

*Issue: Missing cable data in GIS*

In the GIS database, conductor material and/or cross-sectional area is not available for some LV feeders. For example, 25% of LV cables do not have a value recorded for their cross-sectional area.

In future, an intelligent algorithm could be developed to create assumed values, for example by considering the standard asset types for the network area and the ratings of surrounding assets.

### 5.3.3 Other modelling issues

*Issue: Lack of unique identifier for LV feeders in GIS*

In GIS, HV feeders have a unique HV feeder identity field and all cable and OHL sections of the HV feeder also have this identifier. There is no analogous unique LV feeder identity field and a trace tool must be used to identify the feeder circuit and its associated sections. This begins from the fuse in the secondary substation and at the end of each cable or overhead line section, searches for other sections that start at those co-ordinates. The trace tool stops when a cable/overhead line ends or another fuse is reached. The trace tool is run manually in GIS and can be time-consuming to use.

SPEN have an automated version of the trace tool used for another application, which could be adapted however it is also fairly time-consuming to run.

The trace tool does not currently preserve the sequential ordering of cable/OHL sections along the LV feeder.

## 5.4 Recommendations for Network Planning

For LV network planning and connections, our results show that thermal phase imbalance should be considered in more detail. We recommend that standard assumptions be developed for typical levels of phase imbalance on various types of LV customers, networks and numbers of customers. Simple guidelines will add value to the network planning process whilst not also introducing significant additional complexity.

For constrained network areas and areas identified as having high LCT uptake, we recommend more detailed local monitoring particularly in areas where rebalancing of feeders should be cost-effective.

It is not possible to remove all phase imbalance as this is dependent on the stochastic behaviour of the connecting loads and in some cases, the cost of rejoining feeders compared to the likely capacity headroom release may be similar or greater than the cost of laying additional LV cable. Taking a “quality management” approach, network areas where phase imbalance is highest and the cables are close to rating should be addressed first to remove most of the phase imbalance.

We recommend targeting phase re-balancing solutions to approximately 1% of the network containing the most imbalanced LV feeders approaching capacity through actively monitoring LV feeders in areas of increasing volume of LCT connections.

## 6 Phase Imbalance Solutions

### 6.1 LV network design

It is standard practice in DNO LV network design to assume that phases are balanced. Residential customer loads are modelled based on After Diversity Maximum Demand (ADMD) values depending on the heating scheme. These values and the site maximum demand calculation (for a housing development) are generally conservative and the margin between maximum demand and LV cable rating also allows for a degree of phase imbalance. For new PV connections, generation phase imbalance assumptions are also used.

Often for new housing developments, a developer is keen to reduce the size of the connecting LV cables in order to minimise costs. Our analysis provides evidence that for larger residential developments, load diversity should result in fairly balanced LV feeders. In some cases, it may be appropriate to reduce the margins associated with the site maximum demand calculation following a more detailed assessment however this may then lead to a need for earlier reinforcement if there is subsequently EV and heat pump clustering.

Records of the metering class for large loads are available and these indicate whether the connection is single or three phase (although not which phase for a single phase connection). This information could be used to refine the future network monitoring strategy [3] and most cost-effective areas for first investigating phase imbalance and re-balancing where large houses have been converted into doctor's surgeries for example and as increasing uptake of LCT exacerbates any underlying phase imbalance issues.

#### 6.1.1 LV network reinforcement

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 is required, a proposal is prepared.

#### 6.1.2 New connections at LV

At LV, the maximum demands on the secondary transformers are available but the only way to obtain feeder loads is to carry out direct measurements at the secondary substation once a problem has been identified. 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 what reinforcement is required.

### 6.1.3 LV phase imbalance identification

Monitoring of LV feeders will provide conclusive indications of phase imbalance and the available capacity headroom. However, there is currently no wide-scale monitoring of LV feeders and to do so would be prohibitively expensive.

The approach described in [3] is to identify areas of the LV network with high LCT growth and pro-actively deploy detailed monitoring to these areas. Also, once an LV fuse has blown, this should trigger the detailed monitoring of the associated LV feeder/s and secondary substations.

Our analysis above has identified types of networks more likely to experience phase imbalance. Also, phase imbalance may suddenly occur on mixed feeders or on non-standard feeders where for example, someone has converted a large town house to a nursery, with a large extension or a country house to a doctors or dentists surgery. These details may be submitted as a new network connection application and should also be available through local planning authorities. This can be used to refine areas of the network of interest to deploy detailed monitoring to, particularly when accompanied by clustering of LCTs. In general, it can be used to improve network planning practice through simple standard assumptions without significant additional complexity.

## 6.2 LV Network Solutions

If phase imbalance is resulting in an LV feeder being close to rating or voltage exceedance of statutory limits, then a network solution must be considered to ensure security of supply. These may include;

- Re-balance phase loading by re-jointing single phase customer connections
- Re-balance feeder loadings by feeder link box reconfiguration
- A zigzag transformer to balance voltage typically used in the past on long LV overhead lines (not in common use on UK LV networks currently)
- A two Scott transformer balancing method currently under investigation [4]
- Targeted energy efficiency solutions for larger customers (this is being explored in detail in another activity within Flexible Networks)

The level of phase imbalance needs to be high enough to provide a cost-benefit case for phase re-balancing rather than reinforcing (up-rating or overlaying) the LV feeder. This is assessed below.



## 6.2.1 Challenges for rebalancing LV feeders

### 6.2.1.1 Underground cables

SPENs GIS system records which feeder each customer is connected to, but not which phase. The jointing is underground, and sealed within a 'coffin', so cannot be examined. SPENs recommendation is that Greenfield housing customers are connected R, Y, B, B, Y, R. However, in practice a jointer may simply connect to the most accessible phase at each point. Customer phase can be identified by connecting a device in the secondary substation to detect a signal from the customer's home. However, this relies on customer permission. The extensive rollout of smart meters may allow SPEN to rapidly identify which phase customers are on in future.

The phases of the main LV cable are labelled, but it cannot be guaranteed that they are connected that way around. Rebalancing individual domestic LV customers requires excavation of the joint box, severing of the existing connection and rejoining to another phase.

In [1], SSEPD recommend that 3-phase services with 3-phase cut-outs at new and upgraded domestic customers should be reviewed as a means of achieving LV network phase rebalancing at a lower cost than the alternative need for excavation, re-jointing and reinstatement. This will certainly help to reduce phase imbalance to an extent, particularly for new estates with separate LV feeder connections. However, it will not mitigate any existing customer phase imbalance which will increasingly be an issue with clustering of load growth from electric vehicles and heat pumps.

### 6.2.1.2 Overhead lines

For overhead LV feeders, it is easier to move customers from one phase to another as it is possible to visually determine which phase each customer is connected to and no excavation is required.

However, in some areas a single-phase pole mounted transformer has been replaced by a three-phase pole mounted transformer to accommodate a three-phase customer. In this case there would be a long string of customers connected to a single-phase overhead line, and hence it would not be so easy to rebalance the transformer. Also, in rural areas the HV circuit may be a single phase spur so it is not possible to fit a 3-phase transformer.

A zigzag transformer was used in the past on long LV overhead lines to balance voltage however it is not in common use today. Whilst this may be a simple solution and it is mentioned as a solution by SSEPD in [1] (referred to as a Z-wound voltage balancer), there will be some potentially substantial cost associated with deploying an additional transformer. This is not a standard solution and has not been assessed in the cost-benefit case.

### 6.3 Cost Benefit Analysis

A cost-benefit analysis is presented below for various feasible reinforcement options to assess most techno-economic solutions i.e. lowest £/kW, once a candidate feeder for phase re-balancing has been identified using the approach outlined in Section 5.

Table 6-1 gives estimates of the cost for LV feeder monitoring and various phase imbalance solutions for the LV network. The cost of an engineer to investigate, identify and design the most appropriate network reinforcement will be common to all network solutions although for a simple LV connection, this will be minimal.

**Table 6-1 LV phase imbalance typical solution costs**

Activities	Estimated Cost
<b>Common to all Solutions</b>	
LV Monitoring (Secondary substation, 4 feeders (all phases))	£3000 [3]
Engineering time to analyse monitoring data and characterise phase imbalance	£500
<b>Phase Re-balancing Solutions</b>	
<i>Per Domestic Customer</i>	£2000 for cables £500 for OHLs
<i>Change link box configuration</i>	£2000 radial £4000 interconnected CIs -
<b>New LV Cable, Uprating or Overlay</b>	£50k-£75k <sup>†</sup>

<sup>†</sup> Based on £100-£150/m cost of cable and installation (dependent on ground conditions) and typical LV feeder length of 500m

In order to change the phase connection of a typical suburban domestic customer supplied by LV cable, it is necessary to excavate the joint bay, sever and then rejoin the customer service cable. The cost of identifying the phase connection of the customer is minimal compared to the installation works costs. Changing the phase connection of a customer connected to an LV OHL is by comparison a much simpler and less costly process.

Converting a large single phase customer to a three phase connection has not been considered; this is likely to be costly due to installation of a new 3 phase service as well as undertaking rewiring at the customer premises to split loads across the three phases (which the customer is unlikely to want to pay for). It is not reasonably practical for the purposes of rebalancing phases at LV. A large 3

phase connected customer may be easier to rebalance if they have a 3 phase distribution board and where it is feasible to shift some load between phases. For example, in tenement buildings in SPD's area it is relatively simple to move customers between phases.

If there is a link box located along the LV feeder, jointing works can be undertaken to swap phase cores. If the LV feeder is in an interconnected mesh then this will need to be carried out at both ends of the feeder-link box connection. For both radial and interconnected LV feeders, the rejoining procedure will result in loss of supply for several hours. Alternatively, it may be possible to transfer some load on to another LV feeder if the LV network is relatively meshed. This is not likely to resolve the underlying load imbalance across phases but is a low cost temporary measure.

For cabling costs, the cost of LV cable uprating will be similar to the cost of a new LV cable overlay because the existing cable will need to be removed if the cable trench is reused and customers rejointed, thus installation works costs will be comparable or potentially greater. In this case, it is more efficient to retain the existing cable and overlay an additional cable to double the capacity if there is space on the LV board.

For LV OHLs, it is common SP procedure to replace OHLs approaching capacity with LV cables to provide additional headroom whilst reducing future maintenance requirements and improving visual amenity, rather than reconductor or build additional OHLs.

Table 6-2 LV phase imbalance solution cost-benefit

Activities	Estimated Capacity Headroom	£k/Percentage Capacity Headroom
<b>Phase Re-balancing Solutions</b>		
<i>For 4 - 8 domestic Customers*</i>	15% - 30% <sup>†</sup>	0.55 for cables 0.14 for OHLs
<i>Changing link box configuration</i>	up to 30%	≥0.07 for radial ≥0.14 for interconnected
<b>New LV Cable (replacing OHL)</b>	25% - 50%	1 - 3
<b>LV Cable Uprating</b>	20% - 30%	1.7 - 3.75
<b>LV Cable Overlay</b>	100%	0.5 - 0.75

\* Typically up to 50 customers connected per LV feeder with an After Diversity Maximum Demand per domestic property of 2kW [5]

‡ For highly imbalanced LV feeders identified as suitable candidates. Please note that it will not be possible to remove all phase imbalance as it is a transient phenomena.

The cost-benefit analysis above indicates that it is most cost-effective to change the link box configuration as an initial measure to reduce phase imbalance and gain circuit capacity, if a link box is located along the LV feeder cable. The feasibility of this will depend to an extent on the number of customers connected upstream and downstream of the link box. Changing the phase connection of individual customers on LV cables does not appear to be a more techno-economic solution than simply overlaying a new LV and moving some customers off the most heavily loaded phase if required.

However, this may not always be the case. SPEN ground mounted secondary substations typically have a five way board for LV feeders. If the feeder board is already full, then the addition of another LV cable will require another secondary substation to be built which is a much more costly undertaking.

Also, if it is unlikely that the additional capacity of a new LV cable is going to be fully utilised in future then this is essentially a “stranded” asset and the total cost of rebalancing a few customers is less than the total cost of a new LV feeder that will be under-utilised.

For LV OHLs, it is more cost-effective to rebalance customer load connections compared to increasing circuit capacity by laying a new LV cable.

SSEPD in “Demonstrating the Benefits of Monitoring LV Networks with embedded PV Panels and EV Charging Point”, an LCNF Tier 1 project, found that the cost of moving customers to a different phase on an underground network to rebalance was likely to be lower than the cost of standard reinforcement work, at c. £14,000 vs c. £28,000 to rejoin 14 out of 50 customers. Our analysis suggests that phase rebalancing costs will be higher per residential customer connected to LV cables and it may be more cost-effective to first change link box configuration if possible. The cost-benefit of installing a new LV feeder is comparable to rebalancing customers however we have listed several cases in which it is preferable to consider rebalancing customers first before undertaking network reinforcement works.

There should also be potential for reductions in CI and CML due to pro-active identification of phase imbalance that is approaching cable or fuse ratings. The cost of a CI at LV is £15.44 per customer per interruption. For an LV feeder with up to 50 customers, this could provide savings of up to £772 per LV feeder per avoided interruption. This cost saving is not so material compared to the cost of deferred major reinforcements however the key benefit here is ensuring a more secure network for customers.

## 7 References

- [1] Scottish and Southern Energy Power Distribution , “LCNF Tier 1 Close-Down Report Demonstrating the Benefits of Monitoring LV Networks with Embedded PV Panels and EV Charging Point” , February 2013.
- [2] UKPN, PPA Energy, Capula “Distribution Network Visibility LCN Fund Tier 1 Close Down Report” , December 2013.
- [3] SPEN, RIIO-ED1 LCT Network Monitoring Strategy, March 2014.
- [4] Li, Y., Crossley, P.A., “Voltage Balancing in Low Voltage Distribution Networks using Scott Transformers” , CIRED 22nd International Conference on Electricity Distribution, Stockholm, 10-13 June 2013.
- [5] RICHARDSON, I. ... et al, 2010. Domestic electricity use: a high resolution energy demand model. Energy and Buildings, 42 (10), pp.1878-1887.

## Appendix A - Phase Imbalance Analysis Tool

An analysis tool was developed in Visual Basic to assess phase imbalance on LV feeders being monitored as part of the Flexible Networks project. Algorithm design to deliver various functional specifications is described in Table A-1.

Table A-1 Functional Specification of phase imbalance analysis tool

Functional Specification	Algorithm design
The analysis tool must focus on highly loaded times which are most likely to cause thermal overloads and high losses.	The algorithm sorts the LV feeder load data to find the 100 timestamps with the highest loading of any phase.
The tool must provide a quantitative metric for phase imbalance.	The indicator was chosen as the ratio of each phase current to the average phase current. Phases with ratio $>1$ have higher than average loading, and phases with ratio $<1$ have lower than average loading. If all phases have ratios close to 1, the feeder is well balanced.
The tool must indicate whether there is a consistent phase imbalance over all the high loading times.	To show whether the ratio is always above/below 1 for a phase, or varying a lot, the analysis tool gives the mean ratio, the maximum ratio, and the minimum ratio over the 100 highest loaded timestamps.
The tool must give an indication of phase imbalance which can be quickly and intuitively understood.	A graphical output is included.

## Inputs

Data was taken from the data acquisition system, which was installed on LV feeders in the Flexible Networks trial areas in mid-2013. The monitors record a voltage snapshot for each phase of each LV feeder once per minute and a current snapshot once per ten minutes. The data is stored as daily csv files for each secondary substation.

The imbalance tool was developed as Visual Basic code, in order to easily work with csv files. The tool extracts the currents of each phase, at 10 minute intervals between two dates specified by the user.

Some issues were encountered with missing files, where no data has been recorded for certain days due to issues with the data monitors. The analysis tool automatically ignores these days, and outputs the number of files that are missing as part of the results sheet.

## Analysis

A secondary substation is specified along with the location of the data files for that substation, the dates between which to run the analysis, and the fields to extract (normally this would be the current reading for each phase of each feeder). The process followed by the analysis tool is summarised below, and then illustrated with an example and screenshots.

The analysis tool:

1. extracts the currents of each phase of each LV feeder from the specified period of data at 10 minute intervals
2. for each timestamp, for each feeder, finds the average current of the phases and the highest current of the phases
3. for each feeder, sorts all results in descending order of 'highest phase current'
4. outputs a graph showing the current on each phase at the ten highest loading timestamps
5. calculates for each phase the ratio of that phase's current to the average current
6. takes the ratios (see point 3) for the 100 highest loading timestamps, and displays the mean ratio, maximum ratio and minimum ratio for each phase.
7. also displays the maximum current on each phase, so it can be compared with the circuit rating.

## Analysis Methodology Example

This example shows the analysis tool's operation on data from Abbey Walk secondary substation feeder 1 from July 2013 to May 2014.

1. extracts the currents of each phase of each LV feeder from the specified period of data at 10 minute intervals

	A	B	C	D	E	F	G
		Feeder 1 L1 Current Value	Feeder 1 L2 Current Value	Feeder 1 L3 Current Value	Feeder 2 L1 Current Value	Feeder 2 L2 Current Value	Feeder 2 L3 Current Value
1	Event Time						
18380	14/11/2013 15:00:00	61.12	80.5	80	22.38	36.25	18.88
18381	14/11/2013 15:10:00	53.25	69	99.75	16.88	41.12	23
18382	14/11/2013 15:20:00	64.38	82.5	93.62	17.75	62	18.62
18383	14/11/2013 15:30:00	68.38	80	111.5	25.12	60.25	32.38
18384	14/11/2013 15:40:00	57.12	93.5	117.5	24.12	74.12	27.38

Figure A-1 Output of phase imbalance ratios for a LV feeder

2. for each timestamp, for each feeder, finds the average current of the phases and the highest current of the phases

	Feeder 1 L1 Current Value	Feeder 1 L2 Current Value	Feeder 1 L3 Current Value	Average	Highest Phase
Event Time					
14/11/2013 15:00:00	61.12	80.5	80	73.87333	80.5

Figure A-2 Output of phase imbalance ratios for a LV feeder

3. for each feeder, sorts all results in descending order of 'highest phase current'

	A	B	C	D	E	F
		Feeder 1 L1 Current Value	Feeder 1 L2 Current Value	Feeder 1 L3 Current Value	Average	Highest Phase
1	Event Time					
2	01/09/2014 09:00	79.75	105.62	175.25	120.2067	175.25
3	02/04/2014 09:10	105.12	175.25	130.25	136.8733	175.25
4	27/01/2014 10:40:00	94.75	170.88	78.12	114.5833	170.88
5	04/10/2014 09:20	168.5	85.25	94	115.9167	168.5
6	17/12/2013 09:10:00	107.75	95.88	168	123.8767	168
7	20/11/2013 09:10:00	121.25	126	167.38	138.21	167.38
8	20/11/2013 09:40:00	82.25	86.75	167.25	112.0833	167.25
9	30/01/2014 15:30:00	68.5	62.62	167	99.37333	167
10	30/01/2014 08:40:00	67.25	135	166.12	122.79	166.12

Figure A-3 Output of phase imbalance ratios for a LV feeder



- outputs a graph showing the current on each phase at the ten highest loading timestamps

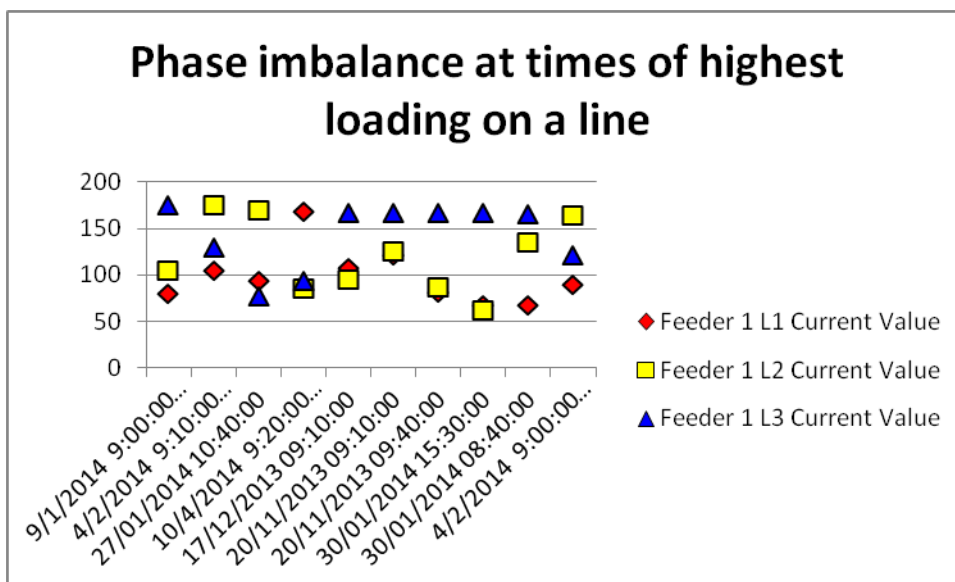


Figure A-4 Output of phase imbalance ratios for a LV feeder

- calculates for each phase the ratio of that phase's current to the average current

A	B	C	D	E	F	G	H	I
Event Time	Feeder 1 L1 Current Value	Feeder 1 L2 Current Value	Feeder 1 L3 Current Value	Average	Highest Phase	Ratio of Feeder 1 L1 Current Value to average	Ratio of Feeder 1 L2 Current Value to average	Ratio of Feeder 1 L3 Current Value to average
01/09/2014 09:00	79.75	105.62	175.25	120.2067	175.25	0.663	0.879	1.458
02/04/2014 09:10	105.12	175.25	130.25	136.8733	175.25	0.768	1.280	0.957
27/01/2014 10:40:00	94.75	170.88	78.12	114.5833	170.88	0.827	1.491	0.682

Figure A-5 Output of phase imbalance ratios for a LV feeder

- takes the ratios (see point 3) for the 100 highest loading timestamps, and displays the mean ratio, maximum ratio and minimum ratio for each phase.
- also displays the maximum current on each phase, so it can be compared with the circuit rating.

	A	B	C	D	E	F
1				Abbey Walk_10July2013to3May2014.xlsx		
2	For each feeder, within the 100 datapoints with the highest loading on a line, ratios of one line to the average of the three lines					
3		Mean ratio	Highest ratio	Lowest ratio	Maximum line loading	
4	Feeder 1 L1 Current Value	0.852	1.606	0.483	168.500	
5	Feeder 1 L2 Current Value	0.927	1.509	0.617	175.250	
6	Feeder 1 L3 Current Value	1.221	1.711	0.657	175.250	

Figure A-6 Output of phase imbalance ratios for a LV feeder

Various decisions were made in refining the functionality of the analysis tool, the implications of these are discussed below.

- The analysis tool sorts the timestamps based on the loading of the **highest loaded phase**. The intention being that generally, the load behaviour of each phase at any one time would be similar. However, this may not be the case; for example, a timestamp with a loading of 90A, 30A, 30A may be ordered above a timestamp of 80A, 100A, 100A if the first phase has a peak load greater than 100A. Presentation of the total maximum feeder load assists in identifying peak loading for each phase.

Also, for LV feeders identified as good candidates for rebalancing, it is recommended that the top 100 to 500 highest loaded timestamps are plotted to provide further characterisation.

The mean, highest and lowest phase imbalance ratios were calculated for **the 100 timestamps** of highest loading. The number of timestamps can be adjusted by the operator however, a much larger number of timestamps (in the order of 10,000) results in the key metrics being influenced by phase imbalance characteristics at lower loading whereas we are interested in phase imbalance at high loading times.

Four LV feeders were analysed and indicated that phase imbalance characteristics and metrics did not change significantly based on 100, 500 and 1000 timestamps with the highest loading of a single phase.

### Other future developments

SPEN network planners already use information from a wide variety of databases and tools. To make the process more efficient, it would be better for analysis tools to be more consolidated. Hence, it should be investigated whether phase imbalance analysis could be integrated with any other LV network analysis tools.

The following features should also be considered;

- Programming of data extraction and analysis algorithms directly into the data acquisition software.
- Refined algorithms to reduce analysis processing times. With increased LV network monitoring installed during RIIO ED1, this could otherwise become very lengthy.

## Appendix B - Candidate feeders for phase rebalancing

Secondary Substation Feeder	Maximum Line Loading (A)	Potential Maximum Capacity Release
Gibson PI Feeder 1 L2	235	50%
Greenside Place s Feeder 1 L1	227	45%
Idwal Plas Madoc Feeder 3 L1	108	43%
Afoneitha Est No.1 Feeder 5 L2	161	42%
Abbey Walk Feeder 2 L2	164	41%
University Library Unit B-1 Feeder 3 L1	253	40%
The Elms Feeder 1 L3	222	35%
Afoneitha Road Feeder 2 L3	253	33%
James Street St A Feeder 5 L2	126	33%
South Castle St Unit B Feeder 1 L3	349	32%
Plas Bennion Feeder 1 L3	234	31%
Auldburn Rd Feeder 5 L1	214	29%
South Street s Feeder 3 L2	426	27%
James Street St A Feeder 2 L2	303	27%
Gibson Hospital A Feeder 3 L3	356	25%
Strathtyrum Farm Feeder 1 L1	161	25%
Castlecliffe s Feeder 2 L3	148	25%
Castlecliffe s Feeder 4 L2	167	25%
Council Houses Feeder 2 L3	229	23%
Peris Plas Madoc Feeder 1 L1	124	23%
Gibson Hospital B Feeder 2 L2	320	21%