WESTERN POWER DISTRIBUTION

INNOVATION

NEXT GENERATION NETWORKS

LOSSES INVESTIGATION

WPD_NIA_005

NIA MAJOR PROJECT PROGRESS REPORT

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Contents

Glossary

Term	Definition
BAU	Business as usual
DG	Distributed Generation
DNO	Distribution Network Operator
DUKES	Digest of UK Energy Statistics
EDMI	Meter design and manufacturing company.
GB	Great Britain
GIS	Geographic information system
GPRS	General Packet Radio Service, the mobile data service on 2G and 3G cellular communications systems.
HH	Half Hourly
HV	High Voltage
I2R	Loss assessment based on an I^2R calculation approach
IPR	Intellectual Property Register
LCT	Low Carbon Technologies
LLF	Line Loss Factor: means the multiplier which, when applied to generation or demand on the distribution system, converts the data to an equivalent value at the transmission system boundary inclusive of distribution system losses
LV	Low Voltage
NHH	Non Half Hourly
NIA	Network Innovation Allowance
NOP	Normal Open Point
PICAS	Paper insulated corrugated aluminium sheath cable
PILCSWA	Paper insulated lead covered steel wire armoured cable
MUA	Manx Utilities (Manx Utilities Authority)
RMS	Root mean square
SCADA	Supervisor Control and Data Acquisition
WPD	Western Power Distribution
XLPE	Cross-linked polyethylene cable

1 Executive Summary

Losses Investigation is funded through Ofgem's Network Innovation Allowance (NIA). Losses Investigation was registered in April 2015 and will be complete by July 2018, reporting October 2018.

Losses Investigation aims to quantify technical losses on the LV and HV network, and determine the minimum information required to accurately predict network losses.

This report details progress of the project, from April 2017 to the end of September 2017.

1.1 Business Case

This project will provide information that should allow us in subsequent work to accurately target the most economically viable mitigation techniques, allowing us to reduce losses where action presents a net benefit.

From the Digest of UK Energy Statistics 2014 (DUKES) the final electricity consumption across the UK was 317TWh in 2013. Of this approximately 25.2% or 83.7TWh is consumed within WPDs network. With the conservative figure of 5.8% losses in the distribution network this means that 4.64TWh is lost on WPDs network, of this approximately 3.34TWh (72%) is lost after transformation down to HV. Using the Ofgem value of £48.42/MWh this is worth £161.9 million directly with a further contribution of £103 million from the value of the carbon emitted generating it (figures of 524.62 TCO2/GWh and £59/TCO2 was used from the NIA benefits guide).

Estimated cost of HV and LV losses on WPD network = £161.9m + £103.5m = £265m per year.

If we can target losses and reduce 10% of the technical losses on the LV and HV networks by 10% then the method cost would be £2.65 million a year.

1.2 Project Progress

This is the second six monthly progress report. It covers progress from April 2017 to the end of September 2017. Progress included:

- Approval of an internal WPD Standard Technique for the installation of pole-mounted transformer monitoring, manufacture of enclosures containing the monitoring equipment, and the subsequent installation of 58 monitors.
- Completion of the installation of the required monitoring equipment on all the 11 selected HV feeders. In total 181 installations (including overhead installations) have been completed.
- Final selection of LV feeders, and completion of the installation of advanced meters and substation monitoring for all 11 LV feeders. In total 335 meters and 15 substations or overhead feeder monitors have been installed.
- Completion of three-phase analysis models for all HV and LV monitored feeders. These are the tools providing both power difference and I2R[1] assessments of feeder losses, plus a wealth of modelled data for comparison to measured values
- Receipt and processing of monitoring data from all 11 HV and 11 LV feeders, with loss assessments ongoing on all feeders. This has included extensive work on confirming acceptable current balances on feeders.
- An investigation of the potential to reduce HV feeder losses through the movement of network normal open points (NOPs).

Focus over the next reporting period will be on:

- Resolution of differences between loss assessment methods;
- Further development and demonstration of the proposed HV loss estimation method; and
- Initial development of the LV loss estimation method.

1.3 Project Delivery Structure

1.3.1 Project Review Group

The Losses Investigation Project Review Group meets on a bi-annual basis. The role of the Project Review Group is to:

- Ensure the project is aligned with organisational strategy;
- Ensure the project makes good use of assets;
- Assist with resolving strategic level issues and risks;
- Approve or reject changes to the project with a high impact on timelines and budget;
- Assess project progress and report on project to senior management and higher authorities;
- Provide advice and guidance on business issues facing the project;
- Use influence and authority to assist the project in achieving its outcomes;

[1] The notation I2R (rather than I^2R) has been used throughout text and graphs for consistency in reasonably available formatting.

- Review and approve final project deliverables; and
- Perform reviews at agreed stage boundaries.

1.3.2 Project Resource

WPD are providing full-time project management resource, plus project oversight and direction.

Academic, loss assessment design, and analytical support is being provided by Loughborough University.

Planning and implementation of HV feeder monitoring is provided by ex-WPD staff through agencies. This work is being undertaken in close collaboration with the local WPD Network Services staff.

Lucy Gridkey have provided substation monitoring equipment and is also providing ongoing data collection services for all the HV feeder monitoring equipment and the LV substation monitoring equipment.

Manx Utilities (MUA) is providing planning, implementation and data provision services for the LV feeder monitoring.

WPD has provided EDMI[2] meters from its metering operation. The project has made use of EDMI's technical support under the WPD umbrella.

1.4 Procurement

The following table details the current status of procurement for this project.

Provider	Services/goods	Area of project applicable to	Anticipated Delivery Dates
Loughborough University	Services (academic, loss assessment design, and analytical support)	• HV & LV feeder loss assessment on monitored feeders • Design and development of loss estimation methods for non-monitored HV & LV feeders	Ongoing until the end of the project
Lucy Gridkey	Goods (supply of established MCU520 LV substation monitoring equipment)	• HV & LV feeder loss assessment on monitored feeders	Over the project period, completion expected June 2017.
Lucy Gridkey	Goods (design, development and	• HV feeder loss assessment on	Complete Feb 2017.

[2] Meter design and manufacturing company

Provider	Services/goods	Area of project applicable to	Anticipated Delivery Dates
	supply of monitoring at HV supply points, based on MCU520 equipment)	monitored feeders	
Lucy Gridkey	Services (data collection for deployed MCU520 equipment)	• HV & LV feeder loss assessment on monitored feeders	Ongoing until the end of the project
MUA	Services (planning, implementation and data provision services)	• LV feeder loss assessment on monitored feeders	Ongoing until the end of the project

Table 1 - Procurement Details

1.5 Project Risks

A proactive role in ensuring effective risk management for Losses Investigation is taken. This ensures that processes have been put in place to review whether risks still exist, whether new risks have arisen, whether the likelihood and impact of risks have changed, reporting of significant changes that will affect risk priorities and deliver assurance of the effectiveness of control.

Section 7.1 of this report shows the current top risks associated with successfully delivering Losses Investigation as captured in our Risk Register.

1.6 Project Learning and Dissemination

Project lessons learned and what worked well are captured throughout the project lifecycle. These are captured through a series of on-going reviews with stakeholders and project team members, and will be shared in lessons learned workshops at the end of the project. These are reported in Section 5 of this report.

2 Project Manager's Report

2.1 Project Background

Distribution Network Operators have an obligation to operate efficient and economic networks. As such the effective management of distribution losses is paramount. Current estimates put the technical losses at between 5.8% and 6.6% of electricity delivered ("Management of Electricity Distribution Network Losses" IFI report) worth approximately £900 million across the UK. Approximately £640 million of these losses occur after transformation down to 11kV.

Some improvements with clear cost benefits across the network are being rolled out, as outlined in WPD's Losses Strategy; however these are restricted to broad brush techniques due to a lack of detailed understanding in the variation of losses across our network. As such reductions in losses on existing network cannot be targeted and the network cannot be optimised.

The Losses Investigation NIA project aims to:

- Quantify technical losses on samples of LV and HV network through the application of load monitoring equipment; and
- Establish loss estimation approaches, using a minimum necessary additional information set, which can be widely applied to HV and HV networks.

The project started in April 2015, and was originally due to be complete by December 2017, reporting March 2018. It is now due for completion July 2018, reporting October 2018.

Key phases to the project are:

- Project mobilisation, partner selection and establishment of appropriate project agreements;
- Initial laboratory testing of proposed load monitoring equipment, and establishment of loss assessment methodologies and calculations;
- Field testing of proposed equipment, installation, data collection, and assessment methods for one pilot HV network, and one pilot LV feeder;
- Installation of monitoring to selected HV and LV feeders;
- Assessment of Losses on monitored HV and LV feeders;
- Development of loss estimation methods for HV and LV feeders, using minimum additional information sets.

2.2 Project Progress

Project activity over this six month period has been focused on:

- Final selection of remaining LV feeders;
- Completion of installation of monitoring of HV and LV feeders;
- Establishment of 3-phase models of all HV and LV feeders to allow the assessment of losses;
- Confirmation that all connected load is being monitored and included in the losses assessment. This has been achieved through the use of current balances[3] for the monitored feeders;
- Establishing initial and ongoing loss estimates for the monitored feeders (including the management of source data);
- Reviews of the loss assessments that are being produced, and some continuing investigation work; and
- Investigation of the potential to reduce HV feeder losses through the movement of network normal open points (NOPs).

As a result:

- The construction/installation phase is now complete; all required monitors are now installed and providing data;
- It is believed that all substations/connection points to HV and LV feeders are now being monitored (based on current balance assessments);
- Initial loss assessments have now been made for all feeders, using both the power difference and I2R methods; and
- Ongoing loss assessments for all HV and LV feeders are being regularly produced.

Some further progress has also been made in the area of estimating losses, with the focus being on modelling of HV/LV transformers, and the availability of a large number of 11kV and LV feeder models. This area will be principle focus in the next six months.

Progress against each of the project phases is summarised in Table 2. Text in grey represents previously reported progress.

[3] Current balances compare the magnitude of current measured at the source, with a sum of the current magnitudes measured at the feeder substation/customer connection points.

Project Phase	Progress
Project mobilisation, partner selection and establishment of appropriate project agreements	**Complete** (reported in March 2017 Six Monthly Report) - The project has selected Loughborough University as its academic and analytical partner, and has confirmed Manx Utilities (Isle of Man) as its partner for investigating losses on LV networks. Collaboration Agreements have been established with both.
Initial laboratory testing of proposed load monitoring equipment, and establishment of loss assessment methodologies and calculations	**Complete** (reported in March 2017 Six Monthly Report) – Loughborough University successfully completed initial laboratory testing of the proposed monitoring and measurement arrangements.
Field testing of proposed equipment, installation, data collection, and assessment methods for one pilot HV network, and one pilot LV feeder	**Complete** (reported in March 2017 Six Monthly Report) – Installation of required monitoring equipment on one HV and one LV feeder was completed in 2016, with successful modelling and loss measurement and assessment being demonstrated. Further details are contained in Appendix A.
Installation of monitoring to selected HV and LV feeders	**Complete** (during this period) - The installation of the required monitoring equipment has been completed on all the 11 selected HV and 11 selected LV feeders. An overview of the monitored feeders is contained in Appendix B.
Assessment of Losses on monitored HV and LV feeders	**Ongoing** (during this period) – • Data now regularly being collected from 335 meters and 196 Gridkey devices; • Loss assessment models/engines now established for all HV and LV feeders; • Current balances established for all HV and LV feeders; and • Initial and regular ongoing loss assessments produced for all HV and LV feeders.
Development of loss estimation methods for HV and LV feeders, using minimum additional information sets	**Ongoing** (reported in March 2017 Six Monthly Report) – • Various approaches to estimating feeder specific losses have been considered and tested. For HV feeders, a preferred approach has been developed; details of this are described in Appendix D. • For LV feeders, initial assessment of key similarities and differences to the successful HV approach has been made. Work on an LV approach continues.

Table 2 - Summary of project progress against project phases

2.3 Installation of Monitoring to Selected Feeders

2.3.1 Progress within this reporting period

Installation of monitoring to the 11 selected HV feeders and 11 selected LV feeders has been completed during this reporting period. Table 3 provides an overview of completion dates. Grey text represents previously reported progress.

Feeder	HV/LV	Installation completion dates
Woodlands (Pilot)	HV	March 2016
Pilot domestic	LV	April 2016
Fox Milne Hotel	HV	July 2016
Wavendon Gate Local	HV	September 2016
Secondary School Walnut Tree	HV	October 2016
Crawley Road Tee Howard Way	HV	November 2016
Amway Tongwell	HV	November 2016
Ackerman Tongwell Aldrich Drive Tee	HV	January 2017
Laxey domestic	LV	January 2017
Ramsey domestic	LV	March 2017
Peel A & B I&C	LV	April 2017
Ballasalla I&C	LV	May 2017
Braddan I&C	LV	May 2017
Santon OH	LV	Jun 2017
The Avenue	HV	July 2017
Riverside Park	HV	July 2017
Silver End	HV	July 2017
Wolverton	HV	August 2017
Abbeylands OH	LV	August 2017
Tromode Domestic	LV	September 2017
Ramsey OH	LV	September 2017

Table 3 - Installation completion dates

Internal approval of a WPD Standard Technique and the manufacturing of pole-mounted enclosures for the Gridkey devices led to an installation programme starting May 2017. By early July 58 units were installed. In total 181 monitors have been installed on HV feeders (including overhead installations).

Final selection of LV feeders to be monitored has led to the completed installation of meter and LV feeder monitors. In total 335 meters and 15 substation/overhead feeder monitors have been installed.

Initial completion of monitoring on both HV and LV feeders was tested through the construction of the three-phase analysis models. These models were then used to assess the current balances on the feeders. The current balance is calculated as the difference between the 1 minute mean measured current at the substation source, and the sum of the 1 minute mean currents measured at the distribution substations (for HV feeders) or the connected customer meters (for LV feeders). An example of a current balance produced to test the completeness of connected-customer monitoring is shown in Figure 1. The three traces on this plot show the difference between the predicted substation current based on the sum of the connected loads and the substation current that was actually measured. Negative values indicate that less current was predicted than measured and therefore indicate the presence of an unmonitored connection. From this it can be seen that there is unmonitored load on L3. By looking at the apparent shape of the difference, and the time of day, it was established that there was an unmonitored street lighting load (switched on with a light detector, and switched off with a time clock). An additional meter was installed to appropriately monitor the load, completing monitoring of the feeder.

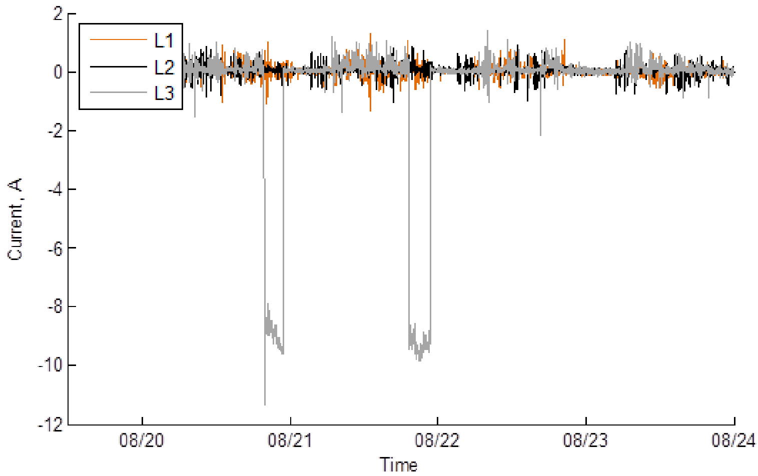

Figure 1 - Example current balance for an LV feeder with missing load.

Another example of the use of current balances is seen in Figure 2. The structured error on L3 was established to be a constant ~1A load missing from the analysis, combined with a street lighting load that was not yet monitored. The current balance differences on L1 were further investigation and determined to be a monitored load that was not actually connected to this feeder as records suggested. Appropriate changes were made and an acceptable current balance was reached.

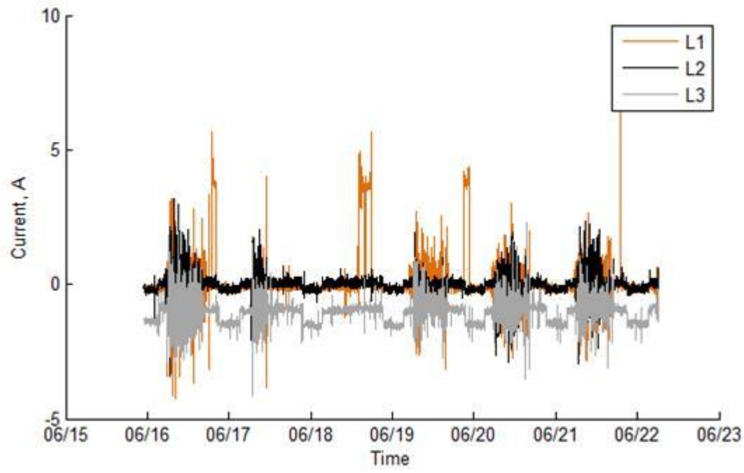

Figure 2 - Example current balance for an LV feeder with both missing load , and load that is not connected to the feeder

In some instances, the initial current balance data was not conclusive about the completeness of load monitoring. An example of such a case is shown in Figure 3. The magnitude of the imbalance did not seem reasonable to dismiss, but there was no structure to a potential error as was seen in previous examples. The possibility of harmonics affecting the analysis was investigated. Whilst the meters do provide a measurement of current total harmonic distortion, this is not directly available from the Gridkey measurements. However, measurements of harmonic energy were available, and with this, estimates of current at fundamental frequency were developed and introduced to the current balance. The results are shown in Figure 4, from which it was concluded that complete monitoring had been achieved for this particular feeder.

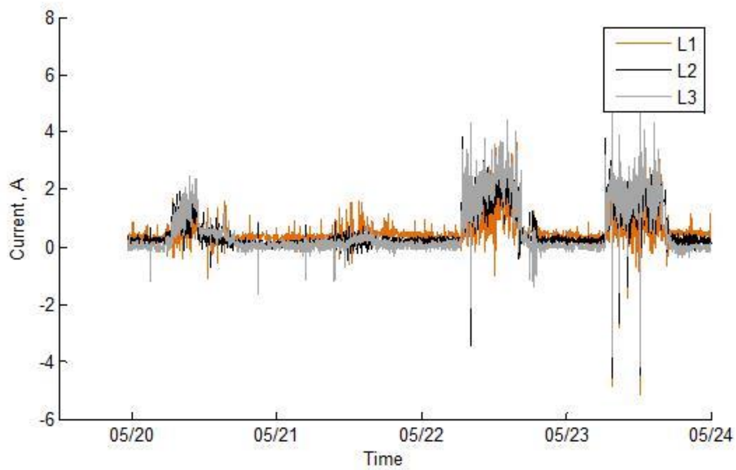

Figure 3 - Initial current balance for an LV feeder suspected of having unmonitored load.

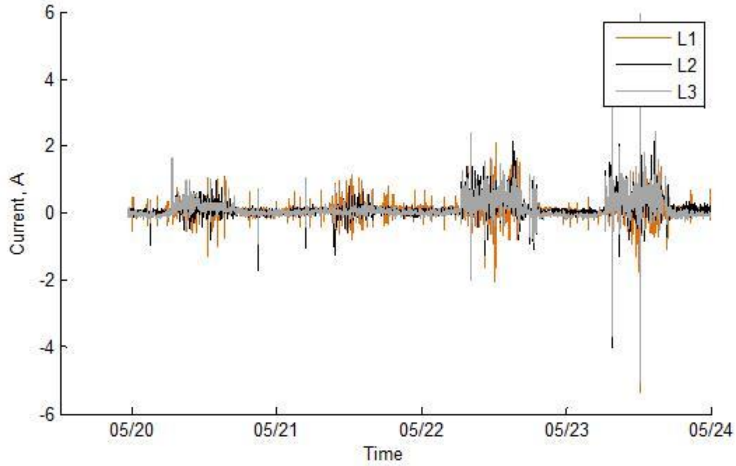

Figure 4 - Example current balance for an LV feeder

The issue of time synchronisation has also clouded confirmation of completeness of load monitoring. Figure 5 shows an LV feeder with concerning levels of apparent current difference; however, the reciprocal nature of the spikes (positive and adjacent negative spikes) suggested time synchronisation issues. The differences are seen to increase each day following the time at which the clocks on the smart meters are reset.

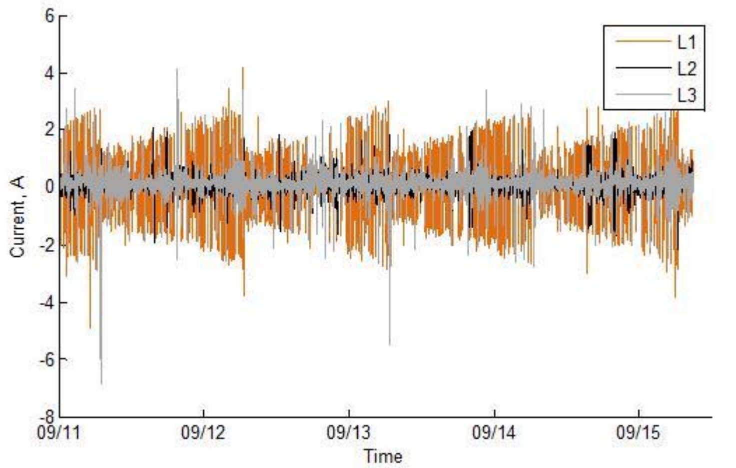

Figure 5 - Example current balance for an LV feeder with meter time synchronisation issues

Averaging over a period of 10 minutes reduced the magnitude of the spikes by a factor of approximately 10 (Figure 6, note the y-axis scale); this was sufficient to conclude that the loads on the feeder were all being monitored.

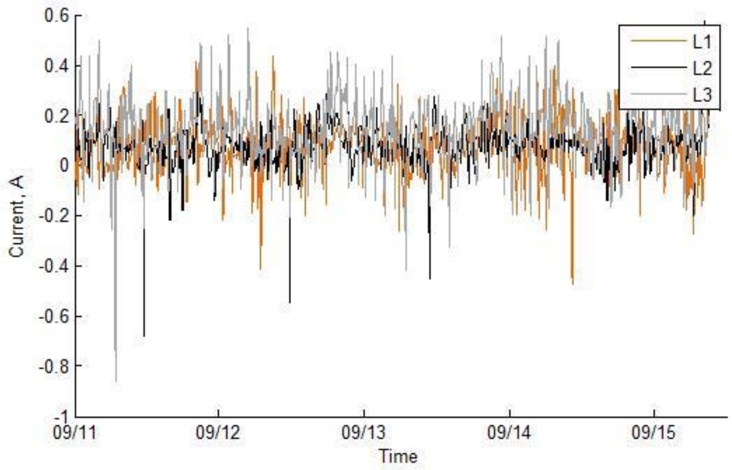

Figure 6 - Example current balance for an LV feeder with meter time synchronisation issues, averaged over 10 minutes

For HV feeders with overhead sections, issues of phasing and the existence of generation have caused uncertainty in confirming that all loads were monitored. Figure 7 shows an example of an HV feeder with significant current balance spikes.

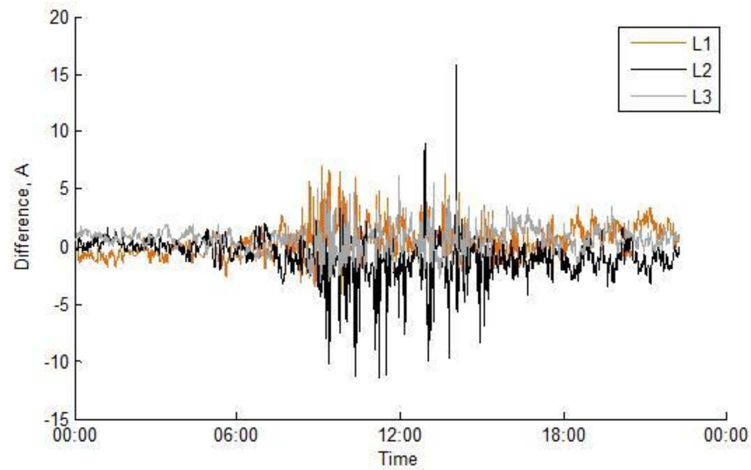

Figure 7 - Example current balance for an HV feeder with significant apparent current balance spikes on L2

Temporary higher time resolution monitoring equipment was installed at the primary substation to further investigate. This revealed instances of reversals of direction of power flow at the primary substation within the 1 minute monitoring periods of the installed project monitoring. These changes in power flow direction result from the variability of a solar farm's output on a day with broken cloud, as its peak output on a given day approaches and slightly exceeds the feeder demand. Figure 8 shows various traces with sub-1 minute data in addition to the Gridkey 1 minute data.

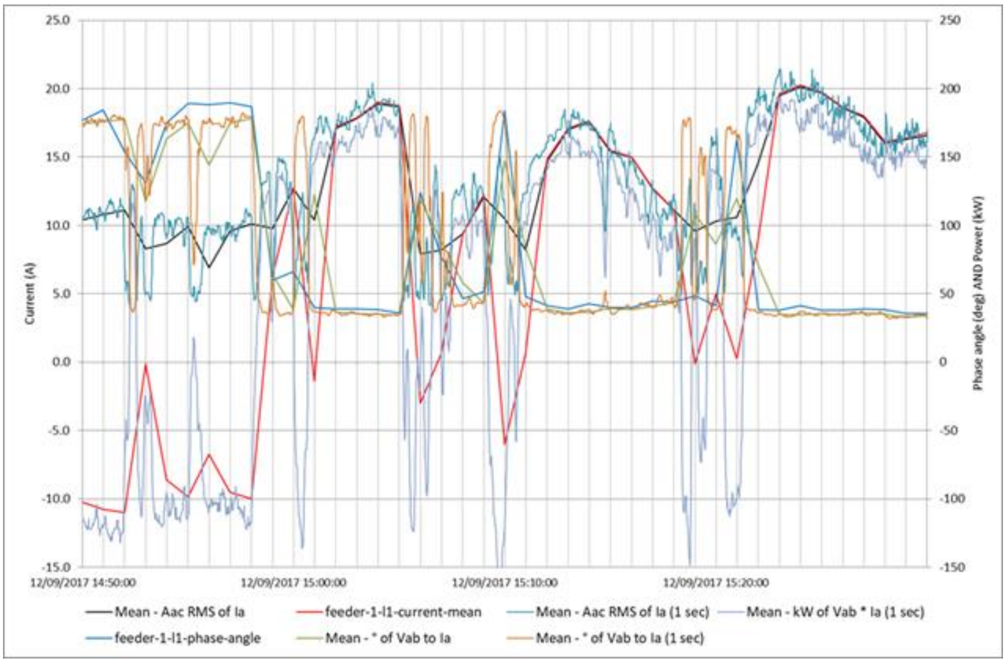

Figure 8 - Example current balance for an HV feeder with significant apparent current balance spikes on L2

The issue with the spikes on the current balance (Figure 7) was found to be due to spurious indications of differences between the modelled and measured current at the primary substation. The measured current was not representative of actual current magnitude for 1 minute periods when the power flow reversed during the 1 minute period, whereas the modelled current proved to give a better representation of actual current at the Primary substation.

As a result of this temporary additional equipment and analysis, it was concluded that the all loads on the feeder were being monitored, and some of the measurements used in the current balance could not be relied upon in specific circumstances.

2.3.2 Next steps

Establishing that all loads on feeders are being monitored has required significantly more analysis effort than had been anticipated. The modelling framework has been extended to provide current balances, estimated current balances at fundamental frequency, and time averaged current balances to provide reasonable evidence that all loads are being monitored for many of the feeders, both HV and LV. This is in addition to the use of the analysis framework to confirm the actual (vs. reported) phase connection of both single phase and three-phase loads.

Questions over current balance remain on some HV and LV feeders, and causes of this are likely to overlap with causes of differences between I2R and Power Difference assessments of feeder loss that are discussed in Section 2.4.

However, whilst work on resolving these questions will continue, the priority for focus over the next reporting period will switch to further development of the estimation processes.

2.4 Ongoing Assessment of Losses on Monitored Feeders

2.4.1 Progress and next steps for HV feeders

Ongoing Loss assessments (both I2R and Power Difference) are now in place for all HV feeders, though available data for the last feeders to be completed is limited.

One way of providing an overview of results to date is to plot long term mean values of feeder load versus mean feeder loss. This can be seen in Figure 9 which shows mean feeder loss vs mean feeder load for HV feeders using both I2R and Power Difference assessments. In addition, an illustrative loss vs. load characteristic is also drawn[4].

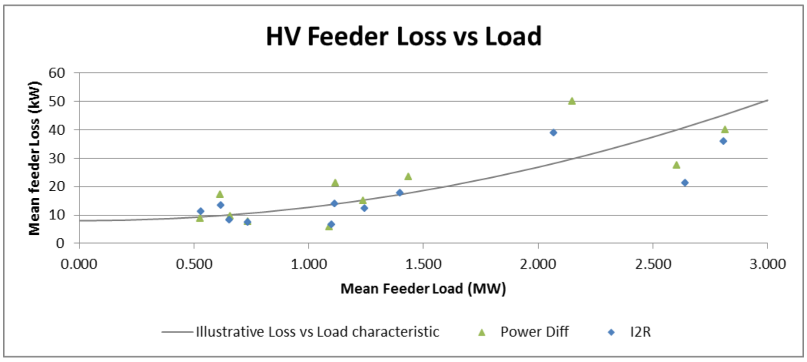

Figure 9 - Mean feeder loss vs mean feeder load for HV feeders using both I2R and Power Difference assessments

Generally it can be seen that the loss assessments conform to the illustrative characteristic (as would be expected given its I^2 term). Differences between any one feeder's loss and the illustrative characteristic line are primarily due to the feeder's unique length, conductor size, distribution of load along the feeder, and how that changes with time.

The Power Difference assessments are higher than the I2R assessments for most but not all the feeders. The differences between I2R and Power Difference loss assessments have been found to be changing over time, and are being investigated further.

Detailed loss assessment results for all HV feeders are shown in Appendix C 1.

[4] This illustrative characteristic for HV feeders takes the form $Loss = fixed\ loss + R_{eq} \times I^2$. The fixed element represents the sum of the transformer no-load losses of the feeders, and is present at all feeder loads, including minimum/no load. This is nominally seen as the extrapolated y-axis intercept on the chart. R_{eq} represents the equivalent impedance of the feeder. This value is broadly governed by the constants of feeder length, conductor size and type; and by the time-varying distribution of load along the feeder. I represents the feeder load.

Variation in mean feeder loss can be seen for feeders with similar mean loads, and this is due to differences between feeders in terms of:

- feeder length and conductor size (affecting R_{eq});
- variation in load distribution along the feeder over time (affecting R_{eq}); and
- variations in the load profile, the degree of 3-phase imbalance and levels of harmonic distortion (causing differences between a nominal mean current and the current actually present over time).

Figure 10 shows the same illustrative loss vs. load characteristic with I2R assessments for HV feeders, showing the broad type of the HV feeders. No significant pattern can be seen for underground feeders compared to feeders with some overhead component.

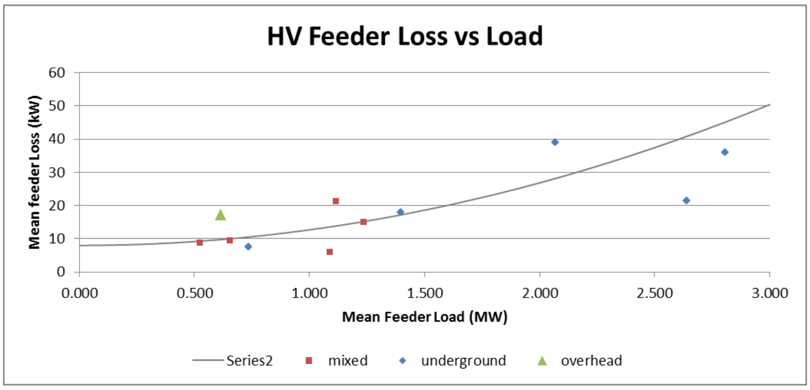

Figure 10 - Mean feeder loss vs mean feeder load for HV feeders using I2R Loss Assessment, showing broad feeder type

Figure 11 shows variation in Line Loss Factor (LLF) between feeders, compared to typical WPD values for the four LLF periods WPD uses[5]. The range of values shown here, although generally lower than the WPD nominal values, is beneficial to testing of the load estimation method that is already in-hand. Once the HV loss estimation process is applied to a wider sample of HV feeders, comparison to the nominal WPD LLF will again be made.

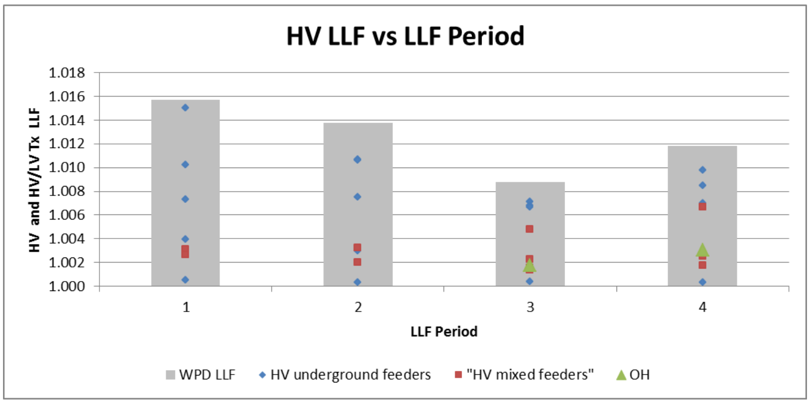

Figure 11 - Variation In Line Loss Factors for monitored HV feeders over the four LLF periods used by WPD

From the results available to date, it can be seen that the measured results broadly conform to expected feeder loss characteristics. They also show a reasonable range and variation that is important as a basis for producing a HV feeder loss estimation method. Key next steps are to demonstrate the existing draft HV feeder loss estimation method with a large sample number, possibly a grid-group set of HV feeders.

[5] LLF1 represents winter peak periods (Monday to Friday, November to February); LLF2 represents winter weekdays (Monday to Friday, November to February); LLF3 represents nights (all days and all months); and LLF4 represents other periods not included in LLFs 1-3.

2.4.2 Progress and next steps for LV feeders

Ongoing Loss assessments (both I2R and Power Difference) are now in place for all LV feeders, though available data for the last feeders to be completed is limited.

As with HV feeders, one way of providing an overview of results to date is to plot mean values of feeder load versus mean feeder loss. This can be seen in Figure 12 which shows mean feeder loss vs mean feeder load for LV feeders using both I2R and Power Difference assessments. An illustrative loss vs. load characteristic has again been drawn[6].

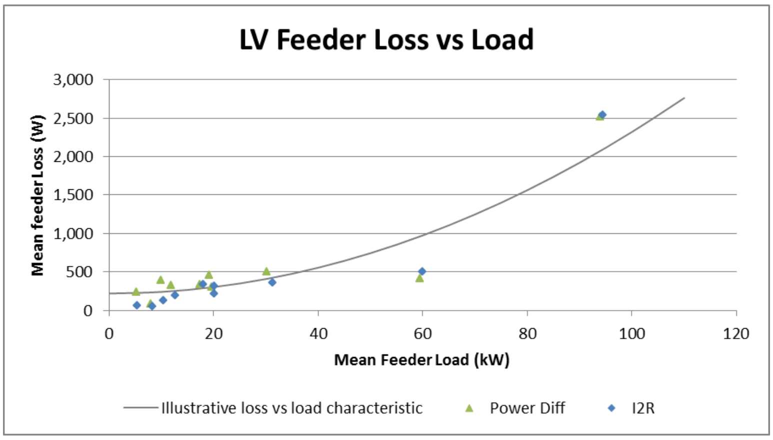

Figure 12 - Mean feeder loss vs mean feeder load for LV feeders using both I2R and Power Difference assessments

Generally it can be seen that the loss assessments conform to the illustrative characteristic (as would be expected) and that the Power Difference assessments are higher than the I2R assessments for most but not all the feeders. This difference is being investigated.

Figure 13 shows the same illustrative loss vs. load characteristic with I2R assessments for LV feeders, identifying the type of LV feeder. From this it can be seen that the industrial and commercial (I&C) feeders provide the most heavily loaded feeders (which vary further from the illustrated characteristic), but the examples of I&C feeders also have mean loading similar to domestic feeders, both underground and overhead.

[6] The illustrative characteristic for LV feeders takes the form $Loss = fixed\ metering\ loss + R_{eq} \times I^2$. The fixed meter loss is the power consumed by the meters, and is present at all loads, including minimum/no load. This is nominally seen as the y-axis intercept on the chart. R_{eq} and I are the same as for HV feeders (see Footnote 4.

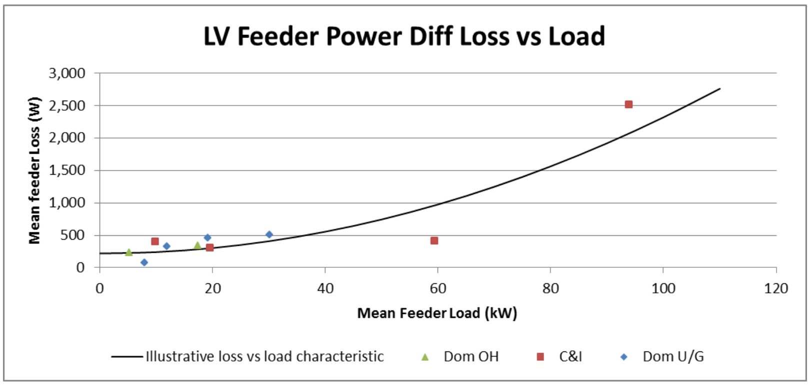

Figure 13 - Mean feeder loss vs mean feeder load for LV feeders using Power Difference Loss Assessment

Figure 14 shows variation in Line Loss Factor (LLF) between feeders, compared to typical WPD values for the four LLF periods WPD uses. For LLF Periods 3 and 4 it can be seen that monitored feeders have a range of values that span the WPD values, though in general are smaller. Winter related equivalent LLFs are only available for two underground domestic feeders, so cannot yet reasonably be compared.

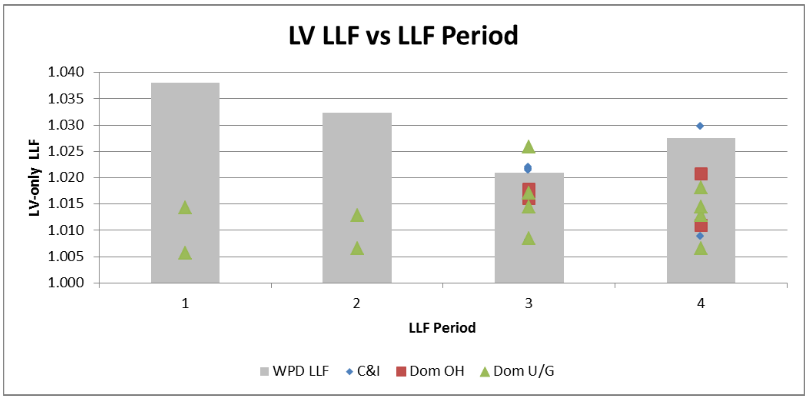

Figure 14 - Variation In Line Loss Factors for monitored LV feeders over the four LLF periods used by WPD.

From the results available to date, it can be seen that the measured results broadly conform to expected characteristics, and show a reasonable range and variation. Key next steps are to produce an estimation method that appropriately agrees with the loss assessments we are now generating. Initial efforts will focus on mimicking for IoM feeders the level of information we might have available for WPD LV feeders, and then apply a similar estimation methodology is working for the HV feeders. This is more complex than the HV feeders.

Further details of the LV loss assessments are contained in Appendix C 2.

2.5 Potential to reduce HV feeder losses by moving Normal Open Points

The potential to reduce losses by moving normal open points (NOPs) has previously been considered as a small part of WPD's FALCON project, and has also now been briefly considered under WPD's Losses Investigation Project.

Several of the trial HV feeders are interconnected at NOPs which break the meshed structure of the HV network into a radial configuration. In cases where the measurement trial includes feeders on both sides of the open point it is possible to simulate the losses that would have occurred if the open point had been moved to different positions on the network, thereby transferring load from one feeder to another.

Sample results from this project's investigation of the potential to reduce HV feeder losses through movement of NOPs are presented in Appendix D. A summary of finding is presented in Table 4.

Feeder	Average reduction in Losses by change to a preferred static NOP (using measured load data)	Average reduction in Losses with a change to a dynamically positioned NOP	Estimated annual Cost savings	Estimated annual reduction in CO2e emissions (tonnes)	Average reduction in Losses by change to a preferred static NOP (using estimated load data)
Amway Tongwell	14.7% (6.55kW to 5.59kW)	14.9%	£405	3.0	7.7kW to 7.3kW (10.8kW to 10.0kW for load model with known incorrect customer info)
Wavendon Gate	15.9% (43.3kW to 36.4kW)	No further improvement	£2,892	21.2	47.4kW to 40.0kW (47.2kW to 40.4kW for load model with known incorrect customer info
Newport Pagnell	3.9% (36.1kW to 34.7kW)	No further improvement	£599	4.4	Not examined

Table 4 – Summary of results from investigation of potential to reduce project HV feeder losses by moving NOPs

Evidence from both these investigations suggests that there is potential benefit from reviewing the current NOP positions on HV networks.

Estimated annual cost savings from (NOP-change) loss reductions, for three of the feeders being considered by the losses Investigation project, are £405, £2,892 and £599. This suggests:

- Modest per feeder savings are possible, though care would have to be exercised in the amount of investment/expenditure that would be economically viable to achieve the benefits (e.g. feeder identification/assessment/modelling and implementing any mitigating network automation/fault passage indication required);
- Over large numbers of feeders the cumulative savings might be material; but
- Significant variation in benefit may occur, and three feeders is not a sample number that can reasonably be projected from.

It should be noted that:

- This is not a saving to a DNO, but a saving to end consumers through further optimising network operation;
- Altering NOPs will change the available capacity on the feeders involved, and will change the numbers of customer connected to a feeder; however,
- Adverse changes to customer numbers on a feeder may occur, and might be mitigated through post-fault automated switching schemes based on fault passage indicators.

Both investigations suggest that the improvement arises through a change from the existing NOP to a preferred static NOP, i.e. there is little further benefit arising from having a dynamic NOP position that changes over peak/off-peak, weekday/weekend or summer/winter periods.

To identify preferred NOP positions and assess potential benefit, some form of modelling is necessary. This requires network data and a (per distribution substation) load model to allow power flow analysis to be iteratively performed. The FALCON project and the Losses Investigation project have tried different approaches to identifying the preferred open points and further consideration of the most cost-effective method would be required.

Loss assessments are reliant on a load model. The Losses Investigation work has shown that an estimated load model can be constructed that results in accurate feeder loss assessments, compared to loss assessments based directly on measured substation loads. Initial work of considering the robustness of these estimated load models for considering changes to NOP positions suggests that:

- Substation load estimation is based on connected customer information, and unsurprisingly errors in this have been found during the project.
- The load model data correctly identified the optimal new NOP position(s); and
- The assessments of loss reduction from estimated load models are in reasonable agreement with the assessments based directly on measured load.

Further work in this area will be undertaken throughout the remainder of this project.

3 Progress against Budget

3.1 Overview of Progress against Budget

Spend Area	Budget (£k)	Expected Spend to Date (£k)	Actual Spend to Date (£k)	Variance to Expected (£k)	Variance to Expected %
LV Feeder Monitoring	£496	£190	£150	£39	21%
HV Feeder monitoring	£1,007	£767	£763	£4	1%
Analysis	£425	£260	£260	£0	0%
Design & Project Management	£417	£247	£247	£0	0%
Contingency	£235	£0	£0	£0	0%
Total	£2,580	£1,463	£1,420	£44	3%

Table 5 - Progress Against Budget

3.2 Comments around variance

1. Variance to Expected Spend for LV feeder monitoring is due to Invoicing for recently completed work yet to be issued.

4 Progress towards Success Criteria

At inception, the project identified five success criteria. These criteria are listed in Table 6 with commentary on progress towards completion.

Project Success criteria	Commentary on progress
1) Construction of fully monitored HV and LV networks	**Construction is now complete.** All required monitoring is now installed on the 11 HV feeders. This includes monitoring at 7 primary substations, 58 pole-mounted transformers 18 HV-customer supply substations and 116 ground-mounted transformer distribution substations. All required monitoring is now installed on the 11 LV feeders. This includes 288 single phase meters, 47 three-phase meters, 13 ground-mounted LV feeder monitors and 2 pole-mounted LV feeder monitors.
2) Measurement of network losses on monitored feeders	**Ongoing loss assessments based on full monitoring data are now available for all HV and LV feeders**. This includes both loss assessment via a Power Difference method (measurement of network losses), and assessment via an I2R method (accurate modelling of the feeders). A snapshot of the Loss assessments for these feeders is shown in Appendix C.
3) Accurate modelling of losses with full information	
4) Several models with limited data sets created and tested	The following progress was reported at the last 6 month report - Various approaches to estimating feeder specific losses have been considered and tested to date. For HV feeders, a preferred approach has been developed that delivers high degrees of agreement to monitoring data assessments. Details of this are described in Appendix D. For LV feeders, initial assessment of key similarities and differences to the successful HV approach has been made. Work on an LV approach is ongoing.
5) Conclusion on level of information needed to accurately predict losses	The following progress was reported at the last 6 month report - Draft Conclusions on the level of information required for HV feeders are available (Appendix D), and will continue to be tested as all HV feeders provide data and representative data for all seasons becomes available. Conclusions on LV feeder specific loss estimation will follow.

Table 6 - Progress towards project Success Criteria

5 Learning Outcomes

Learning during this reporting period has continued to be of a detail-orientated nature and primary associated with calculations. Selected learning from the period is noted in Table 7.

A paper was presented by Loughborough University staff at the CIRED 2017 conference in Glasgow, entitled "Accurate determination of distribution network losses". This compares the power difference and I2R methods of loss calculation and demonstrates that the results from the I2R method are much less vulnerable to errors due to sensor tolerances than the results from the power difference method. The paper can be accessed at https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/25519.

Area of Learning	Learning
Loss calculations	• Calculations of percentage losses need to take account of the possibility of embedded generation from downstream nodes connected to the feeder and also allow for a net export of power from the feeder to the upstream substation. Taking the example of an HV feeder, the percentage losses are now expressed relative to the total power imported into the network, either from the primary substation, or from any of the downstream distribution substations. This metric reflects the high efficiency of the feeder network in cases where the power input from embedded generation matches adjacent power outputs to loads
Instrumentation	• Accuracy tests of the logging instruments at Manx Utilities have demonstrated slight differences in the active and reactive power as recorded by the EDMI smart meter, the GridKey loggers, and an Outram PM7000 used as a high-resolution reference. When values recorded by multiple instruments are compared, both a scaling factor and zero offset need to be applied. None of the instruments has been found to be operating outside of their specified accuracy tolerances, but the small observed differences have the potential to affect loss calculations using the power difference method. Differences in the zero offset values would be particularly visible in power difference calculations at low loads. • The time resolution of the measurement data has been found to introduce inaccuracies into the loss calculations for periods when the phase angle of the load currents is rapidly changing. This occurs rarely, but causes errors in the calculations when the direction of active power flow changes within the 1-minute measurement averaging periods, such as when cloud cover variations affect the net output from substations with solar PV generation. The error arises because the current is represented in the analysis as a vector with the amplitude given by the measured average current amplitude, and the phase angle given by the measured average complex power. This differs from the average current vector if the phase angle changes.

Area of Learning	Learning
Instrumentation (continued)	• Measurements of the current amplitude by the GridKey loggers are also affected by the use of signed current amplitude data in the averaging algorithm. A negative sign is applied to the current amplitude to indicate reverse power flow. The aggregation of a period with both forward and reverse active power flow can therefore result in the average current amplitude being recorded as zero.
HV feeder losses	• Losses for the HV trial feeders are broadly consistent with the mean losses indicated in the 2008 E.ON Loss Calculation Study. The HV cable losses for the trial are mostly lower than figures from the study but the distribution transformer load losses are generally higher. The loss study used different assumptions for the transformer parameters and had predicted higher no-load losses than are indicated by the rated iron losses for the transformers on the trial feeders. • The losses for all of the HV trial feeders are lower than the losses for the HV feeder and distribution transformers stages included in the generic LLF calculations. A review of the spreadsheet used to calculate the generic LLFs shows that the factor used to define distribution substation no-load losses is approximately double the equivalent no-load loss factor derived from the rated iron losses that is used in the trials calculations. The reasons for this difference will be investigated further. • The loss factor used in the generic LLF calculations to define the load-dependent cable and overhead line losses is also higher than the corresponding losses observed on all of the HV trial feeders. This difference will be investigated for a wider range of feeders by comparing losses calculated using the estimation method with the generic LLF figures. • The HV loss analysis has been verified against simulations using IPSA power-flow analysis. This provides further confidence in the loss calculations using the I2R method. • The HV loss estimation method has been developed further such that this could use IPSA data file to define the network topology. IPSA does not directly model transformer no-load losses and so additional elements need to be added to the schematic in order to fully represent the losses.

Area of Learning	Learning
HV feeder losses (continued)	• HV feeders with multiple overhead sections can have phase reversals and rotations. Power-flow analysis of the network does not predict the primary substation current amplitude correctly if the phase connectivity is not accurately represented in the model. The HV loss analysis software has been extended to assist in identifying the correct connectivity at each junction node. Methods tested include correlation of the primary and substation HV voltages and also correlation of the differences between measured and simulated primary substation current with the HV load current from each distribution substation. These methods provide guidance in identifying the correct connectivity but are not yet 100% reliable. • Losses on HV feeders can be reduced by changes in the NOP location. Three inter-connected feeders have been studied, demonstrating scope to reduce the combined losses of the paired feeders by 14.7%, 15.9% and 3.9%. This corresponds to an annual cost saving of £405, £2892, and £599 for the three feeders.
NOP position and reductions in HV feeder loss	• For the three feeders studied for NOP position, nearly all of the potential benefit is realised by a one-off movement of the NOP location, with little further reduction in losses if the NOP location were to be optimised on a half-hourly basis. • In two of the studied NOP position cases the majority of the loss reductions could be achieved using an NOP location on substations near to the optimal network node. This provides some degree of flexibility if the optimal location cannot be selected for operational reasons. • Simulations using the HV loss estimation method with half-hourly demand data have provided similar results to those obtained using the trials measurement data. This suggests that reductions in losses can be predicted without requiring the high resolution trials measurements. • Results using the estimation method are dependent on the quality of the input data describing the assignment of metered demand data to distribution substations. For the examples studied here, these load configuration errors did not compromise the determination of the optimal NOP locations but, for one feeder, the potential scope cost saving and carbon emissions reductions were significantly under-estimated.

Area of Learning	Learning
LV feeder losses	• Losses for the LV trial feeders are generally lower than the mean losses indicated in the 2008 E.ON Loss Calculation Study. There is a range of losses between 0.2% and 2.6% and this spread is consistent with the predicted wide spread of percentage losses in the E.ON study. • The losses for the trial LV feeders are generally lower than the losses for the LV distribution stage included in the generic LLF calculations. However, feeders recently included in the trials (and so far with only a few months of measurement data) have higher losses than the earlier trial feeders so this disparity may be reduced when the winter period is included in the measurement data. • A review of the generic LLF has shown that these included a no-load loss for the LV feeders that is approximately consistent with the metering losses that have been included in the I2R loss calculations for the trial feeders. • The standing losses due to the smart meters are likely to be lower than previously assumed. Smart meter vendor EDMI has provided test results showing power consumption of 1.1 W and 4 VA per single-phase meter and this is consistent with lab tests. This updated information reduces the calculations of LV losses which had previously used limits based on standards rather than actual test values. • Following the adoption of lower values for the metering losses, the trials measurements generally demonstrate an increased disparity between losses calculated based on the power difference method and losses calculated using the I2R method. The cause of this difference is thought to be due to zero offsets in the measurement instrumentation. Although these offsets are small (typically less than 2 W per customer connection), the cumulative impact is noticeable in the results from the power difference method. • Loss calculations using the I2R method are known to be under-estimated due to the smoothing impact of the 1-minute averaging used by the measurement data logging instruments. This particularly affects the LV loss calculations where the demand is less aggregated and therefore has more spikey variations. A method has now been developed such that the recorded maximum and minimum current within the 1-minute averaging periods can be used to calculate an approximate upper bound to the actual losses. The results indicate that the actual losses for three of the LV feeders analysed so far could be up to 9% higher than the I2R calculations suggest.

Area of Learning	Learning
LV feeder losses (continued)	• The phase allocation of single-phase service connections can be detected using a voltage correlation method. This compares the voltage measured on each phase at the substation with the voltages measured at the single-phase customer connection. Phase allocations identified by this process have been found to match reliably with the phase allocations determined by on-site phase tracing tests on the trials feeders. • Measurements on one of the LV trial feeders have demonstrated that the neutral current at a link box is non-zero and follows a similar diurnal profile as the phase currents on the feeder. This demonstrates that it cannot necessarily be assumed that all of the neutral current due to unbalance on the phase conductors returns to the substation by the same cable route. Further investigation will be required in order to characterise the extent to which the measured neutral currents are inconsistent with the assumed approximation that the feeders can be modelled by a radial equivalent circuit.

Table 7 - Illustrative and key learning

6 Intellectual Property Rights

A complete list of all background IPR from all project partners has been compiled. The IP register is reviewed on a quarterly basis.

7 Risk Management

Our risk management objectives are to:

- Ensure that risk management is clearly and consistently integrated into the project management activities and evidenced through the project documentation;
- Comply with WPDs risk management processes and any governance requirements as specified by Ofgem; and
- Anticipate and respond to changing project requirements.

These objectives will be achieved by:

- ✓ Defining the roles, responsibilities and reporting lines within the Project Delivery Team for risk management;
- ✓ Including risk management issues when writing reports and considering decisions;
- ✓ Maintaining a risk register;
- ✓ Communicating risks and ensuring suitable training and supervision is provided;
- ✓ Preparing mitigation action plans;
- ✓ Preparing contingency action plans; and
- ✓ Monitoring and updating of risks and the risk controls.

7.1 Current Risks

The Losses Investigation Risk Register is a live document and is updated regularly. There are currently eight live project related risks. Mitigation action plans are identified when raising a risk and the appropriate steps then taken to ensure risks do not become issues where reasonably possible. Table 8 provides details of the project's top five current risks. For each of these risks, a mitigation action plan has been identified and the progress of these are tracked and reported.

Details of the Risk	Risk Rating	Mitigation Action Plan	Progress
Overall losses assessment methodology has uncertainties that are too large for the intended purpose.	Moderate	• Adoption of Pilot approach. • Retention of both power difference and I2R calculation methods. • Review of differences between the loss assessment of the two calculation methods	• The successful pilots largely mitigated this risk, and as each feeder is checked with initial data, the risk of material impact diminishes further. • Possible causes of differences between the loss assessment methods are currently being further examined.
Unavailability of Distribution Transformer parameters /insufficiency of type values for loss assessment.	Minor	• Retention of both power difference and I2R calculation methods as a cross-check to identify if transformer values are material issues.	• Whilst differences do exist between power difference and I2R values, they are not sufficiently large to threaten findings from the project. Work on establishing and validating transformer parameters/ assumptions continues.
Time synchronisation of data available from different field devices is not adequate.	Minor	• Adoption of Pilot approach. • Ongoing review of accumulated data.	• Time synchronisation of data sources is probably only to ±5 seconds. This does cause some noise in current balance and power diff loss assessments, but does not affect the average loss values being arrived at. • Will be reviewed on an ongoing basis
Accuracy/detailed operation of measurement devices proves inadequate for the intended purpose.	Minor	• Adoption of Pilot approach. • Review of differences between the loss assessment of the two calculation methods	• Possible causes of differences between the loss assessment methods are currently being further examined.
Captured EDMI meter data cannot be adequately transmitted to a central data store for required roll out	Minor	• Project plan always included the implementation of a volume meter data collection system. • Collaborative testing	• Volume data collection system is now undergoing final testing.

		of the proposed system.	

Table 8 - Top five current risks (by rating)

Figure 15 provides a snapshot of the risk register, detailed graphically, to provide an on-going understanding of the projects' risks.

Likelihood = Probability x Proximity						
	Certain/Imminent (21-25)	0	0	0	0	0
	More likely to occur than not/Likely to be near future (16-20)	0	0	0	0	0
	50/50 chance of occuring/ Mid to short term (11-15)	0	0	0	0	0
	Less likely to occur/Mid to long term (6-10)	0	2	0	0	0
	Very unlikely to occur/Far in the future (1-5)	0	3	2	0	1
		1. Insignificant changes, re-planning may be required	2. Small Delay, small increased cost but absorbable	3. Delay, increased cost in excess of tolerance	4. Substantial Delay, key deliverables not met, significant increase in time/cost	5. Inability to deliver, business case/objective not viable
		Impact				

	Minor	Moderate	Major	Severe	
Legend	7	1	0	0	**No of instances**
Total	8				No of live risks

Figure 15 - Snapshot of Risk Register

Figure 16 provides an overview of the risks by category, minor, moderate, major and severe. This information is used to understand the complete risk level of the project.

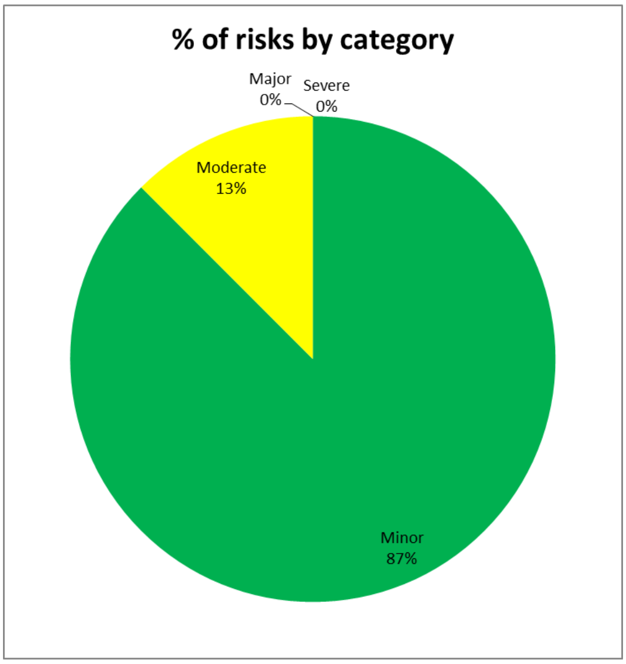

Figure 16 - Graphical view of Risk Register by Risk Category

8 Consistency with Project Registration Document

The scale, cost and timeframe of the project has remained consistent with the current registration document >>following this link[7]<<.

9 Accuracy Assurance Statement

This report has been prepared by the Losses Investigation Project Manager (Chris Harrap), reviewed and approved by the Future Networks Manager (Roger Hey).

All efforts have been made to ensure that the information contained within this report is accurate. WPD confirms that this report has been produced, reviewed and approved following our quality assurance process for external documents and reports.

[7] http://www.smarternetworks.org/NIA_PEA_PDF/WPD_NIA_005_3145.pdf

Appendix A Loss Assessment Pilots

Appendix A 1 Pilot phase conclusions and recommendations

The pilot phase of the project generated the following conclusions and recommendations:

- Both HV and LV feeders can credibly be assessed for technical losses, using the implemented reasonably available devices, data collection and data processing arrangements.
- The loss analysis using the I2R method has a low uncertainty. It is therefore recommended that this method be the primary method to be used for the loss analysis, rather than the power difference method.
- It is also recommended that the additional measurement devices required for the power difference method are maintained. These devices enable consistency checking of the I2R data, which has proven to be valuable in detecting additional connected loads that would otherwise not be included in the loss analysis.
- Comparisons of assessed losses to other indicators of UK network loss have been demonstrated. These show that the assessed losses on both the HV and LV pilot feeders are less than might have been expected. Further work is underway within the project around this finding.
- It is recommended that the demonstrated devices and preferred processes are rolled out to a selection of HV and LV feeders, in-line with the original project intention, to provide a detailed loss information-set for both HV and LV feeders.

Appendix A 2 Overview of Pilot Implementation

Pilot monitoring has been installed on an HV feeder at Milton Keynes in the WPD East Midlands license area. The upstream power flow on the monitored network is measured at a 33/11kV Primary Substation, and the downstream power flows on this network are monitored with equipment installed at each of the Distribution Substations served by the feeder. The Primary Substation monitoring is provided by a new (HV variant) of Gridkey's MCU 520 substation monitoring equipment. The downstream sensors (established Gridkey MCU 520 LV monitoring devices) are installed on the LV side of the distribution transformers. The end-to-end losses measured in this trial therefore include the 11 kV feeder cable and the 11 kV to LV Distribution Substations.

The LV pilot trial uses a network in the Isle of Man where monitoring equipment has been installed on one LV feeder. Upstream power flow to the LV feeder is monitored on the LV side of the Distribution Substation (using established Gridkey Distribution Substation monitoring), and advanced meters (of a type not previously used in the Isle of Man) are installed at each of the 13 customer connections on this feeder to monitor downstream power flow. Of the 13 connections, 11 connections supply domestic customers and the other 2 connections serve public lighting circuits.

Collectively, the HV and LV pilot trials therefore provide an end-to-end loss measurement that is representative of the distribution networks between the Primary Substations and the customer.

The measurement data is stored as one minute averages within the monitoring equipment and then collected periodically by GPRS-based data connections. For the advanced meters, the number of measurement parameters (e.g. power, voltage, current, averages, maximums, minimums etc.) and the selected time resolution of the measurement data defines the volume of data collected and requiring transmission. This volume is constrained by the memory size within the instruments and the time/resource needed to download the data. For both the HV and LV pilot trial, 1 resolution of 1 minute has been selected, so as to minimise any errors in estimating the losses due to under-sampling the time variation of the demand. The number of meter measurements points has been consequentially selected to make maximum use of device memory.

The collected data has been forwarded to Loughborough University for analysis of the losses. Two loss analysis methods have been used: 1) estimation of the losses based on the power difference between the single upstream power flow and the total downstream power flows on the network and 2) estimation of the losses using an I2R calculation primarily based on current measurements at each downstream point on the networks. Additional information is needed for use with the I2R method in order to specify the resistance of each network branch and to define the connection topology such that the currents on the un-monitored branches within the network can be calculated. The load losses and no-load losses of the transformers must also be specified. Significantly difference tolerances in assessed losses arise from the two different methods, the I2R method having lower (better) tolerances.

The mean end-to-end losses in the HV feeder over a 27 day period in March/April 2016 (with >99% data availability) have been estimated using the I2R method as 1.23% of the delivered power. An uncertainty of ±0.06% of the delivered power or ±5% of the mean losses applies to this estimate.

The losses for each 1 minute sample in the HV pilot period are shown in Figure 17. As expected, the losses vary with the demand, and also with the distribution of load along the feeder (such that higher losses occur if the demand is greater for substations that are electrically further along the feeder). The levels of unbalance for the HV trial feeder were low, particularly for higher demands, and so unbalance made little contribution towards increasing the losses.

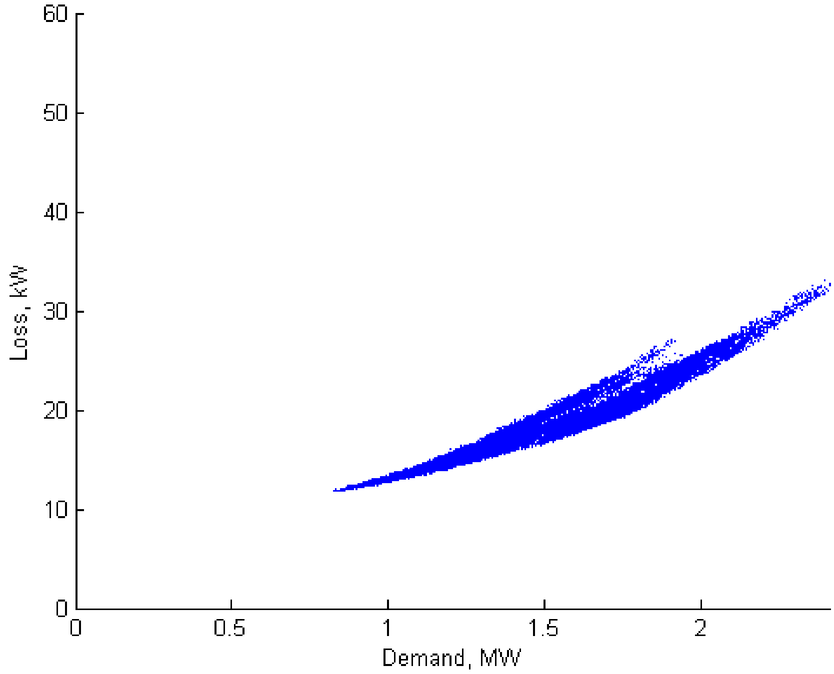

Figure 17 - Pilot HV feeder losses for each 1 minute sample calculated with I2R method

Using the I2R method, the losses from the HV trial can be calculated separately for the HV feeder cable and for the Distribution Substations. The mean losses in the HV cable were estimated as 0.26% of the delivered power (line loss factor of 1.0026), a figure that is approximately one quarter of the losses indicated by the generic line loss factors from the WPD schedule of charges (around 1%). A previous loss study also suggested a higher figure (0.69%). Over the measured period, the losses for the HV feeder cable, which is believed to have typical levels of demand, were therefore much lower than previous estimates would suggest. It should be emphasised that this is a single feeder finding, and wider conclusions should not be drawn.

The mean losses for the distribution transformers on the HV trial feeder were calculated as 0.97% of the delivered power (line loss factor 1.0098). This is approximately half of the losses predicted by the generic line loss factors (around 2%) but consistent with the estimates from the previous loss study (1.11%).

The mean losses for the LV trial over a 10 day period in April/May 2016 (with data availability >99%) were calculated using the I2R method as 0.21% of the delivered power (line loss factor 1.0021). An uncertainty of ±0.02% of the delivered power or ±10% of the mean losses applies to this estimate. The individual loss estimates have a much greater variation than those for the HV trial feeder, with differences due to the changes in the three-phase balance and in the electrical distance of the demand along feeder as individual customer loads switch on and off. The variation in the losses for individual 1 minute samples during the pilot period is shown in Figure 18.

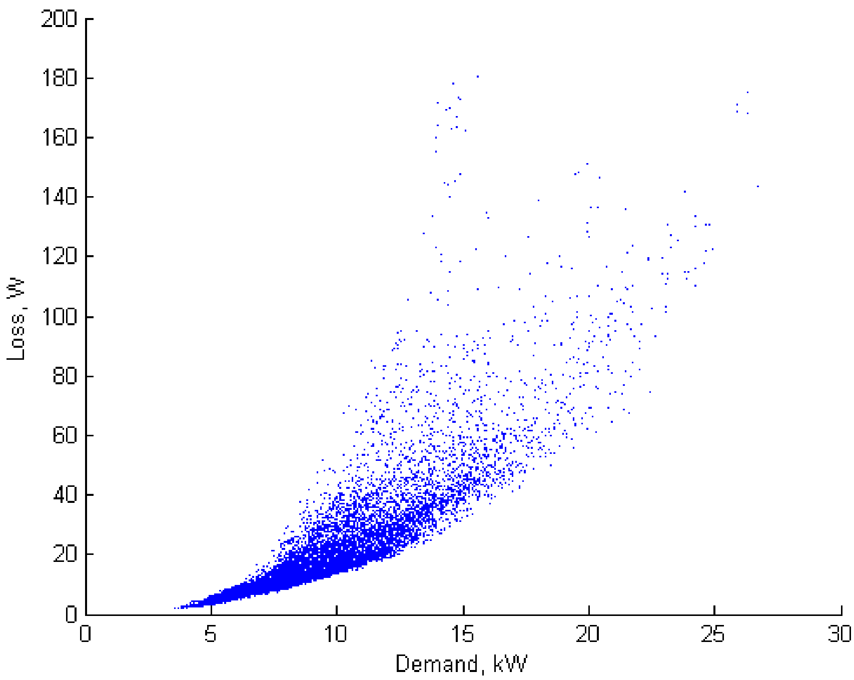

Figure 18 - Pilot LV feeder losses for each 1 minute sample calculated with I2R method

The mean losses were very much lower than previous LV network estimates with the generic line loss factors suggesting over 2% (although these figures also include non-technical losses) and a previous loss study suggesting 1.29%. The LV trial feeder may have unusually low losses as the cable between the substation and the nearest customer connection is relatively short and has a large conductor size (300 mm^2) considering the routinely connected load.

The loss analysis method has also been able to highlight inconsistencies in the network database, correctly identifying one connection point that was recorded as being on the wrong phase and also that the initial network data had omitted a customer connection.

Figure 19 compares the loss calculations from the power difference and the I2R method for the LV trial feeder. For both the HV trial feeder and the LV trial feeder, losses calculated using the power difference method are subject to much wider tolerances. For the power difference method, the tolerance on assessed loss is based on uncertainty in the measured power (i.e. modest percentages of large numbers), whereas the tolerance on assessed loss for the I2R method is based on calculated component losses (i.e. modest percentages of small numbers). Therefore the I2R method of loss calculation is fundamentally very much less sensitive to the same intrinsic instrument tolerances.

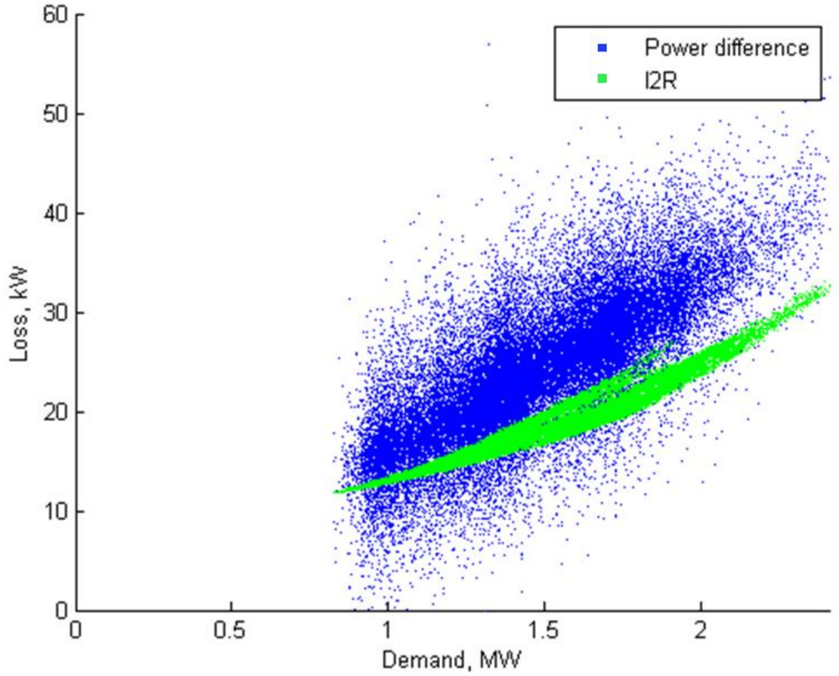

Figure 19 - Pilot HV feeder losses for each 1 minute sample calculated with the power difference method and with the I2R method

Appendix B Overview of monitored feeders

Appendix B 1 Overview of HV monitored feeders

Feeder	Overview	Detailed Feasibility	Primary Sub work	Secondary Sub work	Data Available
***Pilot feeder** - 940037-02 (Marlborough Street: The Woodlands)*	*UG2A, 4.8km. 11 GM Subs.*	*Complete*	*Complete*	*Complete.*	*Yes*
940043-03 (Fox Milne: Fox Milne Hotel)	UG2B, 13.3km. 16 GM Subs.	Complete	Complete	Complete.	*Yes*
940046-03 (Wavendon Gate: Wavendon Gate Local)	UG1B, 2.1km. 8 GM Subs.	Complete	Complete	Complete.	*Yes*
940046-08 (Wavendon Gate: Secondary School Walnut Tree)	UG2A, 8.5km. 13 GM Subs, 2 HV sites.	Complete	Complete	Complete.	*Yes*
940041-10 (Newport Pagnell: Howard Way Tee Crawley Road)	UG1A, 3.8km. 3 GM Subs, 3 HV sites.	Complete	Complete	Complete.	*Yes*
940041-08 (Newport Pagnell: Amway Tongwell)	MA1A, 19% OH, 2.4km. 4 GM Subs, 7 HV sites.	Complete	Complete	Complete.	*Yes*
940041-09 (Newport Pagnell: Ackerman Tongwell Tee Aldrich Drive)	MB1A, 29% OH, 8.3km. 7 GM Subs, 4 PM sites.	Complete	Complete	Complete.	*Yes*
940041-04 (Newport Pagnell: Riverside Park)	MA2A, 10% OH, 8.6km. 12 GM Subs, 2 HV sites, 7 PM sites.	Complete	Complete	Complete.	*Yes*
940046-02 (Wavendon Gate: The Avenue)	MB2A, 37% OH, 12.0km. 8 GM Subs, 2 HV sites, 11 PM sites.	Complete	Complete	Complete.	*Yes*
940036-11 (Wolverton: Energy from Waste RMU C))	MC1B, 76% OH, 15.7km. 7 GM Subs, 1 HV site 14 PM sites.	Complete	Complete	Complete.	*Yes*
940045-04 (Olney: Silver End Olney)	OH1B, 87% OH, 23.9km. 8 GM Subs, 22 PM sites.	Complete	Complete	Complete.	*Yes*

Table 9 - Overview of HV monitored feeders

Appendix B 2 Overview of LV monitored feeders

Feeder	Overview	Feasibility & Modelling Info	Secondary Sub work	Meter work	Data Available
Pilot feeder – around Douglas	*277m u/g mains cable* *187m u/g service cable* *13 – 1ϕ*	*Complete*	*Complete*	*Complete.*	*Yes*
Dom#1 – Laxey	770m u/g mains cables 1054m u/g service cables 57 - *1ϕ*	*Complete*	*Complete*	*Complete.*	*Yes*
Dom#2 - Ramsey	431m u/g mains cables 742m u/g service cables 53 - *1ϕ + 1 – 3 ϕ*	*Complete*	*Complete*	*Complete.*	*Yes*
Dom#3 – Tromode	794m u/g mains cables 885m u/g service cables 56 - *1ϕ*	*Complete*	*Complete*	*Complete.*	*Yes*
I&C#1 – Peel Feeder A	383m u/g mains cables 159m u/g service cables 9 - *3ϕ*	*Complete*	*Complete*	*Complete.*	*Yes*
I&C#1 – Peel Feeder B	408m u/g mains cables 189m u/g service cables 8 - *3ϕ* + 12 - *1ϕ*	*Complete*	*Complete*	*Complete.*	*Yes*
I&C#2 – Ballasalla	426m u/g mains cables 357m u/g service cables 6 - *1ϕ + 11 - 3ϕ*	*Complete*	*Complete*	*Complete.*	*Yes*
I&C#3 – Braddon	484m u/g mains cables 118m u/g service cables 8 - *1ϕ +11 - 3ϕ*	*Complete*	*Complete*	*Complete.*	*Yes*
OH#1 – Santon o/h	89m u/g mains, 289m OW mains 183m u/g, 114m o/h services 16 – *1ϕ*	*Complete*	*Complete*	*Complete.*	*Yes*
OH#2 – Abbeylands	368m u/g mains, 546m ABC, 173m OW mains 488m services 26 - *1ϕ + 4 - 3ϕ*	*Complete*	*Complete*	*Complete.*	*Yes*
OH#3 – Ramsey OH	337m u/g mains, 393m OW mains 882m services 48 - *1ϕ* + 1 - *3ϕ*	*Complete*	*Complete*	*Complete.*	*Yes*

Table 10 - Overview of LV monitored feeders

Appendix C Ongoing Loss Assessments

Appendix C 1 HV feeders

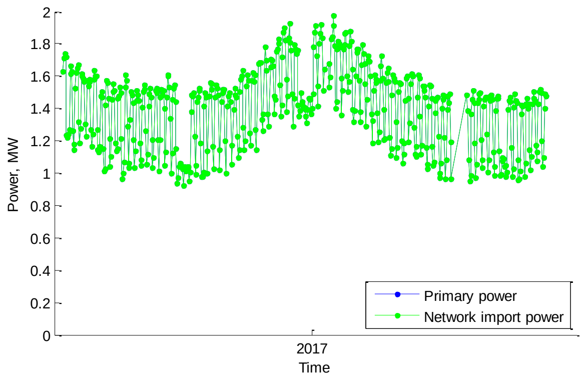

Figure 20 - Long term mean daily feeder demand (Woodlands HV feeder)

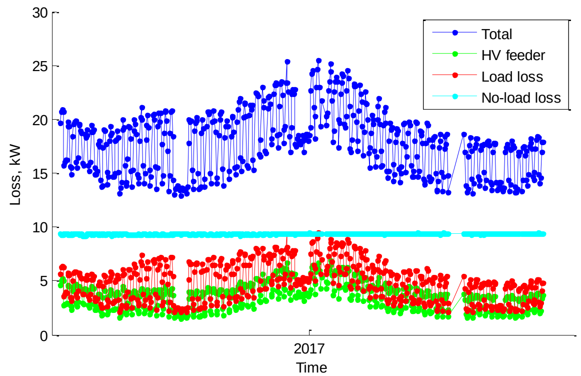

Figure 21 - Long term mean daily (I2R) loss (Woodlands HV feeder)

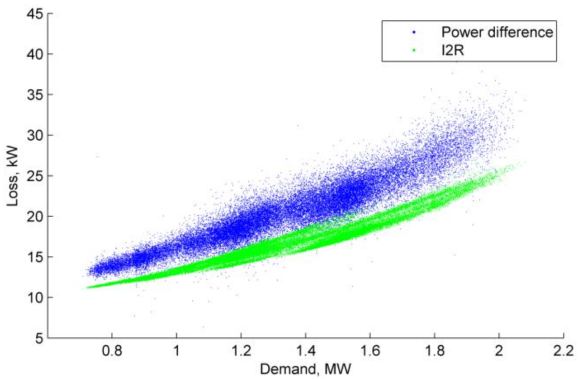

Figure 22 - September 2017 Loss, kW vs demand (Woodlands HV feeder)

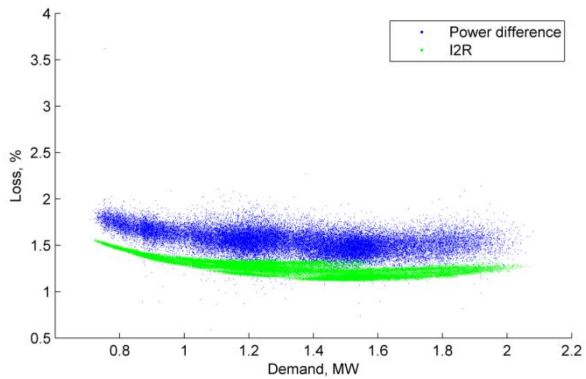

Figure 23 - September 2017 Loss, % vs demand (Woodlands HV feeder)

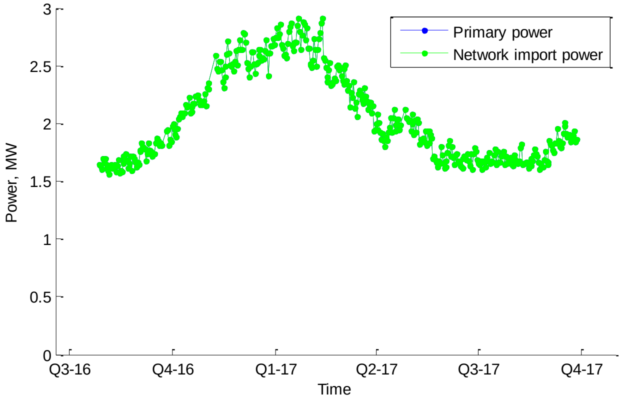

Figure 24 - Long term mean daily feeder demand (Fox Milne Hotel HV feeder)

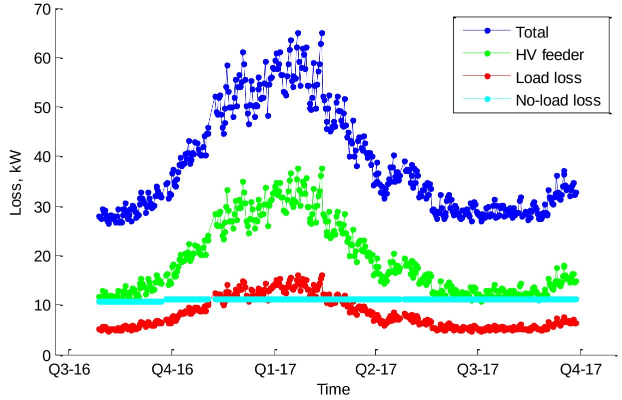

Figure 25 - Long term mean daily (I2R) loss (Fox Milne Hotel HV feeder)

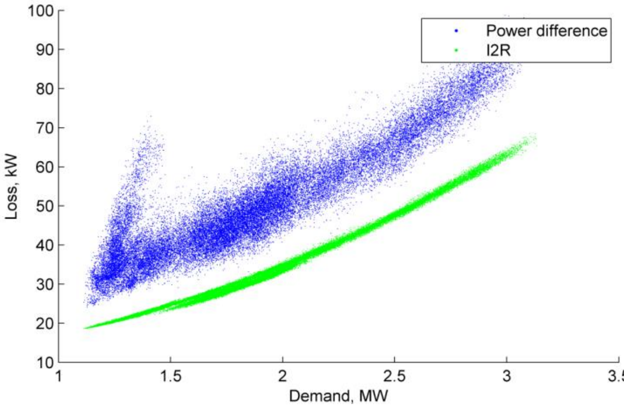

Figure 26 - September 2017 Loss, kW vs demand (Fox Milne Hotel HV feeder)

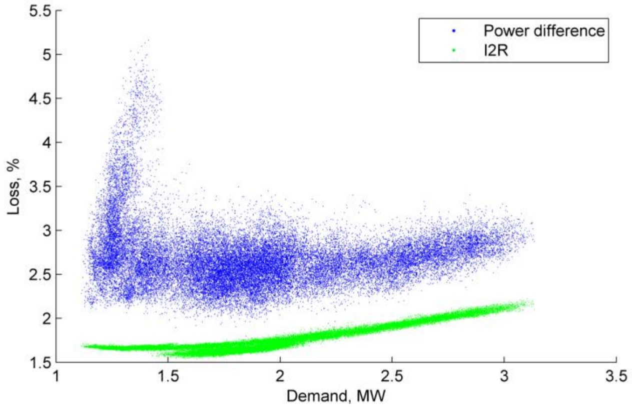

Figure 27 - September 2017 Loss, % vs demand (Fox Milne Hotel HV feeder)

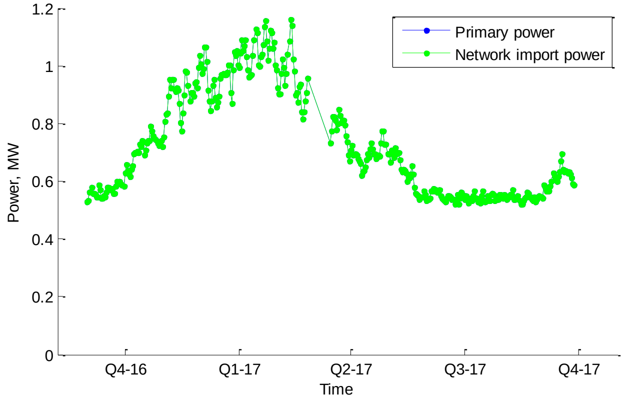

Figure 28 - Long term mean daily feeder demand (Wavendon Gate Local HV feeder)

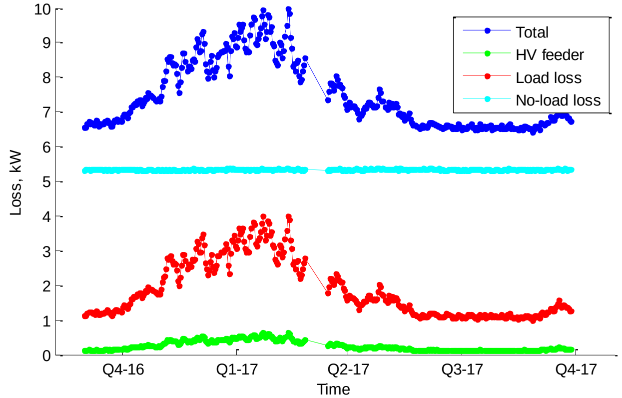

Figure 29 - Long term mean daily (I2R) loss (Wavendon Gate Local HV feeder)

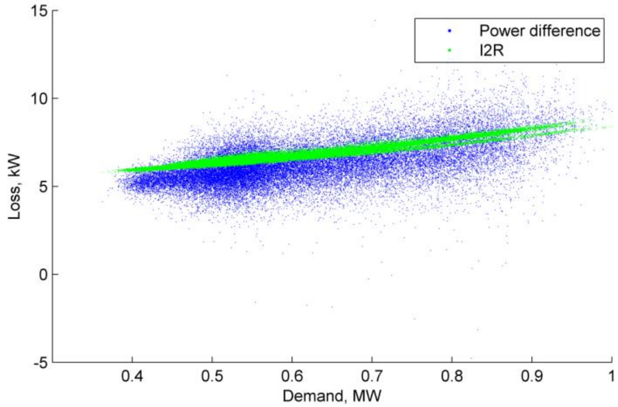

Figure 30 - September 2017 Loss, kW vs demand (Wavendon Gate Local HV feeder)

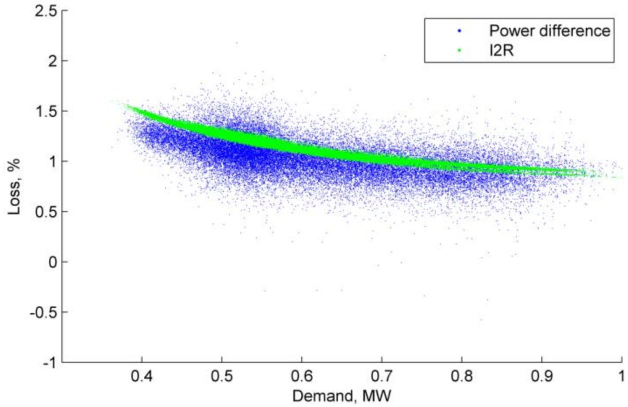

Figure 31 - September 2017 Loss, % vs demand (Wavendon Gate Local HV feeder)

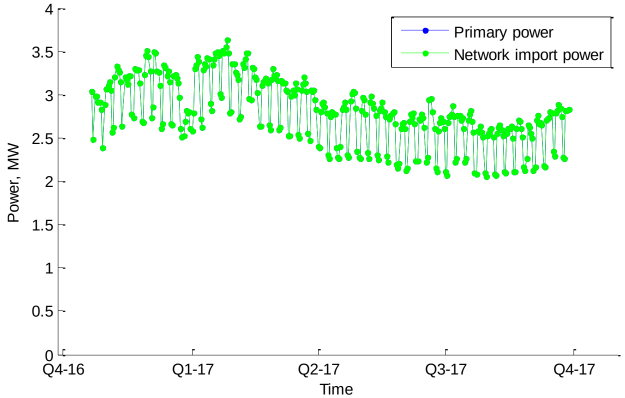

Figure 32 - Long term mean daily feeder demand (Secondary School Walnut Tree HV feeder)

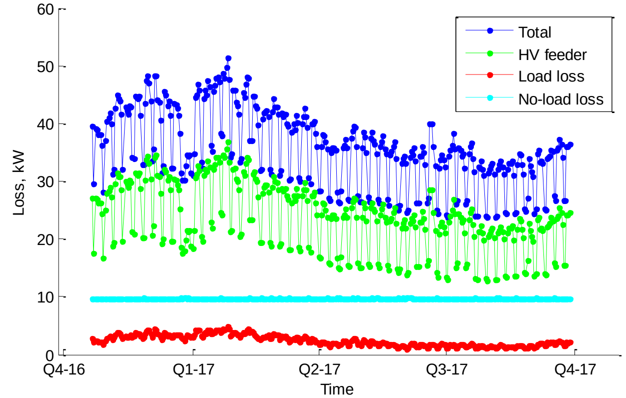

Figure 33 - Long term mean daily (I2R) loss (Secondary School Walnut Tree HV feeder)

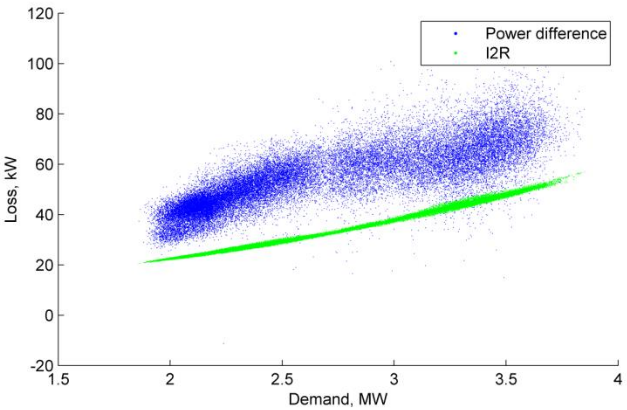

Figure 34 - September 2017 Loss, kW vs demand (Secondary School Walnut Tree HV feeder)

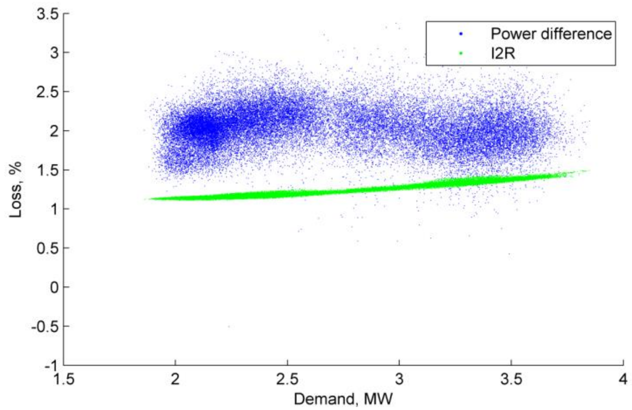

Figure 35 - September 2017 Loss, % vs demand (Secondary School Walnut Tree HV feeder)

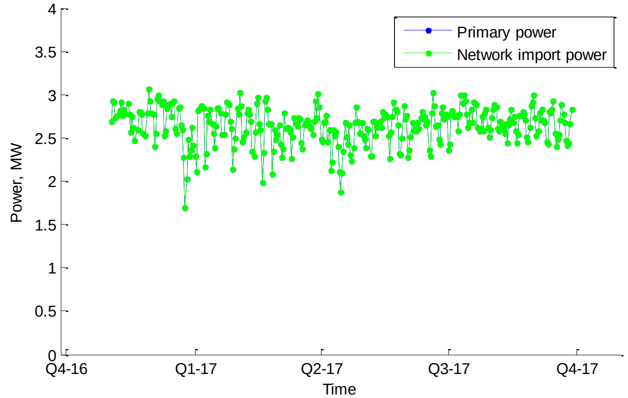

Figure 36 - Long term mean daily feeder demand (Crawley Road Tee Howard Way HV feeder)

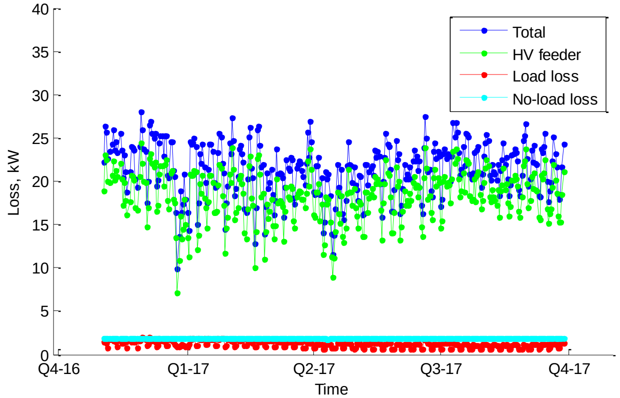

Figure 37 - Long term mean daily (I2R) loss (Crawley Road Tee Howard Way HV feeder)

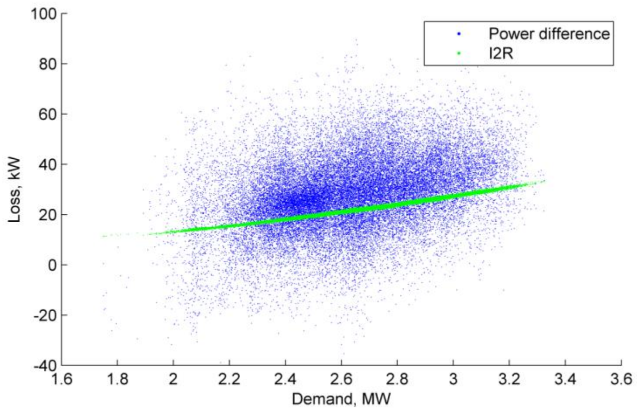

Figure 38 - September 2017 Loss, kW vs demand (Crawley Road Tee Howard Way HV feeder)

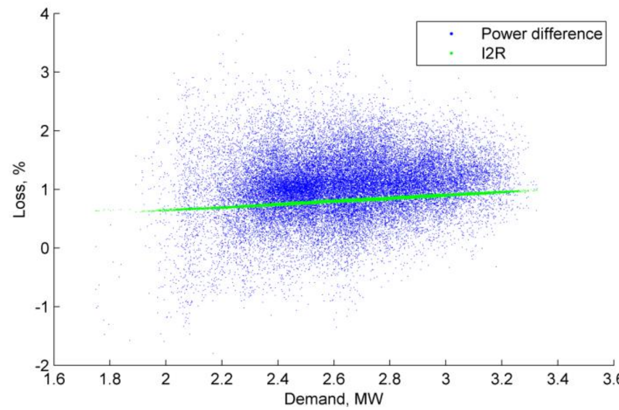

Figure 39 - September 2017 Loss, % vs demand (Crawley Road Tee Howard Way HV feeder)

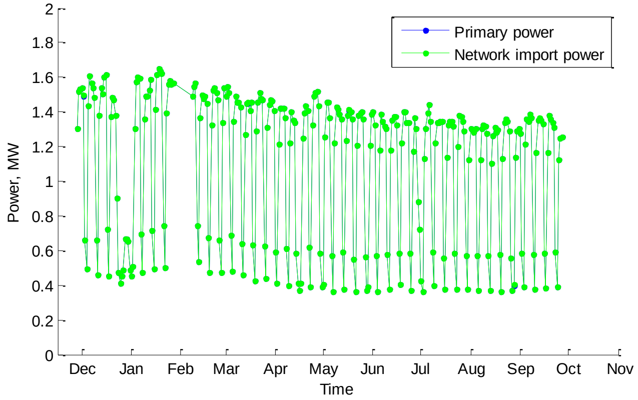

Figure 40 - Long term mean daily feeder demand (Amway Tongwell HV feeder)

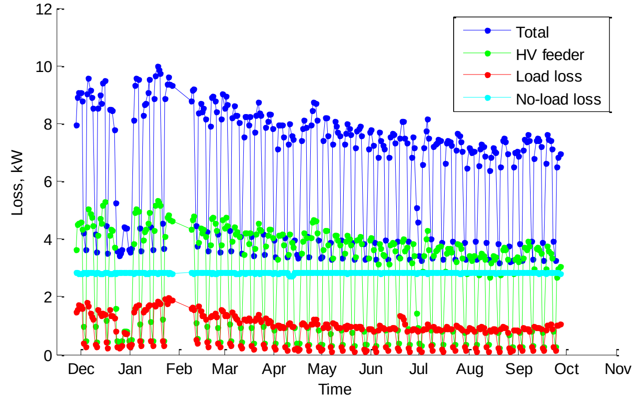

Figure 41 - Long term mean daily (I2R) loss (Amway Tongwell HV feeder)

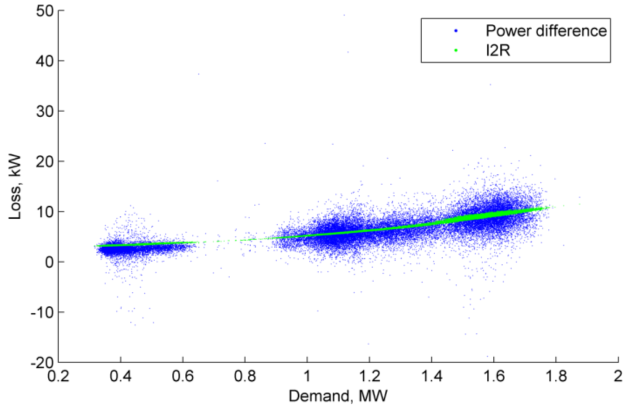

Figure 42 - September 2017 Loss, kW vs demand (Amway Tongwell HV feeder)

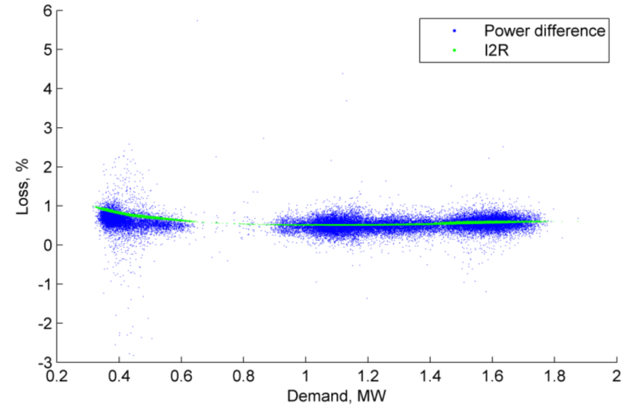

Figure 43 - September 2017 Loss, % vs demand (Amway Tongwell HV feeder)

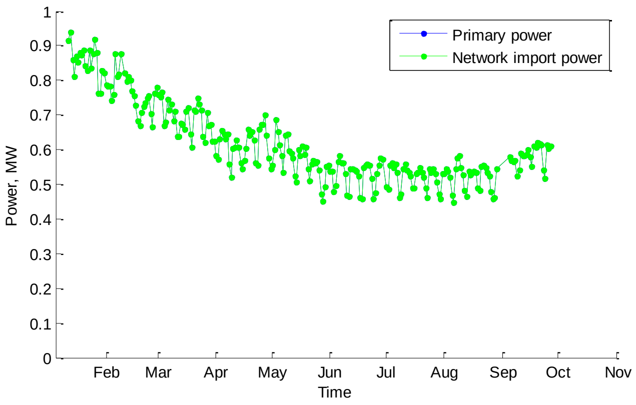

Figure 44 - Long term mean daily feeder demand (Ackerman Tongwell Aldrich Drive Tee HV feeder)

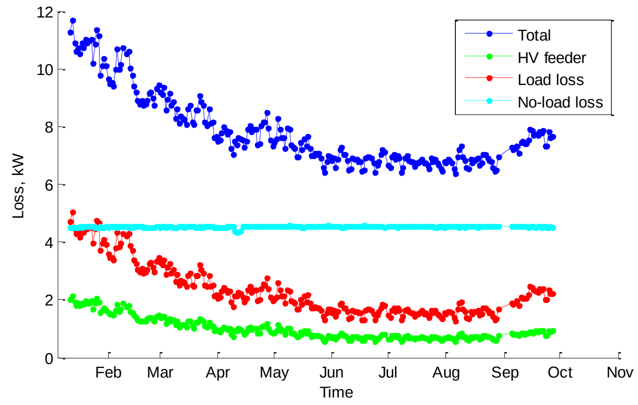

Figure 45 - Long term mean daily (I2R) loss (Ackerman Tongwell Aldrich Drive Tee HV feeder)

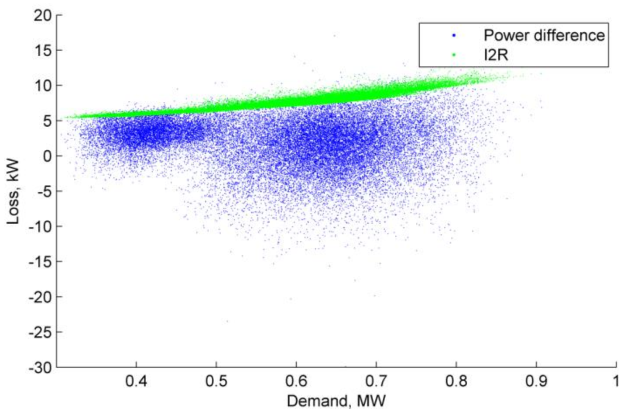

Figure 46 - September 2017 Loss, kW vs demand (Ackerman Tongwell Aldrich Drive Tee HV feeder)

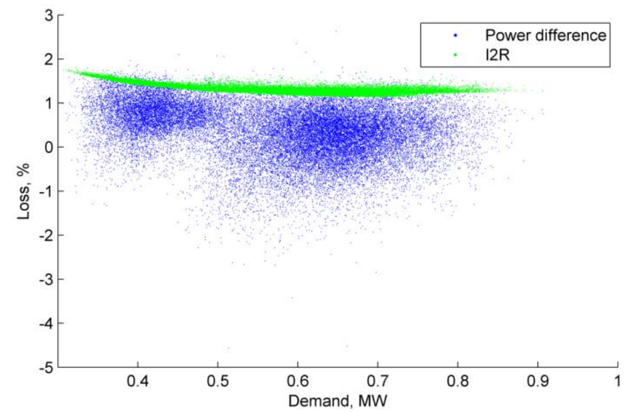

Figure 47 - September 2017 Loss, % vs demand (Ackerman Tongwell Aldrich Drive Tee HV feeder)

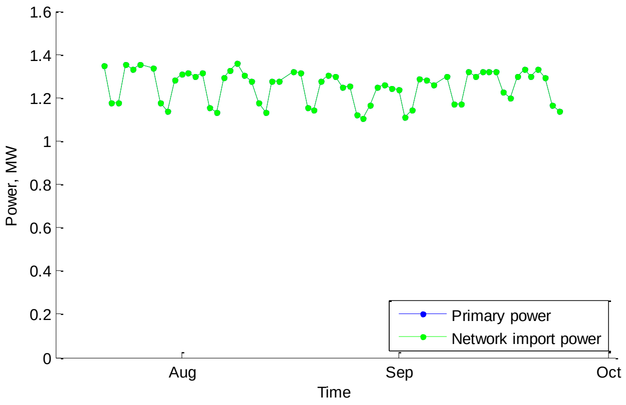

Figure 48 - Long term mean daily feeder demand (The Avenue HV feeder)

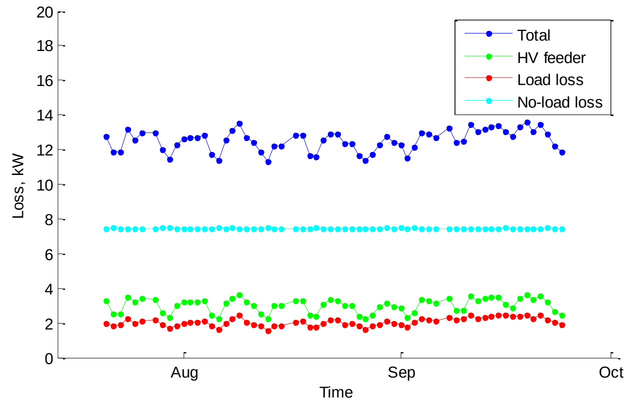

Figure 49 - Long term mean daily (I2R) loss (The Avenue HV feeder)

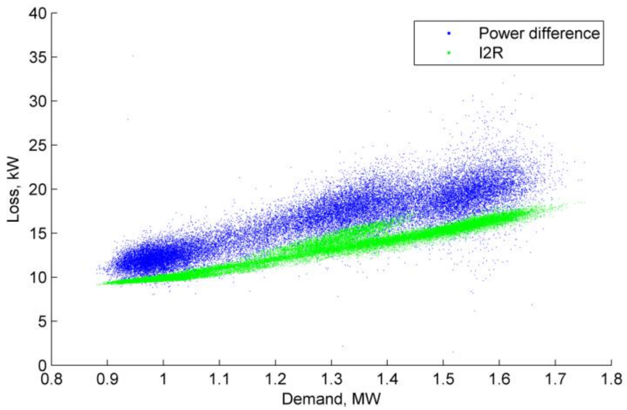

Figure 50 - September 2017 Loss, kW vs demand (The Avenue HV feeder)

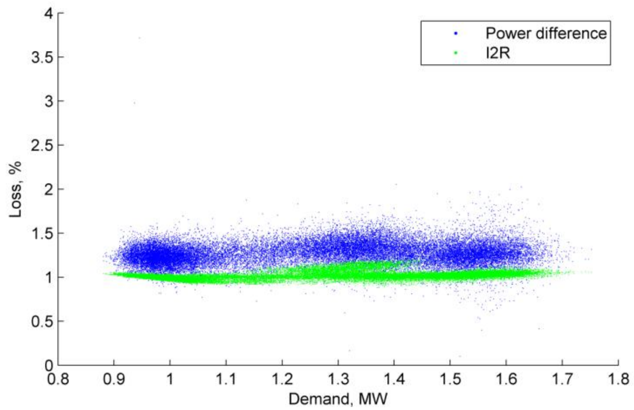

Figure 51 - September 2017 Loss, % vs demand (The Avenue HV feeder)

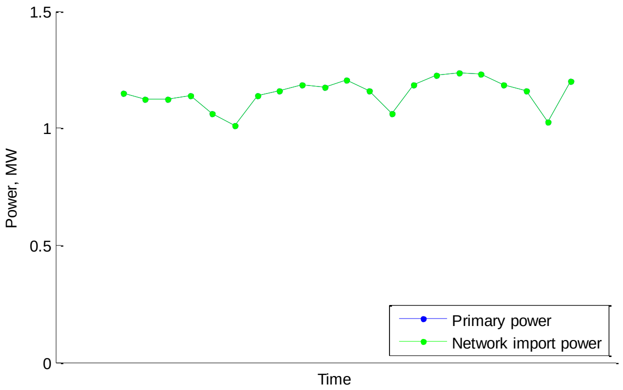

Figure 52 - Long term mean daily feeder demand (Riverside Park HV feeder)

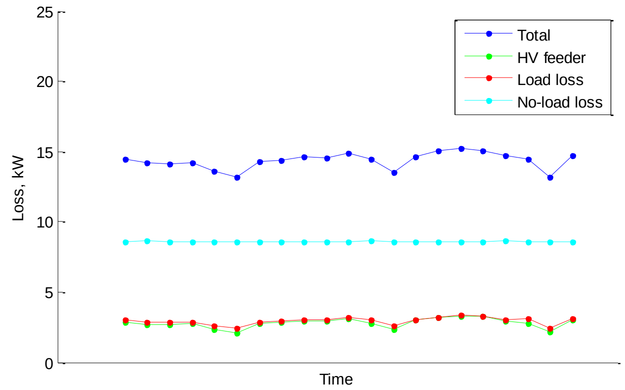

Figure 53 - Long term mean daily (I2R) loss (Riverside Park HV feeder)

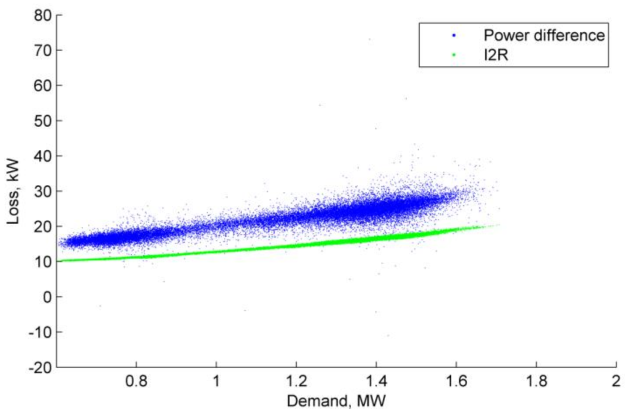

Figure 54 - September 2017 Loss, kW vs demand (Riverside Park HV feeder)

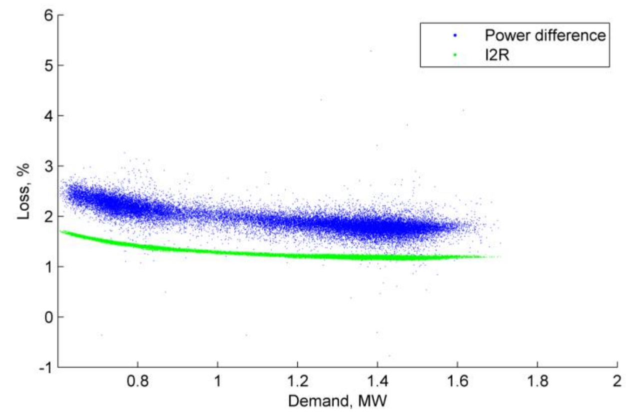

Figure 55 - September 2017 Loss, % vs demand (Riverside Park HV feeder)

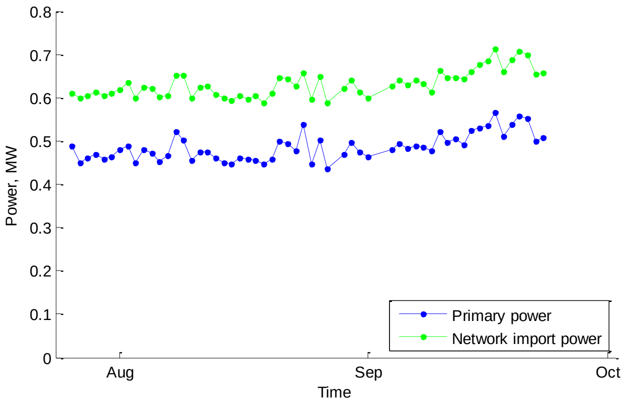

Figure 56 - Long term mean daily feeder demand (Silver End HV feeder)

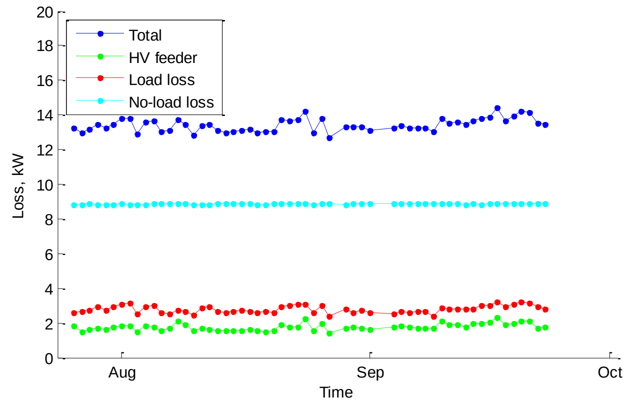

Figure 57 - Long term mean daily (I2R) loss (Silver End HV feeder)

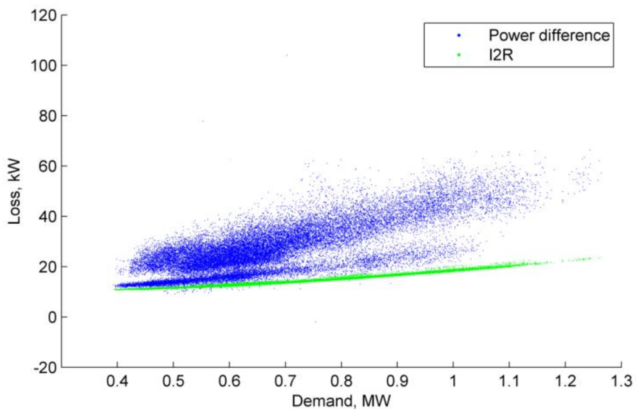

Figure 58 - September 2017 Loss, kW vs demand (Silver End HV feeder)

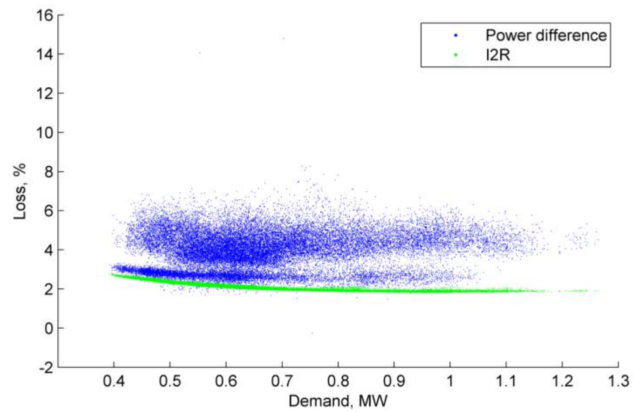

Figure 59 - September 2017 Loss, % vs demand (Silver End HV feeder)

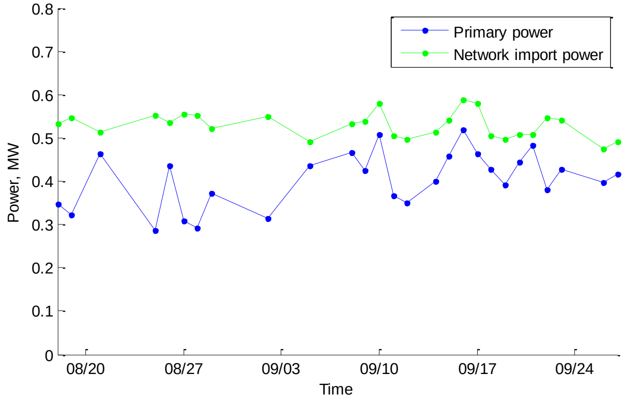

Figure 60 - Long term mean daily feeder demand (Wolverton HV feeder)

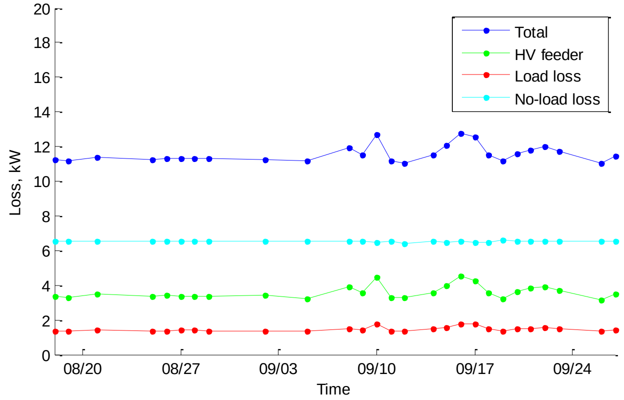

Figure 61 - Long term mean daily (I2R) loss (Wolverton HV feeder)

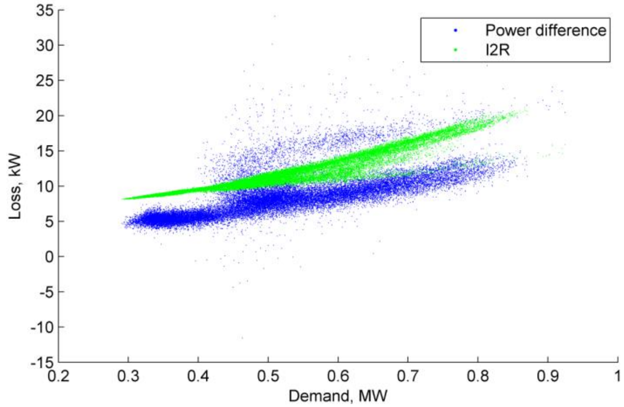

Figure 62 - September 2017 Loss, kW vs demand (Wolverton HV feeder)

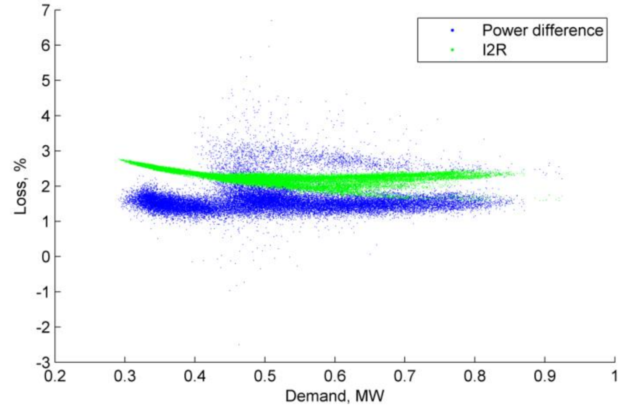

Figure 63 - September 2017 Loss, % vs demand (Wolverton HV feeder)

Appendix C 2 LV feeders

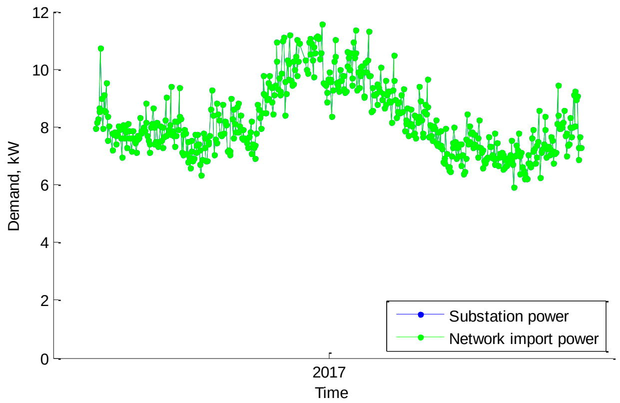

Figure 64 - Long term mean daily feeder demand (Domestic Pilot LV feeder)

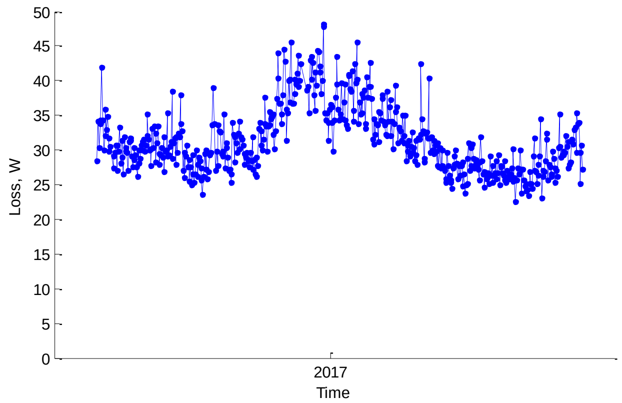

Figure 65 - Long term mean daily (I2R) loss (Domestic Pilot LV feeder)

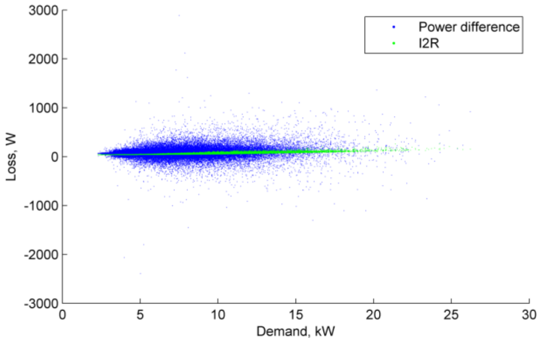

Figure 66 - Jul and Aug 2017 Loss, kW vs demand (Domestic Pilot LV feeder)

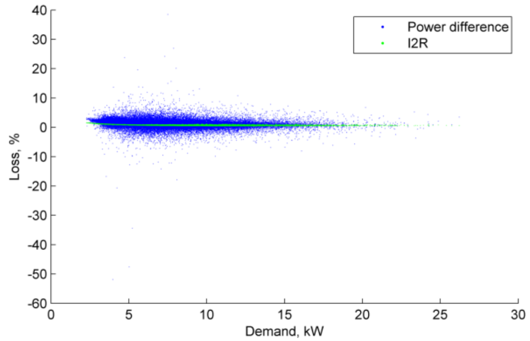

Figure 67 - Jul and Aug 2017 Loss, % vs demand (Domestic Pilot LV feeder)

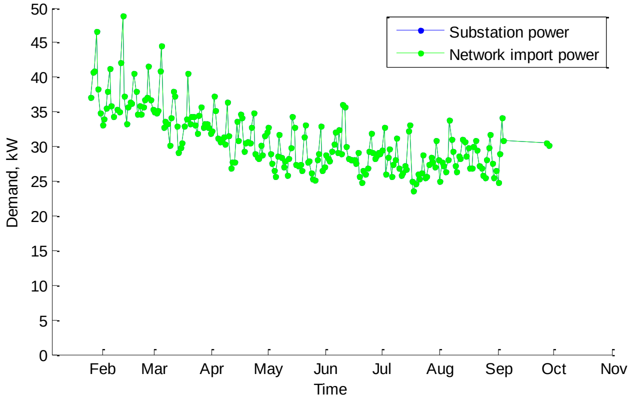

Figure 68 - Long term mean daily feeder demand (Laxey Domestic LV feeder)

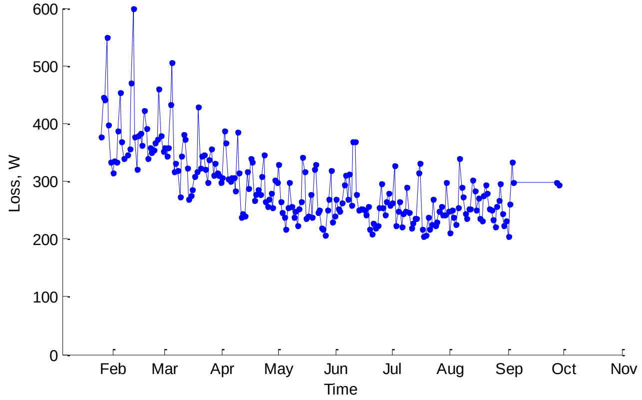

Figure 69 - Long term mean daily (I2R) loss (Laxey Domestic LV feeder)

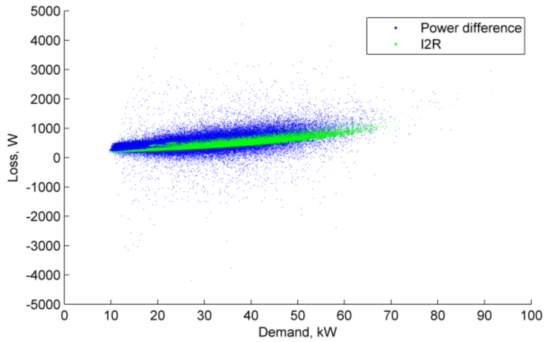

Figure 70 - Jul and Aug 2017 Loss, kW vs demand (Laxey Domestic LV feeder)

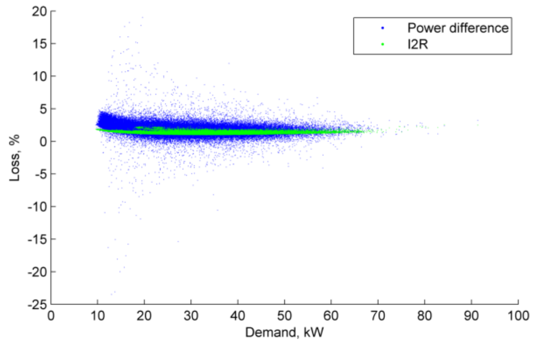

Figure 71 - Jul and Aug 2017 Loss, % vs demand (Laxey Domestic LV feeder)

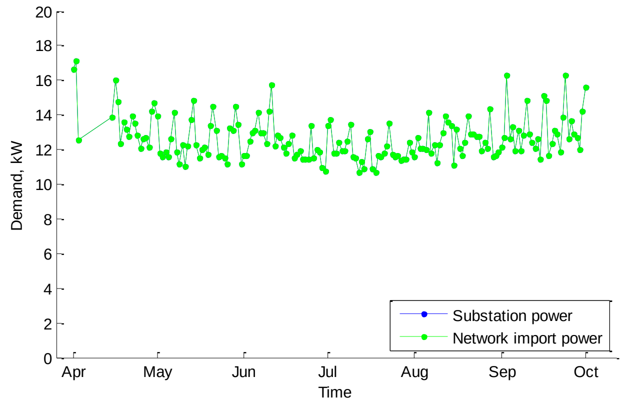

Figure 72 - Long term mean daily feeder demand (Ramsey Domestic LV feeder)

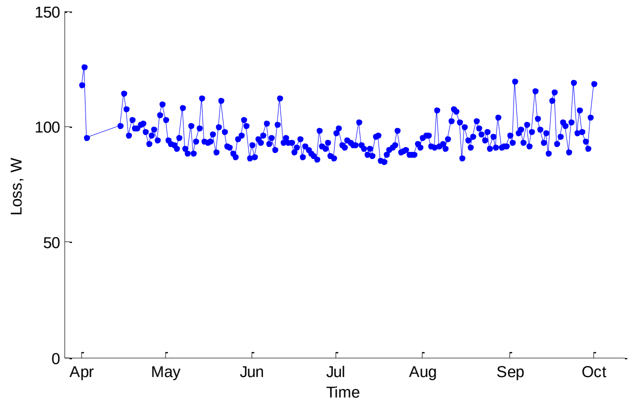

Figure 73 - Long term mean daily (I2R) loss (Ramsey Domestic LV feeder)

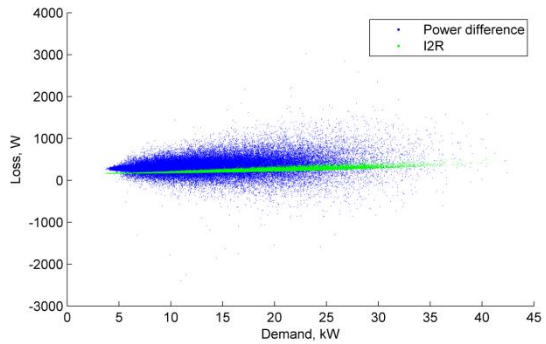

Figure 74 - Jul and Aug 2017 Loss, kW vs demand (Ramsey Domestic LV feeder)

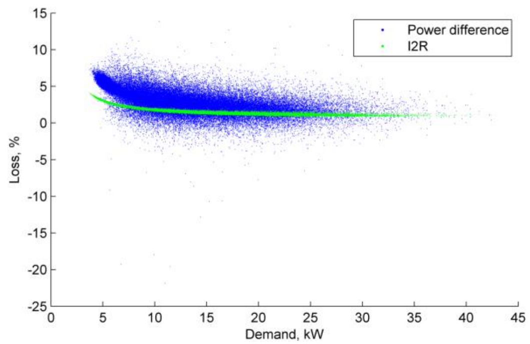

Figure 75 - Jul and Aug 2017 Loss, % vs demand (Ramsey Domestic LV feeder)

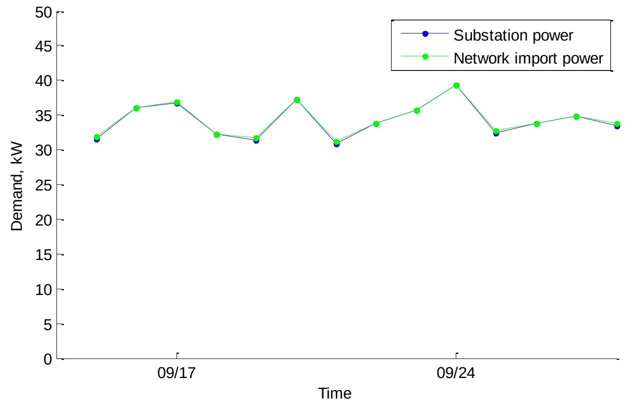

Figure 76 - Long term mean daily feeder demand (Tromode Domestic LV feeder)

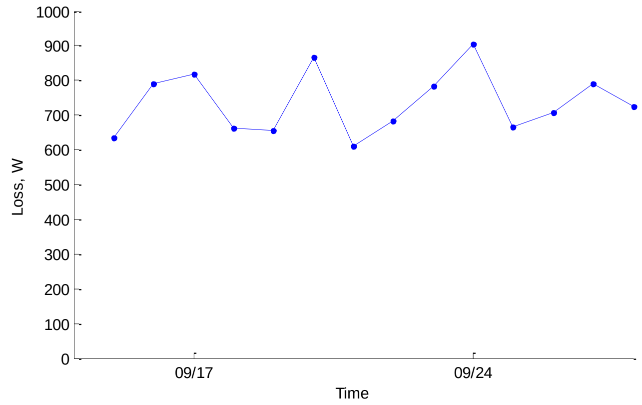

Figure 77 - Long term mean daily (I2R) loss (Tromode Domestic LV feeder)

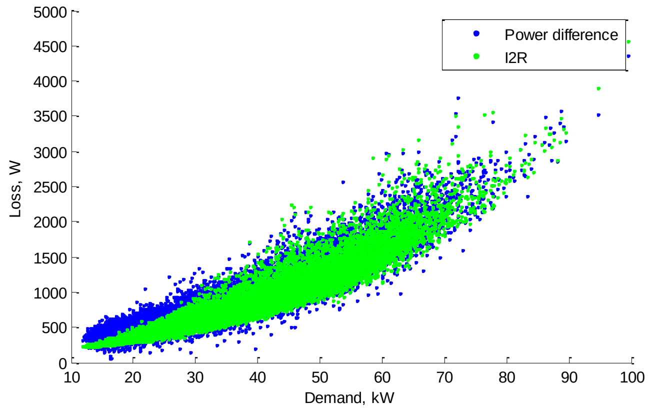

Figure 78 - September Loss, kW vs demand (Tromode Domestic LV feeder)

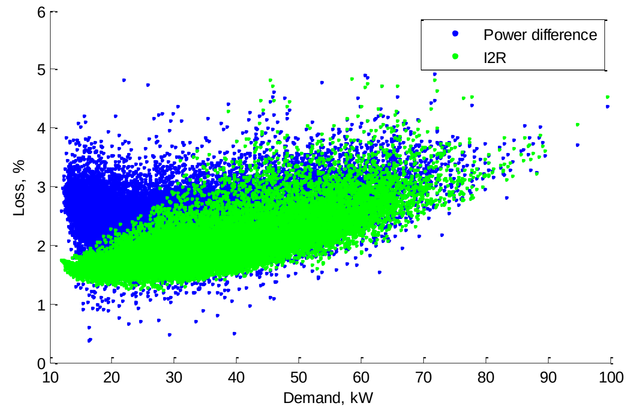

Figure 79 - September 2017 Loss, % vs demand (Tromode Domestic LV feeder)

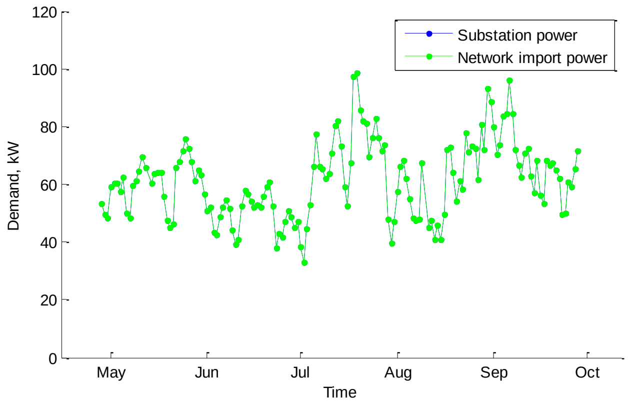

Figure 80 - Long term mean daily feeder demand (Peel A I&C LV feeder)

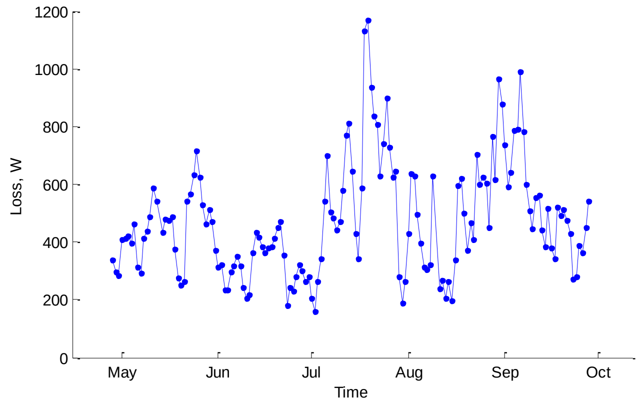

Figure 81 - Long term mean daily (I2R) loss (Peel A I&C LV feeder)

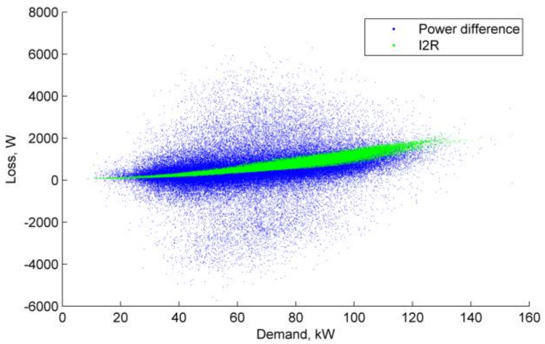

Figure 82 - Jul and Aug 2017 Loss, kW vs demand (Peel A I&C LV feeder)

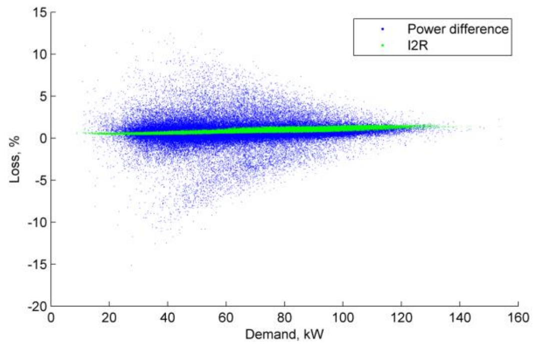

Figure 83 - Jul and Aug 2017 Loss, % vs demand (Peel A I&C LV feeder)

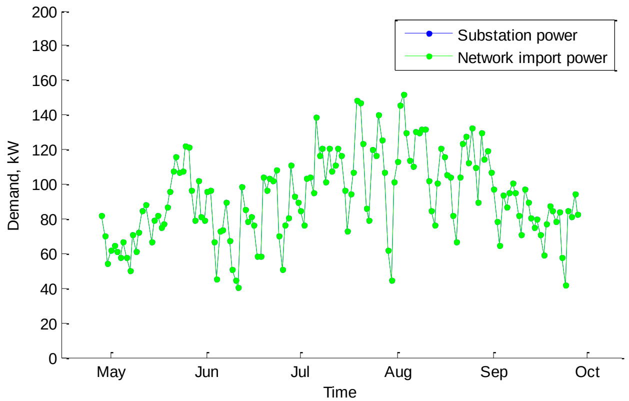

Figure 84 - Long term mean daily feeder demand (Peel B I&C LV feeder)

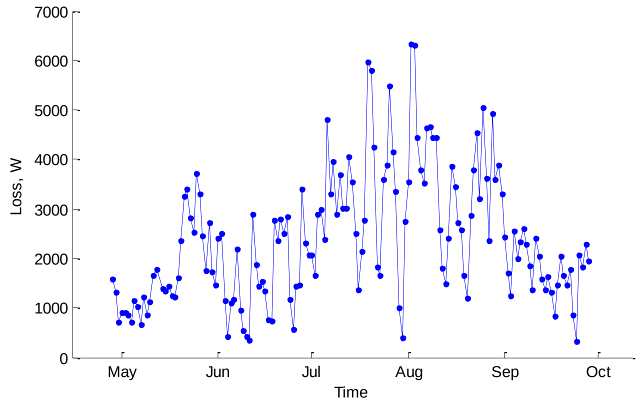

Figure 85 - Long term mean daily (I2R) loss (Peel B I&C LV feeder)

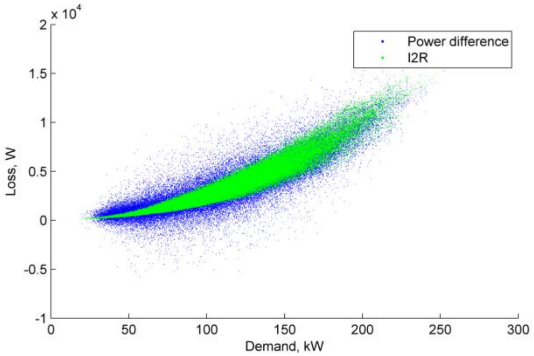

Figure 86 - Jul and Aug 2017 Loss, kW vs demand (Peel B I&C LV feeder)

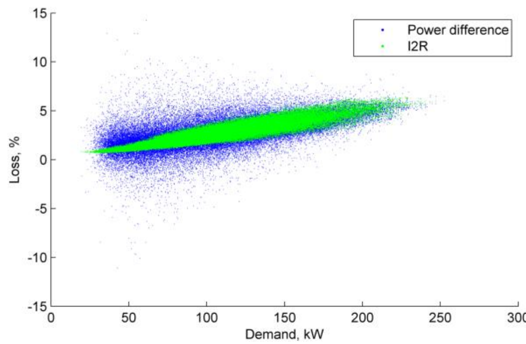

Figure 87 - Jul and Aug 2017 Loss, % vs demand (Peel B I&C LV feeder)

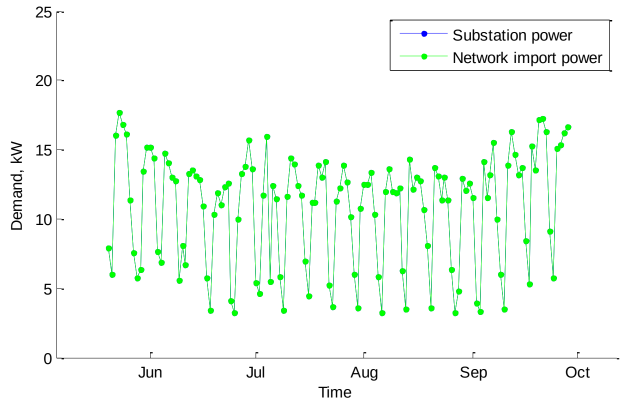

Figure 88 - Long term mean daily feeder demand (Ballasalla I&C LV feeder)

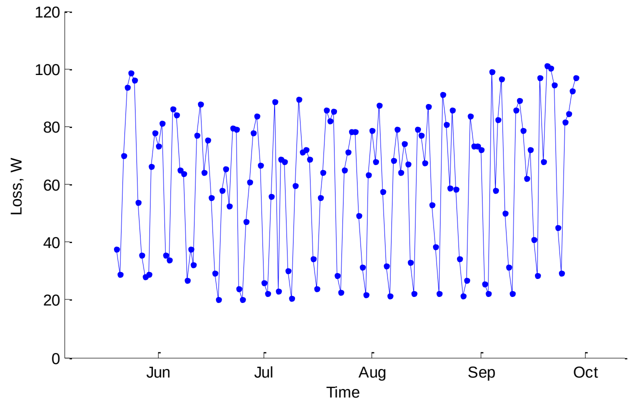

Figure 89 - Long term mean daily (I2R) loss (Ballasalla I&C LV feeder)

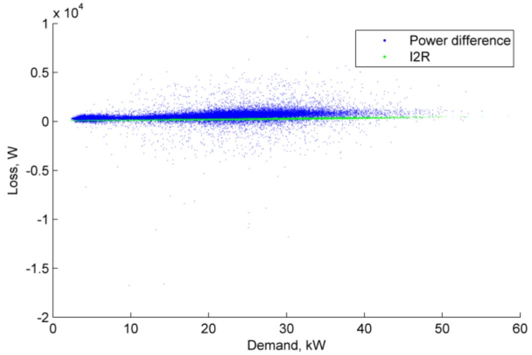

Figure 90 - Jul and Aug 2017 Loss, kW vs demand (Ballasalla I&C LV feeder)

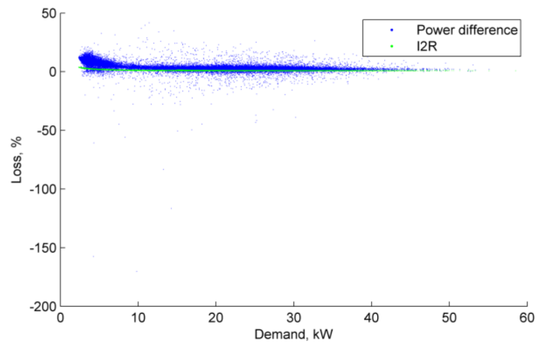

Figure 91 - Jul and Aug 2017 Loss, % vs demand (Ballasalla I&C LV feeder)

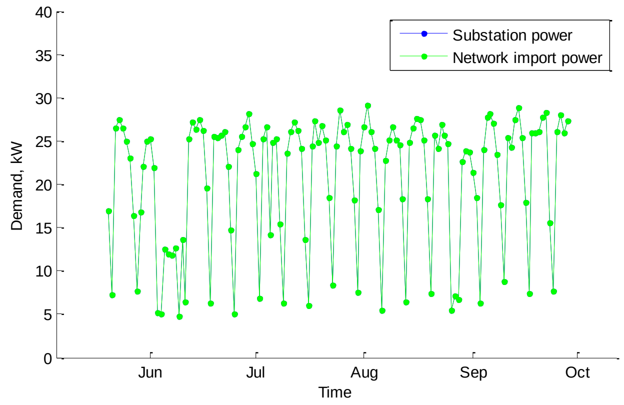

Figure 92 - Long term mean daily feeder demand (Braddan I&C LV feeder)

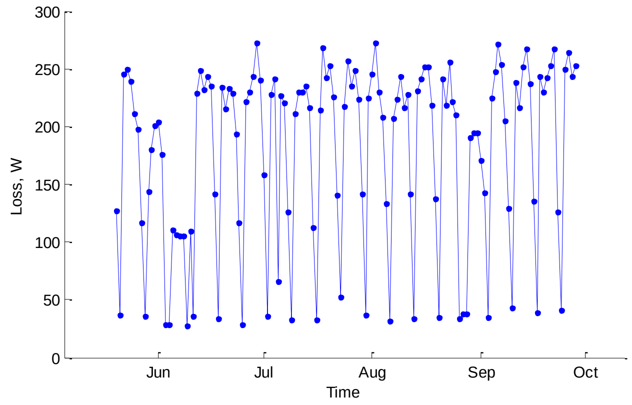

Figure 93 - Long term mean daily (I2R) loss (Braddan I&C LV feeder)

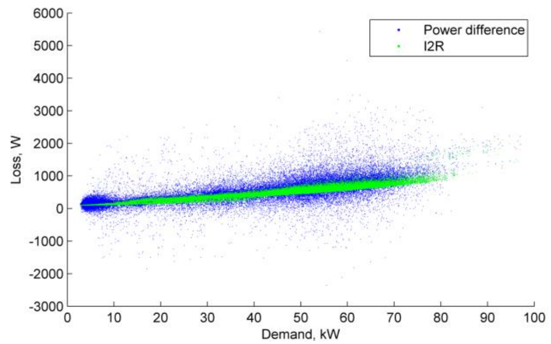

Figure 94 - Jul and Aug 2017 Loss, kW vs demand (Braddan I&C LV feeder)

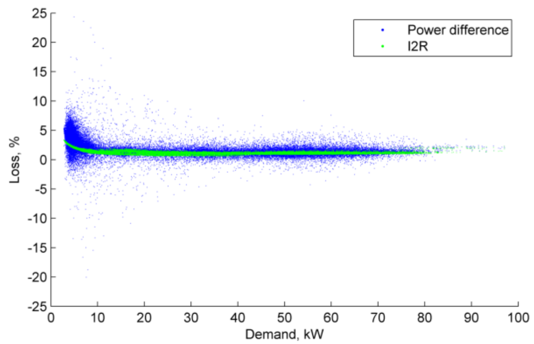

Figure 95 - Jul and Aug 2017 Loss, % vs demand (Braddan I&C LV feeder)

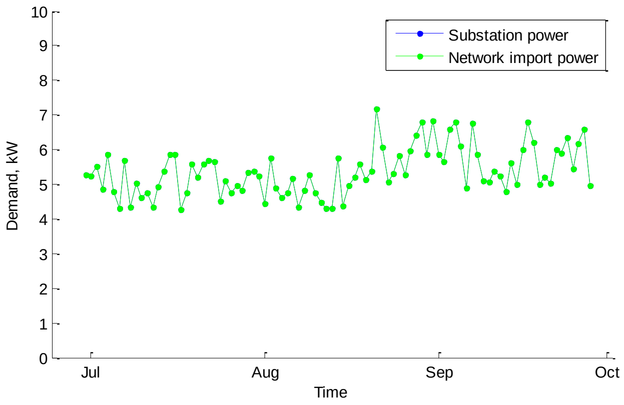

Figure 96 - Long term mean daily feeder demand (Santon OH LV feeder)

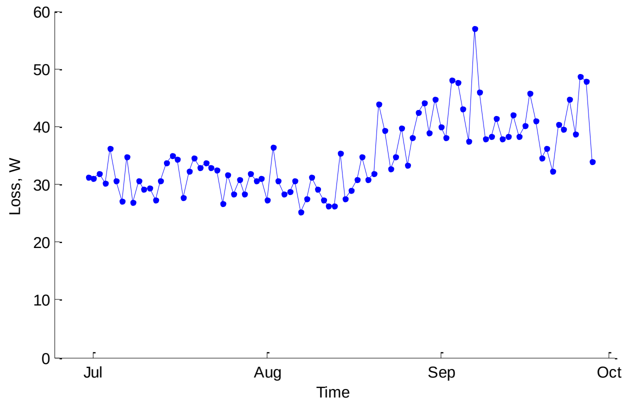

Figure 97 - Long term mean daily (I2R) loss (Santon OH LV feeder)

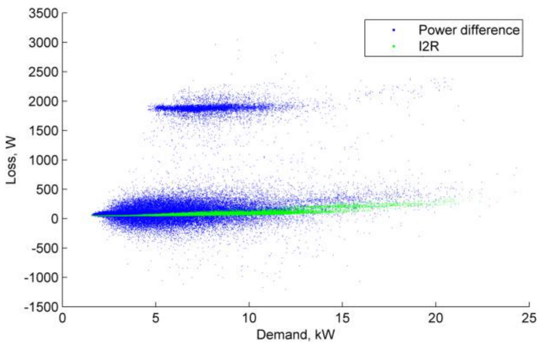

Figure 98 - Jul and Aug 2017 Loss, kW vs demand (Santon OH LV feeder)

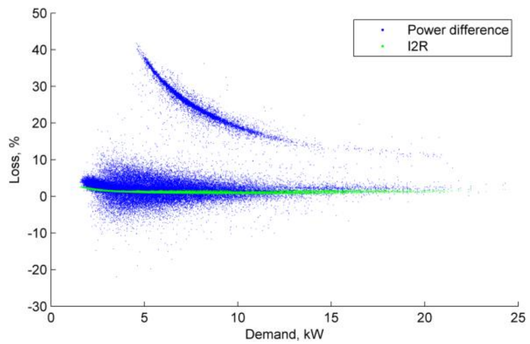

Figure 99 - Jul and Aug 2017 Loss, % vs demand (Santon OH LV feeder)

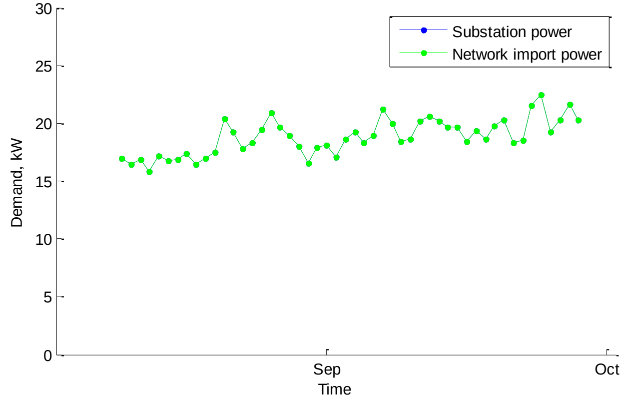

Figure 100 - Long term mean daily feeder demand (Abbeylands OH LV feeder)

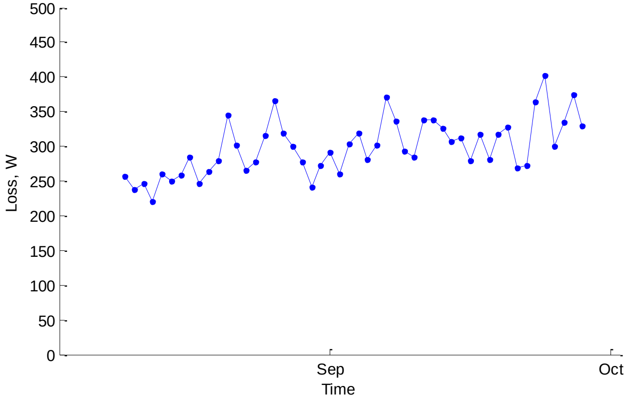

Figure 101 - Long term mean daily (I2R) loss (Abbeylands OH LV feeder)

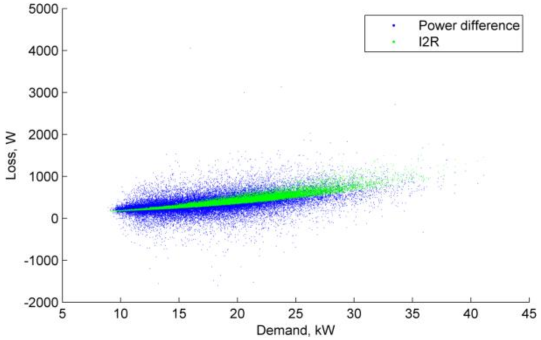

Figure 102- Jul and Aug 2017 Loss, kW vs demand (Abbeylands OH LV feeder)

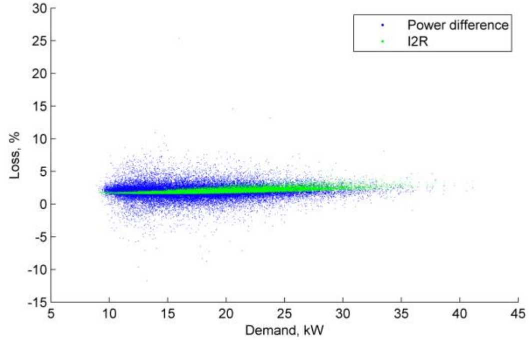

Figure 103 - Jul and Aug 2017 Loss, % vs demand (Abbeylands OH LV feeder)

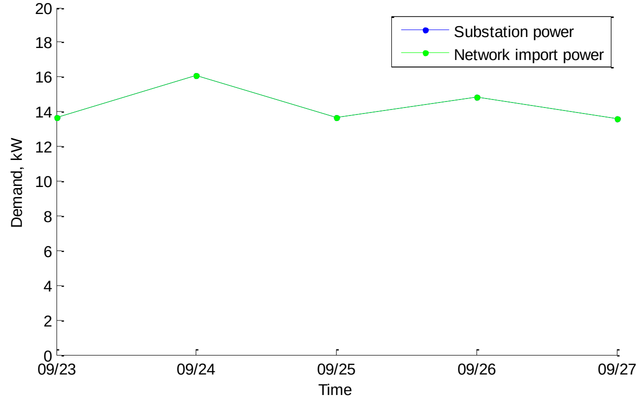

Figure 104 - Long term mean daily feeder demand (Ramsey OH LV feeder)

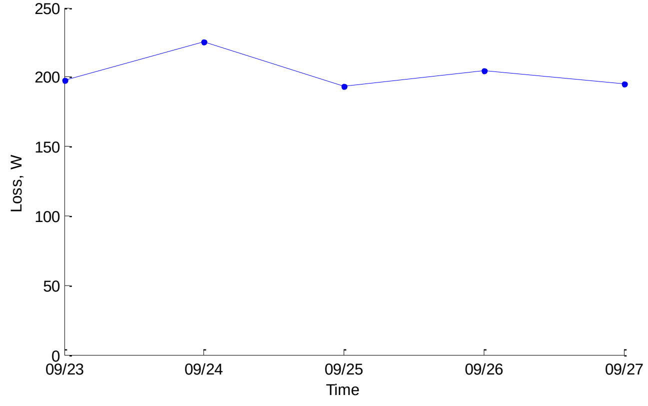

Figure 105 - Long term mean daily (I2R) loss (Ramsey OH LV feeder)

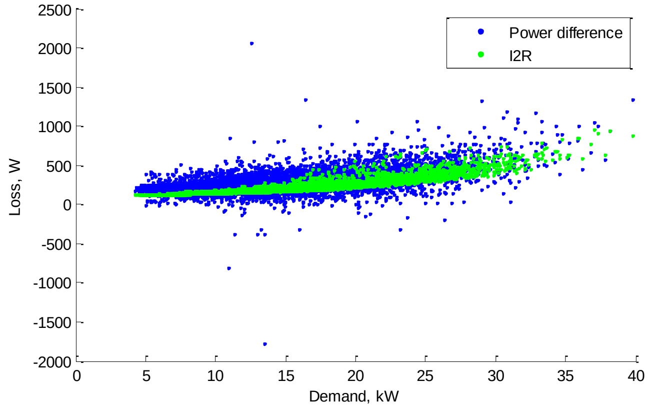

Figure 106 - September 2017 Loss, kW vs demand (Ramsey OH LV feeder)

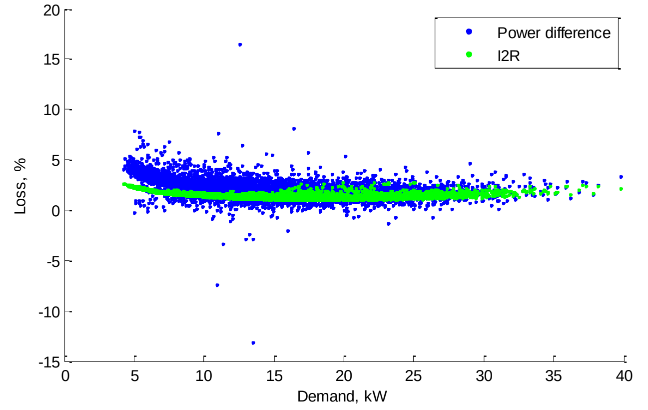

Figure 107 - September 2017 Loss, % vs demand (Ramsey OH LV feeder)

Appendix D Sample results from investigation of potential to reduce HV losses by moving NOPs

The Wavendon Gate primary supplies two feeders, Wavendon Gate Local and Secondary School Walnut Tree, as shown in Figure 108. The Secondary School Walnut Tree feeder (shown highlighted in green) connects at the existing NOP (case 1) to the Wavendon Gate Local feeder (shown in red). There are fewer substations on the Wavendon Gate Local side of the NOP and these also typically have lower demand. It was therefore found that there was no benefit to be gained by moving the NOP along the Wavendon Gate Local feeder, but losses could be reduced if the NOP were to be moved along the Secondary School Walnut Tree feeder. The spur between nodes shown as case 9 and case 10 carries a high demand and so there no benefit in exploring NOP positions beyond this.

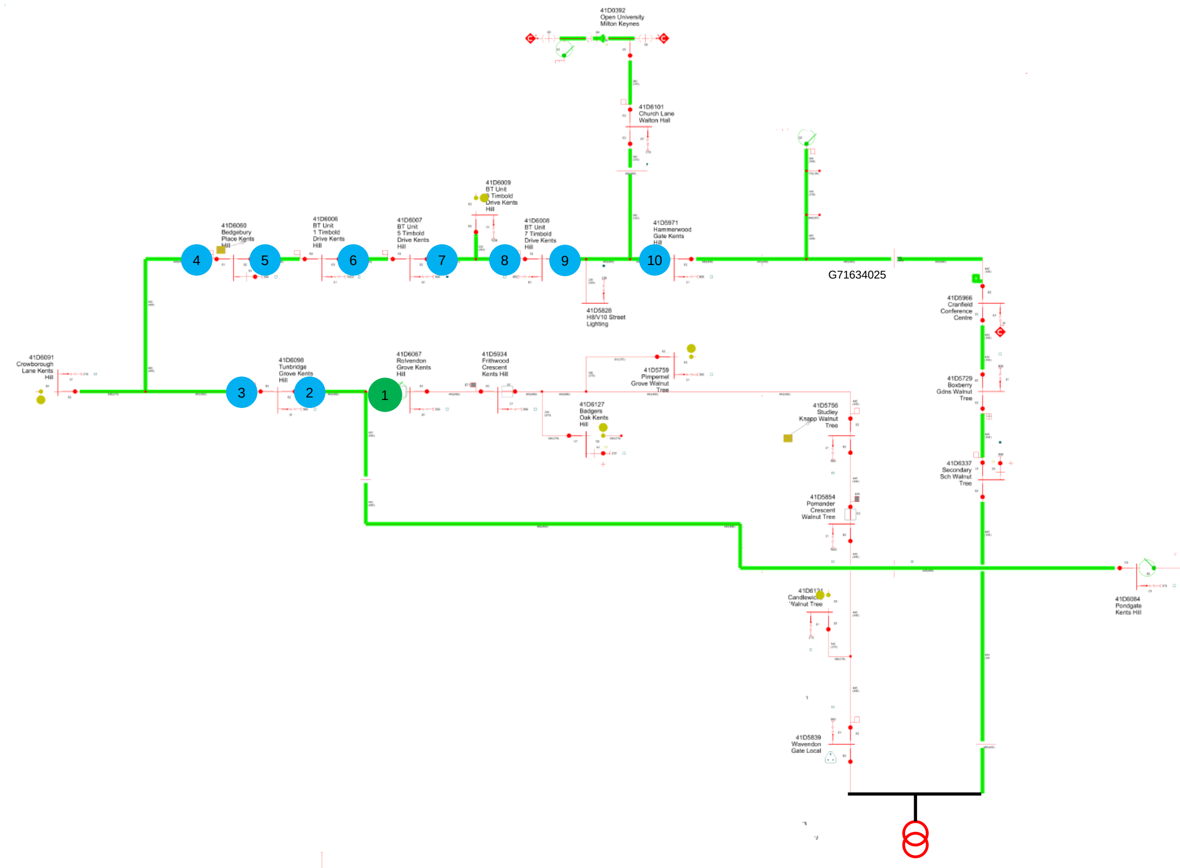

Figure 108 - Wavendon Gate NOP study feeder network

The combined losses over the two feeders have been calculated for the period from 21st October 2016 to 2nd October 2017, representing close to a full year of measurements. The results in Table 6 and Figure 22 show that the HV cable losses can be reduced by 30%, giving an overall reduction of 15.9% when the fixed transformer losses are taken into account. In the final scenario (case 10) the NOP has been moved such that all of the demand from the spur between NOP locations at cases 9 and 10 has been included on the Wavendon Gate Local feeder and this gives increased losses.

Case	NOP location	Loss, kW	HV cable losses	Load losses	No-load losses	% change
Case 1	G71871762 to 41D6067	43.29	23.88	4.36	15.05	0.0%
Case 2	41D6098 to G71871762	42.61	23.19	4.36	15.06	-1.6%
Case 3	G71636864 to 41D6098	40.71	21.28	4.35	15.08	-6.0%
Case 4	41D6060 to G71636864	39.75	20.31	4.35	15.09	-8.2%
Case 5	41D6006 to 41D6060	39.25	19.80	4.35	15.10	-9.3%
Case 6	41D6007 to 41D6006	38.34	18.88	4.35	15.11	-11.4%
Case 7	41D6009 to 41D6007	38.09	18.62	4.35	15.11	-12.0%
Case 8	41D6008 to 41D6009	36.95	17.48	4.35	15.12	-14.6%
Case 9	G71634606 to 41D6008	36.41	16.94	4.35	15.12	-15.9%
Case 10	41D5971 to G71881878	48.04	28.65	4.35	15.04	11.0%

Table 11 - Loss reduction for Wavendon Gate feeders using long term measurement data

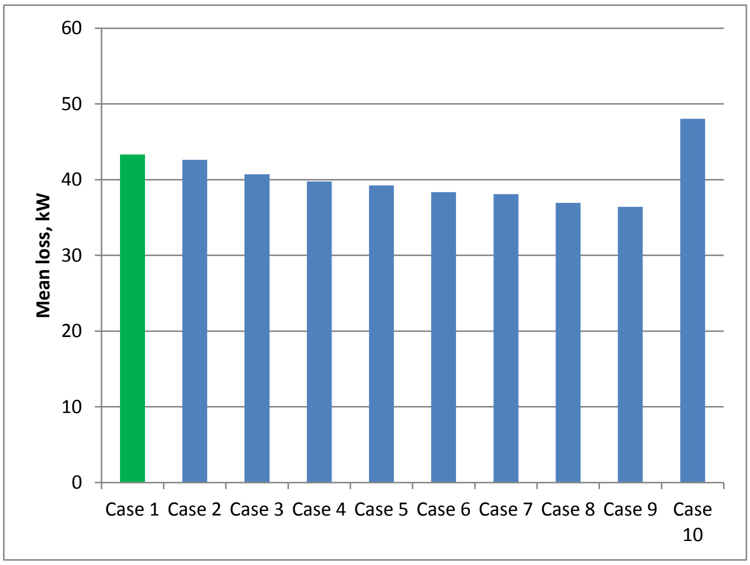

Figure 109 - Loss reduction for Wavendon Gate feeders using long term measurement data

There was found to be no variation in the optimal NOP location if the losses were considered at each half-hour period. The reduction in losses can therefore be provided by a one-off change and no dynamic movement of the NOP is required.

Appendix E Loss estimation methodology details

Appendix E 1 Summary of progress to date

The development of a method to estimate feeder-specific losses using a minimum information set is the second key aim of the project (Section 2.1 - Project Background).

The HV feeder loss assessment information described in Section 2.4 and shown in Appendix B has been used to consider how specific feeder losses could be reasonably accurately assessed without the need to install additional monitoring equipment.

A preferred method of estimating feeder losses has been established, and this results in:

- Reasonable agreement between loss assessment using monitoring data and an initial estimate of losses using raw load information; and
- Very high degree of agreement if corrections are made to errors that exist in the initially available load information.

The preferred HV feeder loss assessment method contains the following key steps:

- Assembly of input data;
- Assembly of a representative 365 day load model for each substation on the feeder;
- Preparation of a load flow model with a data flow control script (an example is IPSA with Python based scripts); and
- Run the load flow scripts.

Further details on the key aspects of pre-existing information or learning from the project that have been used in developing the estimation approach, and expanded information on the key steps are contained in Appendix E 2 below.

Table 12 presents the results from loss estimation for the available seven HV feeders.

HV Feeder	Loss Assessment (using monitoring data)	Initial Loss Estimate	Revised Loss Estimate
Woodlands			
Mean feeder demand, MW	1.59	1.62	1.61
Loss power, kW	20.2	21.4	20.4
Loss percentage, %	1.27	1.33	1.27
Fox Milne Hotel			
Mean feeder demand, MW	2.60	2.50	2.50
Loss power, kW	53.3	47.5	51.2
Loss percentage, %	2.05	1.90	2.05
Wavendon Gate Local			
Mean feeder demand, MW	0.95	0.94	No
Loss power, kW	8.6	8.4	Revisions
Loss percentage, %	0.90	0.90	Made
Secondary School Walnut Tree			
Mean feeder demand, MW	3.10	2.99	2.99
Loss power, kW	40.8	38.6	38.6
Loss percentage, %	1.32	1.29	1.29
Crawley Road Tee Howard Way			
Mean feeder demand, MW	2.73	2.72	No
Loss power, kW	22.8	22.6	Revisions
Loss percentage, %	0.84	0.83	Made
Amway Tongwell			
Mean feeder demand, MW	1.20	1.23	1.23
Loss power, kW	7.3	10.8	7.7
Loss percentage, %	0.60	0.87	0.63
Ackerman Tongwell Aldrich Drive Tee			
Mean feeder demand, MW	0.86	0.79	No
Loss power, kW	10.8	9.8	Revisions
Loss percentage, %	1.26	1.24	Made

Table 12 - Comparison of Feeder Losses using monitoring data and estimation method

Initial work has been undertaken to verify that an IPSA model with appropriate data flow control and load flow calculation control scripts could be used. To date, a single HV feeder for a single day (48 HH periods) has been used to demonstrate that scripting is reasonably achievable and that comparable results (to Loughborough project-bespoke model) are achievable. This exercise resulted in high precision agreement between the IPSA model and the Loughborough model, and it has been concluded that this presents a realistic assessment implementation approach. Further work will follow.

To date, the majority of development work has been undertaken on HV feeders because this is where a reasonable amount of project data is now available. Initial considerations of LV feeders have also been made, and the following points are note:

- There is less certain information about network connectivity and resultant intermediate LV branch lengths;
- There is significant variation in demand within minutes, and from one minute to the next;
- There is significantly more transient and persistent phase unbalance;
- With time, the implementation of advanced metering will significantly change the amount of information available.

It is therefore anticipated that the LV feeder loss estimation will involve the following further activities in addition to those for HV feeder loss estimation.

- Network estimation (not required to significant extents for HV)
- Enhanced Load estimation (whilst required at HV, further factors will be required e.g. sub-division of estimated substation loads between LV feeders, phase connection and unbalance)

Appendix E 2 Further details of current preferred approach to loss estimation

The preferred approach for HV feeders is built on the following pre-existing information or learning from the project:

- Loss is proportional to the square of the feeder current – this is seen as an increasing gradient in the charts of Loss, kW vs demand in Appendix B;
- Variation in the level of loss for a particular level of demand on a feeder is driven by variation in the distribution of load along a feeder. This can often characteristically occur at differ times of the day/different days of the week between commercial/industrial load and domestic load;
- Load across phases is relatively balanced on the HV feeders; and
- The HV load is relatively consistent from one minute to another creating the potential to half hour periods for estimation purposes;
- That HV network information is available and relatively reliable;
- That Customer information is reasonably available and relatively reliable;
- That average feeder demand (L2) is available.

The preferred HV feeder loss assessment method contains the following key steps:

- Assembly of input data:
    - A feeder model is assembled comprising of: Distribution Substation nodes, with HV feeder branch lengths, and conductor cross-sections;
    - Distribution Substation Node information is assembled comprising of type of distribution supply point (i.e. HV or LV); and for LV supply points, estimates or actual values for distribution transformer load and no-load losses;
    - Half hourly (HH) load information aggregated by Distribution Substation Node;
    - Non-half hourly (NHH) estimated annual consumptions aggregated by Profile Class and Distribution Substation Node;
    - Elexon Profile Class profiles; and
    - Half hourly average feeder demand derived from the Supervisor Control and Data Acquisition (SCADA).
- Assembly of a representative 365 day load model for each substation on the feeder:
    - An initial estimate of demand for each substation of each half hour period in a representative year is calculated from the HH data and the NHH EAC data combine with Elexon profiles;
    - The initial estimate of demand is compared to the measured value of SCADA feeder demand; and
    - The initial estimate of demand is scaled to match the measured value of SCADA feeder demand. This is achieved by scaling only the NHH element of the estimated load.
- Preparation of a load flow model with a data flow control script (an example is IPSA with Python based scripts):
    - Preparation of feeder models within the load flow calculation environment or scripts to import feeder and node information into the load flow calculation environment;
    - Scripts to import the load circumstances, 365*48 half hour periods in a representative year;
    - Scripts to initiate the load flow calculations; and
    - Scripts to export loss assessments resulting from load flow calculations for each half hourly period.
- Run the load flow scripts.