WESTERN POWER DISTRIBUTION

INNOVATION

NEXT GENERATION NETWORKS

LOSSES INVESTIGATION

WPD_NIA_005

NIA MAJOR PROJECT PROGRESS REPORT

REPORTING PERIOD:

OCT 2017 – MAR 2018

Report Title	:	NIA MAJOR PROJECT PROGRESS REPORT: LOSSES INVESTIGATION
Report Status	:	FINAL
Project Ref	:	NIA_WPD_005
Date	:	10/05/2018

Document Control

	Name	Date
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Revision History

Date	Issue	Status
12/04/2018	V0.1	Initial Draft
13/04/2018	V0.2	Draft following review with Loughborough University
23/04/2018	V0.3	For approval following internal review.
10/05/2018	V1.0	Final

Contents

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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.
Elexon	The not-for-profit company fulfilling the role of the Balancing and Settlement Company within the UK wholesale electricity market
GB	Great Britain
GIS	Geographic information system
GPRS	General Packet Radio Service, the mobile data service on 2G and 3G cellular communications systems.
GWh	Gigawatt hour
HH	Half Hourly
HV	High Voltage
I^2R	Loss assessment approach based on I^2R
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
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
Var	Volt-ampere reactive
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 October 2017 to the end of March 2018.

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 third six monthly progress report. It covers progress from October 2017 to the end of March 2018. Activities and progress included:

- Ongoing receipt and processing of monitoring data from all 11 HV and 11 LV trial feeders, with the preparation of loss assessments on all feeders. This has included ongoing refinement of loss assessment calculations for HV feeders, improving the handling of reverse power flows at the primary due to embedded generation.
- Continued detailed development of loss estimation processes for HV feeders, essentially using existing business-as-usual data sets. This novel and innovative data processing is moving towards demonstration of the capability to assess losses on HV feeders at DNO/regional scale. This requires outputs from multiple business database sources to be integrated, bringing together network data, metering data, transformer asset data and SCADA logging.
- Further background development of data anticipated to be required for the assessment of losses on LV feeders, following the conclusion of development work on HV feeders.

Focus over the next reporting period will be on concluding HV and LV feeder data collection and processing, plus completing and demonstrating the project's work on developing a loss assessment capability for HV and LV feeders.

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;
- 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 Electric 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[1] 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 Electric Gridkey	Goods (supply of established MCU520 LV substation monitoring equipment)	• HV & LV feeder loss assessment on monitored feeders	Complete June 2017.

[1] Meter design and manufacturing company

Provider	Services/goods	Area of project applicable to	Anticipated Delivery Dates
Lucy Electric Gridkey	Goods (design, development and supply of monitoring at HV supply points, based on MCU520 equipment)	• HV feeder loss assessment on monitored feeders	Complete Feb 2017.
Lucy Electric 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 WPDs Losses Strategy; however these have limits 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 on a feeder specific basis and the network cannot be fully 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 LV 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:

- Ongoing receipt and processing of monitoring data from all 11 HV and 11 LV trial feeders, with the preparation of loss assessments on all feeders, this included the development of a Visual Basic script to improve management of LV feeder data;
- Continued detailed development of loss estimation processes for HV feeders, enabling losses to be estimated on a regional scale using business-as-usual data, rather than using project data for specific feeders; and
- Further background development of data anticipated to be required for the assessment of losses on LV feeders.

As a result:

- Loss assessments (based on the installed instrumentation on 11 HV feeders and 11 LV feeders) have continued to be produced, providing further and now longer term data on feeder technical losses. This data will be used for comparison with loss estimation method results and summary charts are contained in Appendix C;
- Estimates of HV feeder losses have been produced using processes developed within the project that use business-as-usual data sources:
    - DINIS (WPD's HV power flow analysis tool) for HV feeder network data;
    - CROWN (WPD's asset management system) for installed HV/LV transformer details;
    - CROWN for substation aggregates of estimated annual consumption by profile class;
    - Substation aggregates for Half-Hourly consumption data;
    - SCADA data for half-hourly average HV feeder current.
- The capability to process DINIS data interface files to provide 11kV network data for loss estimation has progressed from single feeder files, through multi-feeder/primary files, to DNO-scale multi-primary files; and
- The process and data requirements for estimation of LV feeder losses have been further developed and it is now anticipated that network data will be based on approximated LV network models provided by the WPD Electric Nation project. The impact of using the approximated network data (compared to full network connectivity models verified for this project) will be examined though investigations using the IoM networks.

In addition:

- Presentations on project progress and findings to date have been made to WPD's Losses Strategy Stakeholder consultation Event (November 2017), and at the LCNI Conference (December 2017).

- Analysis of (LV) neutral current ratios for the monitored feeders was undertaken and provided as an input to the internal review of WPD's Losses Strategy document. An overview of the analysis is provided in Appendix D.

Progress against each of the project phases is summarised in Table 2.

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 344 meters and 196 Gridkey devices; • Loss assessment models/engines have been refined to improve the handling of reverse power flows at the primary due to embedded generation; • Ongoing loss assessments are produced for all HV and LV feeders.
Development of loss estimation methods for HV and LV feeders, using minimum additional information sets	**Ongoing** (during this period) – • Detailed development work on the capability to widely estimate losses on HV feeders is nearing completion; a description of progress in this period is included in Section 0. Demonstration is expected in Q2 2018.

Project Phase	Progress
	• For LV feeders, background work on the anticipated estimation method has continued. In the absence of comprehensive LV network connectivity data, it is expected that LV feeder estimates will be based on approximated models of the network connectivity. The estimation method and software will largely follow the HV feeder processing capability that is currently being developed.

Table 2: Summary of project progress against project phases

2.3 Further development of Loss Estimation for HV Feeders

2.3.1 Overview of progress within this reporting period

The HV loss estimation work previously undertaken used input data prepared by WPD for each of the trials feeders. The input data describing both the network topology and the substation loading was contained in Microsoft Word and Excel documents, and compiled based on information extracted from the WPD asset database, and checked and verified using the experience of the WPD project team engineers. Loughborough University then extracted data from the Word and Excel documents to create a set of text files that were used by the MATLAB loss estimation software. The end-to-end process, including preparation of the data by WPD and further processing at Loughborough, was mostly a manual task and so would not be suitable for use when calculating losses over a large number of feeders. This first version of the process is described here as loss estimation using 'bespoke project data', and resulted in 'phase 1 estimation results'.

The method has now been developed further such that the network and demand data is extracted more directly from a set of files that have been exported from WPD database systems. This development has been undertaken to extend and make reasonably practical the estimation of losses for large numbers of HV feeders, plus this revised approach allows for the loss analysis to be extended in the future to include other WPD DNO areas, additional time periods, and their associated network topology and customer loads.

An overview of the developed data processing and analysis architecture is shown in Figure 1. This approach is based on 'business-as-usual' data sources' and generates 'phase 2 estimation results'

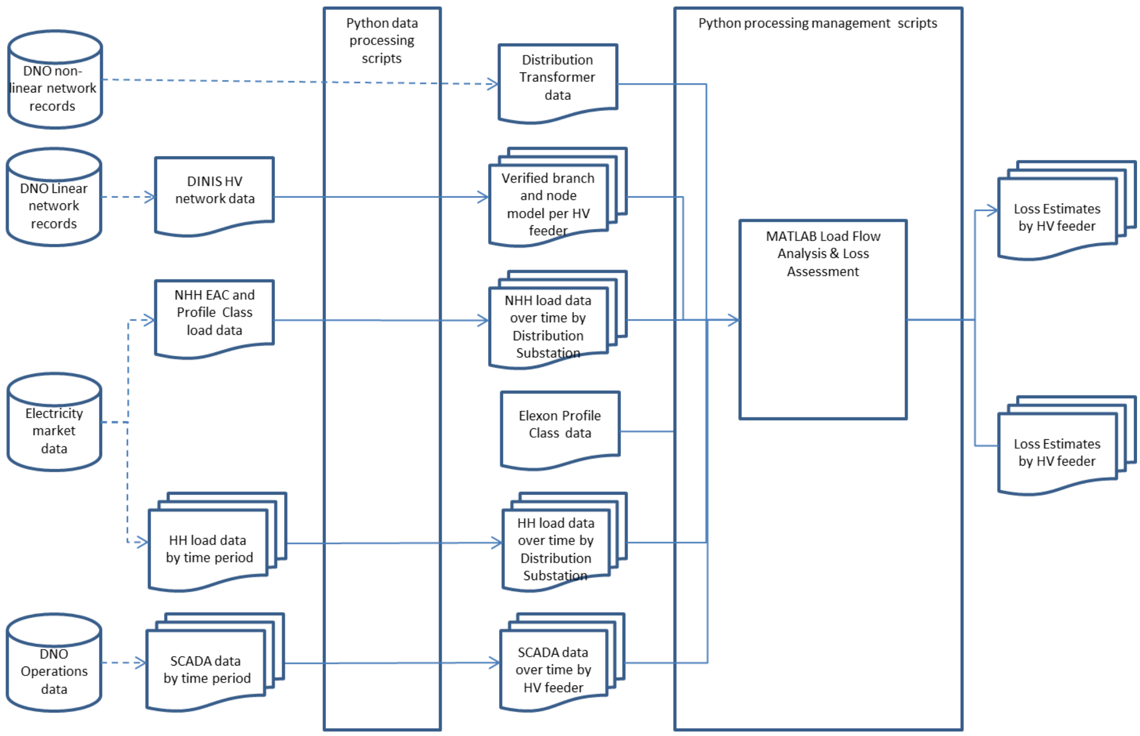

Figure 1: Graphical view of network data for a single feeder extracted from a DINIS data interface file for a Primary substation.

A key feature of the approach is the use of business-as-usual data, and to pre-process this data to confirm: internal consistency of the data within a single source (e.g. checking for changes in feeder labels without indication of a feeder open point with network topology data); and consistency across data sources (e.g. association of distribution substations to HV feeders being different within the non-linear records, to traces undertaken within the non-linear records).

As a result of this pre-processing a "quarantining" approach is also taken, whereby feeders that present inconsistencies, or contain features that can't be processed at present, are flagged and excluded from the final stages of processing.

Some further details of the processing of data follow:

- The network topology is extracted from a file exported from the DINIS network analysis software routinely used by WPD for HV network modelling for planning purposes. DINIS files are interpreted using a Python script to identify the connectivity of individual HV feeders. The interpreted node and branch connectivity is then written to a set of feeder-specific files, which are used as input by the MATLAB loss estimation method software developed previously.
- A progressive approach has been taken to the development of the Python scripting for the incorporation of DINIS data, where incrementally larger and more complex files have been progressively used. This started with transition from using 'bespoke

project data', to the use of a DINIS file containing network data for a single feeder. Progressively, network data has now been extracted from a multi-feeder/primary level DINIS file, and is now being extracted from a multi-primary/DNO level DINIS file.

- Transformer details to accompany the DINIS network data are based on extracts from CROWN, WPD's asset management system. Transformer-specific load and no-load loss values are relatively unavailable for the East Midlands region. In addition, actual operating tap position is also not available as a coherent data set. Therefore estimated load and no-load loss values for transformers are based on a "nominal values" table, with values selected based on a specific transformers rating, number of phases and year of manufacture. Further work will be undertaken in this area. Consideration of the impact of uncertainty of operating tap position has taken place, and initial findings are that there is a limited impact due to this.
- An example of a graphical view of the extracted network data for one feeder of a primary substation can be seen in Figure 2.

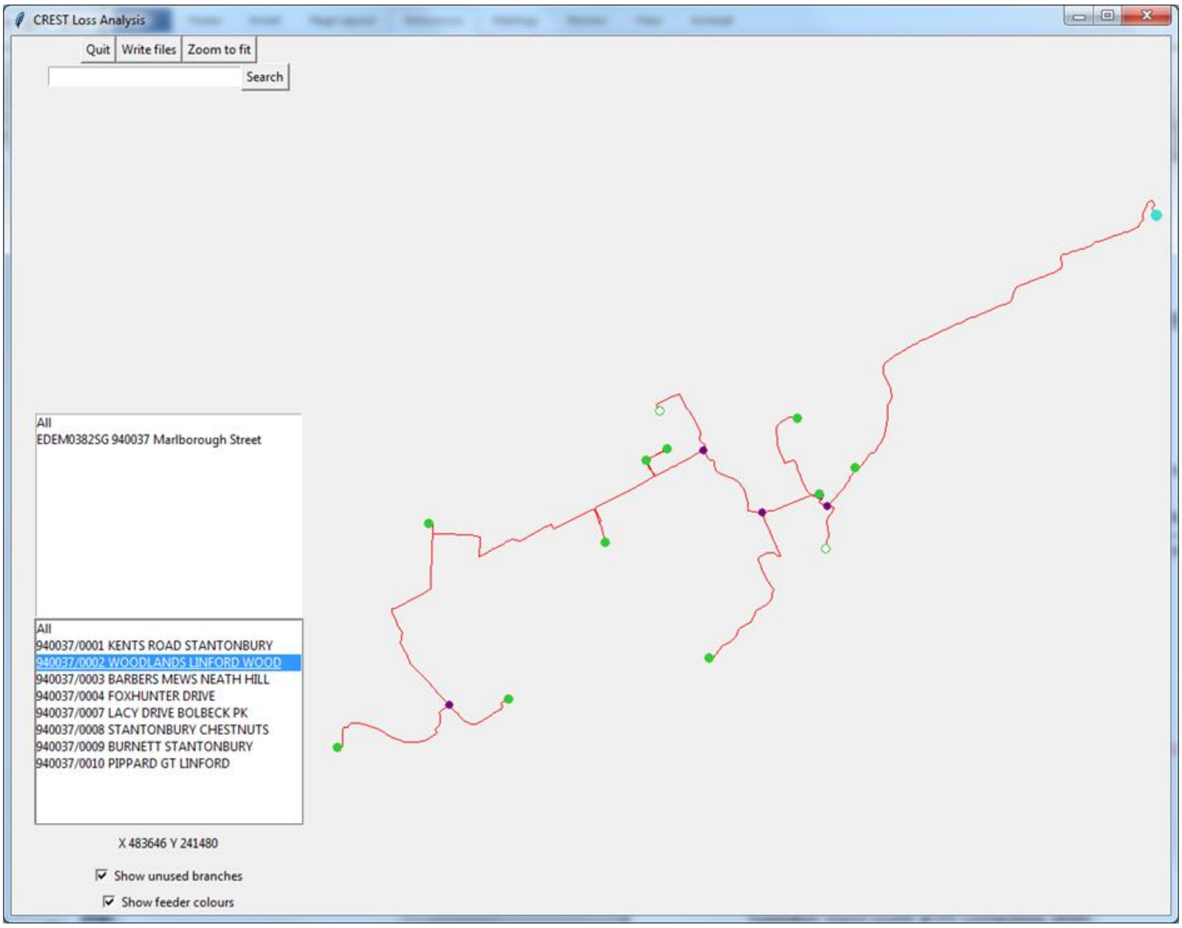

Figure 2: Graphical view of network data for a single feeder extracted from a DINIS data interface file for a Primary substation.

- An example of the capability to extract network data from a single wider-area DINIS file can be seen in Figure 3, which graphically shows a selection of 11kV feeders in the Milton Keynes area.

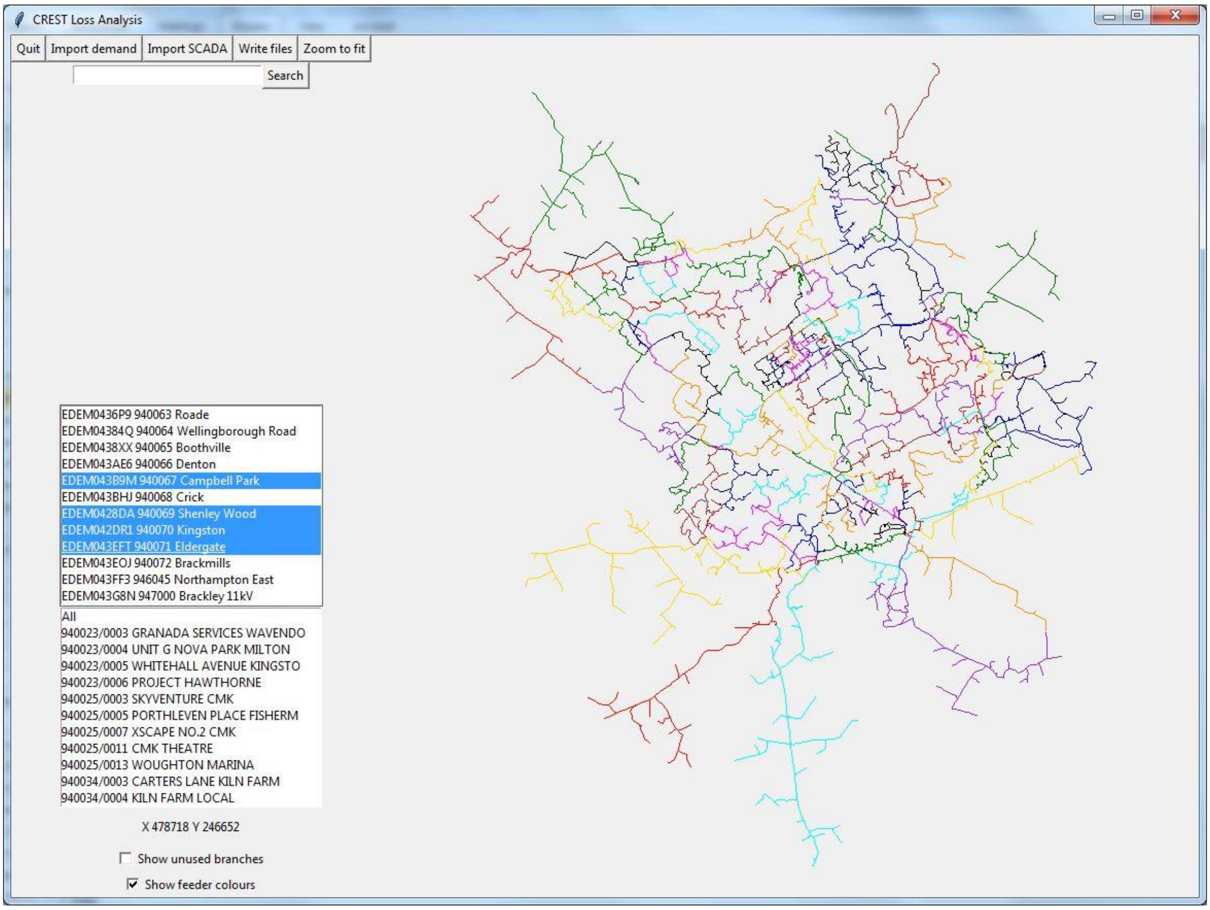

Figure 3: Graphical view of extracted and validated network data from a multi-primary DINIS data interface file for the Milton Keynes area.

- In addition to network data, the Python scripts also extract demand data from a set of text files containing the details of half-hourly and non-half-hourly information, and produces initial NHH and HH substation load estimates. These initial substation load estimates are then modified by scaling the NHH loads such that the total modelled demand at the primary is consistent with logged SCADA feeder current data. The scaling allows for the half-hourly deviations from the averaged Elexon profiles that occur with realistic loads. The revised load model is then used by the same previously developed MATLAB loss estimation method.

2.3.2 Comparison of Estimated Feeder Losses for Monitored HV Feeders

The development of processes to incorporate DINIS network data, with revised load modelling (i.e. the use of 'business-as-usual' data), has led to 'Phase 2 loss estimate results' for the 11 originally monitored HV feeders. The loss estimates from these revised processes have been compared to previously produced estimates for the monitored feeders and found to be in good agreement. High-level results are shown in Table 3.

Feeder	Feeder Metric	I2R loss percentages for actual and approximate phase allocations	'Phase 1 estimation results'	'Phase 2 estimation results'
The Woodlands (28/11/2016 to 26/12/2016)				
	Mean feeder demand, MW	1.59	1.61	1.60
	Mean Loss percentage, %	1.27	1.27	1.26
Fox Milne Hotel (28/11/2016 to 26/12/2016)				
	Mean feeder demand, MW	2.60	2.50	2.50
	Mean Loss percentage, %	2.05	2.05	1.87
Wavendon Gate Local (28/11/2016 to 26/12/2016)				
	Mean feeder demand, MW	0.95	0.94	0.94
	Mean Loss percentage, %	0.90	0.90	0.89
Secondary School Walnut Tree (28/11/2016 to 26/12/2016)				
	Mean feeder demand, MW	3.10	2.99	2.96
	Mean Loss percentage, %	1.32	1.29	1.24
Crawley Road Tee Howard Way (28/11/2016 to 26/12/2016)				
	Mean feeder demand, MW	2.73	2.72	2.71
	Mean Loss percentage, %	0.84	0.83	0.78
Amway Tongwell (28/11/2016 to 26/12/2016)				
	Mean feeder demand, MW	1.20	1.23	1.24
	Mean Loss percentage, %	0.60	0.62	0.72
Ackerman Tongwell Aldrich Drive Tee (28/11/2016 to 26/12/2016)				
	Mean feeder demand, MW	0.86	0.80	0.80
	Mean Loss percentage, %	1.26	1.24	1.23
The Avenue (01/05/2017 to 29/05/2017)				
	Mean feeder demand, MW	1.24[2]	1.33	1.31
	Mean Loss percentage, %	0.99[1]	0.94	0.98
Riverside Park (01/09/2017 to 01/10/2017)				
	Mean feeder demand, MW	1.15	1.15	1.16
	Mean Loss percentage, %	1.25	1.19	1.17

Table 3: Comparison of 'Phase1' and 'Phase 2' loss estimates, also showing loss assessments using monitoring data

[2] Loss assessments using monitoring data are from July 2017.

Detailed review of the ‘phase 2’ estimation results has noted the following points:

- Minor network topology differences to the original network data were identified in the DINIS files (open point locations and some variations in network length, typically less than 2% where found).
- Cable impedance differences – phase 1 estimation results used cable impedance data derived for this project using a finite element analysis approach, phase 2 estimation results use data from the DINIS line code file.
- Changes to customer connectivity – this should be anticipated as network connections/individual customers at connection points are not static over time

The ‘phase 2 estimation results’ include these differences.

Although the phase 2 results show some differences to the phase 1 results, the estimated losses are broadly consistent. This demonstrates the feasibility of estimated losses on a wider scale using data from business-as-usual sources, and without requiring additional measurements or manually verified modelling data.

2.3.3 DNO-scale HV Feeder Loss Estimation and Next Steps

Input data (DINIS data, CROWN data extracts, HH meter data extracts and SCADA data) has now been assembled in preparation for analysis of HV feeders across the East Midlands DNO area.

The development of the Python scripts that read and validate the East Midlands DINIS file, and assemble the associated load information is nearing completion. A graphical view of the validated DINIS network data is shown in Figure 4.

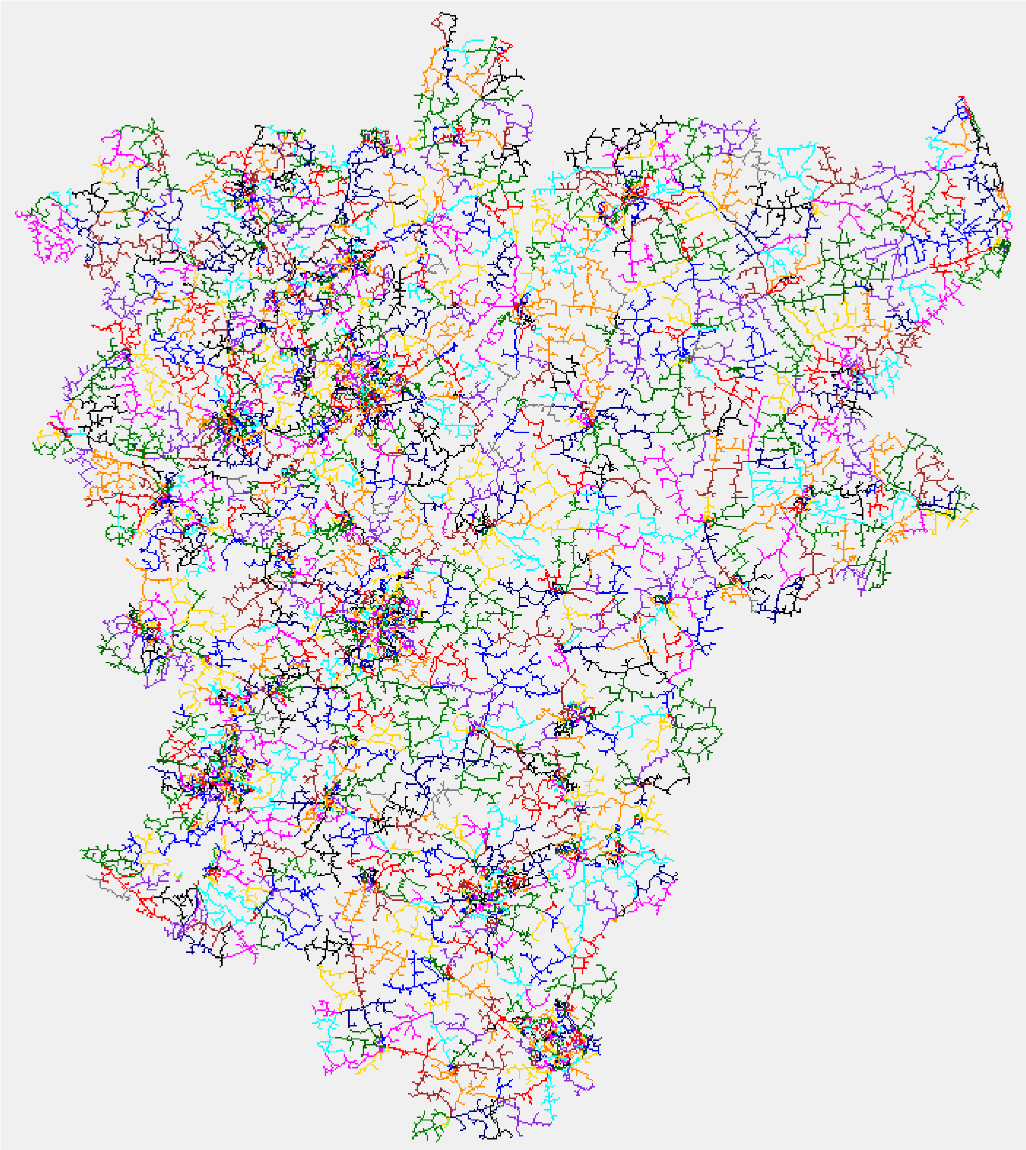

Figure 4: Graphical view of extracted and validated network data from the East Midlands DINIS data interface file.

At present, feeders can be processed by the project loss estimation method if they are: radial; 11 kV[3]; and three-phase[4] only feeders.

Over the East Midlands area, 2739 feeders have been identified within the currently available DINIS file, of these:

- 360 are feeders with loops[5]

[3] Across the East Midlands area there are a number of 6.6 kV feeders, either supplied directly from the primary or following an 11 kV to 6.6 kV transformer. The loss estimation method does not handle 6.6 kV feeders at present.

[4] Whilst the MATLAB based loss calculation engine developed and used by the project can and does calculate losses for 2 phase HV feeder sections, the pre-processing/validation of DINIS data to provide this network data is still under construction.

[5] There are a number of DINIS-data derived feeders that include loops within the topology. At present, the existence of different categories of loops has been identified but further work is needed to determine how each should be interpreted.

- 108 are feeders with mismatched feeder labels within a "discovered" feeder
- 511 feeders contain some non-three phase sections
- 160 feeders are not 11 kV

It is currently anticipated that looped, mismatched labelled and non-11kV feeders will not be included in the scope of the developed analysis. The present aim is that ~2100 of the identified 2739 feeders will be available for (at least) initial analysis, representing around 75% of the East Midlands HV feeders.

As data issues are identified, material is being collated to provide feedback to the business owners of the data, with a view to correcting the data/revising data processing to correct the encountered issues. Examples of this include:

- Duplicate nodes within the EM DINIS file (4 found)
- Branch records without corresponding start/end node records (4 found)
- Primary substations with no apparent feeders (5 found)
- Branches apparently not connected to a primary substation source (841 branches)
- Cable types with (some) missing data (19 cable types affecting 24 branches on the network)
- Multiple geographic locations with the same WPD site reference (2 that potential appear to have the potential for erroneous results)
- Missing open points (a list of 109 apparently missing open points has been prepared, this is understood to be associated with a known issue of interpreting distribution sites with switchboards or multiple ring main units)

It is anticipated that demonstration of "widely applied" HV feeder loss analysis will be completed in Q2 2018.

2.4 Further development of Loss Estimation for LV Feeders

2.4.1 Preparatory work on network approximations

As with loss estimation for HV feeders, the preferred project approach for LV feeders is to undertake load flow analysis for each considered feeder, using best available network and load information. This approach is also being taken in WPD's Electric Nation Project.

In comparison to HV feeders, the key issue is the widespread relative unavailability of established network/load connectivity data in a format that can be used in load flow analysis.

Key (large scale searchable) data uncertainties for load flow analysis for the purpose of assessing losses are:

- The identification of which traceable LV cables constitute the topological feeders from a distribution substation. For example, it may be known that a group of customers are on LV feeder 3, but it is not clear from the network diagrams which set of cable routes constitute this feeder as the numbering is not specified.
- The existence of open points between LV feeders, in the form of data tables, with appropriate referencing to LV feeders. Inaccurate knowledge of the connectivity at link boxes can cause customer loads to be omitted or included erroneously on an LV feeder.
- The connection points for loads along the LV feeders (particularly larger commercial and industrial loads)

The Electric Nation project has demonstrated methods that provide estimates of WPD LV networks emanating from distribution substations, the association of connected customers to particular estimated feeders, and a nominal connection point onto the feeder main for each identified customer. An example of such a set of estimates is shown in Figure 5.

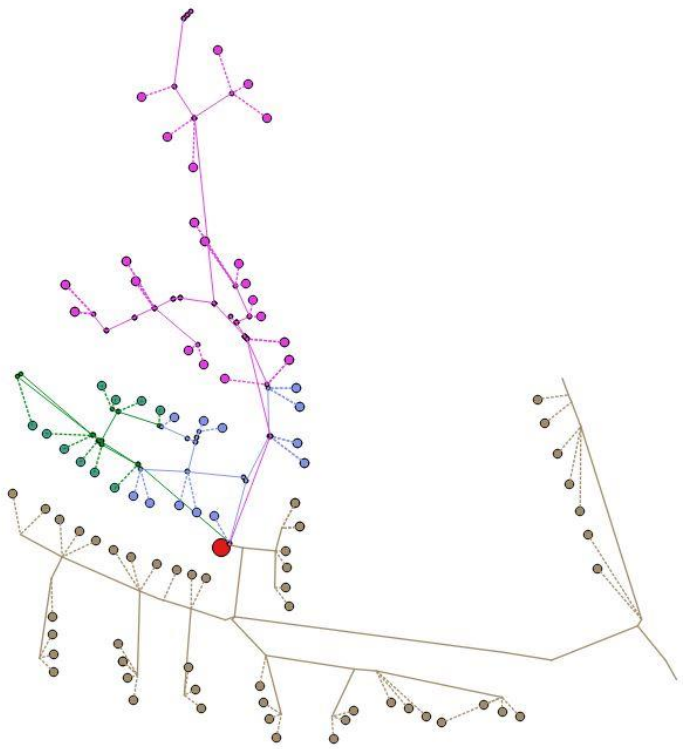

Figure 5: Example LV network estimate from the Electric Nation Project

The working approach for the Losses Investigation Project is therefore to build on the available network/load connection data that is expected from the Electric Nation Project, to add in further elements of the network model necessary for loss assessment (e.g. services), and further develop the load model (in keeping with the aspiration to provide an annual assessment of electricity losses for an LV feeder, and the financial consequences of that).

To validate this approach (of using approximated network topology and the associated load connection points), the Isle of Man monitored feeders will be further scrutinised to assess the possible impact of such network/connection approximations.

Preparatory work has been undertaken to assemble “approximated” versions of the monitored LV networks, such that load flow analysis can be carried out on a “full” model and an “approximated” model (in the style of the Electric Nation project), and the results compared.

An example of this is shown in Figure 6, which shows one LV feeder as a “full” model. In a “full” model:

- The substation is shown as a red filled circle.
- LV mains are shown as solid straight black lines between a start and end node, with the actual length of the main recorded as data associated with any particular section of main.
- Services are shown as straight dashed black lines from their actual point of connection to the main, to the customer point of connection. As with LV mains, the services are shown as straight lines, with actual route lengths recorded as data associated with the service.
- Customers are shown as blue filled circles.

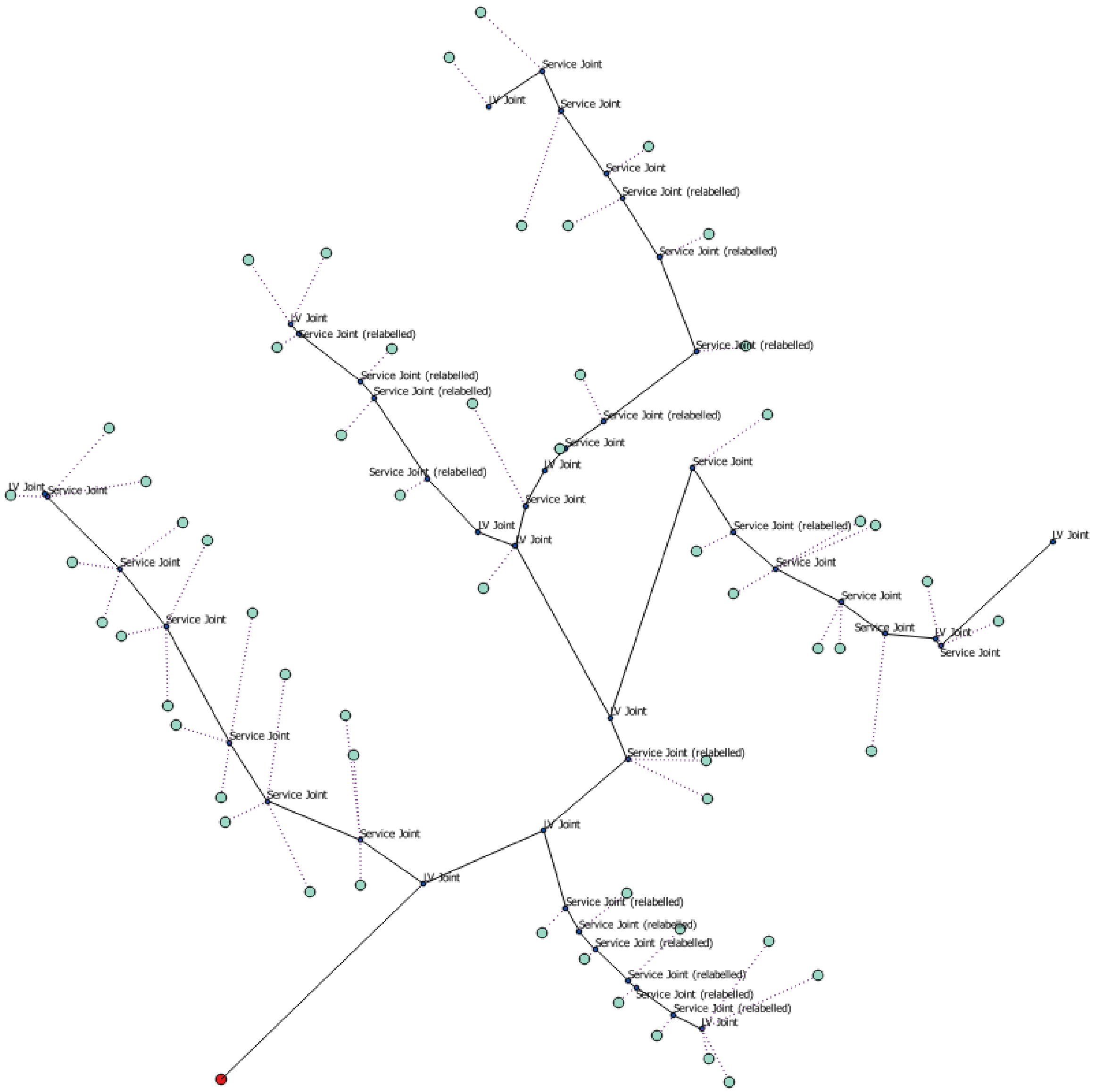

Figure 6: Example LV Feeder, with full network details

- Approximations are then applied to the full model data to arrive at a model of similar specification as are being created for Electric Nation. These applied approximations are: actual services are replaced by derived services that run from (the same) customer point of connection, to the nearest LV joint (not service joint) within the model, mimicking the Electric Nation approximation result;
- The length of a derived service is the straight line distance from the customer point of connection to the nearest LV joint; and
- LV mains start/end points and sections lengths are retained as per the full model, including cable type and cross-sectional area for each section of LV main.

The resultant approximated network is shown in Figure 7. While significant difference are visibly apparent (service length increases and service joint locations polarise between start of ends of branches), the impact in terms of network losses will be quantifiably tested through load flow analysis, with the same load model applied to both network models.

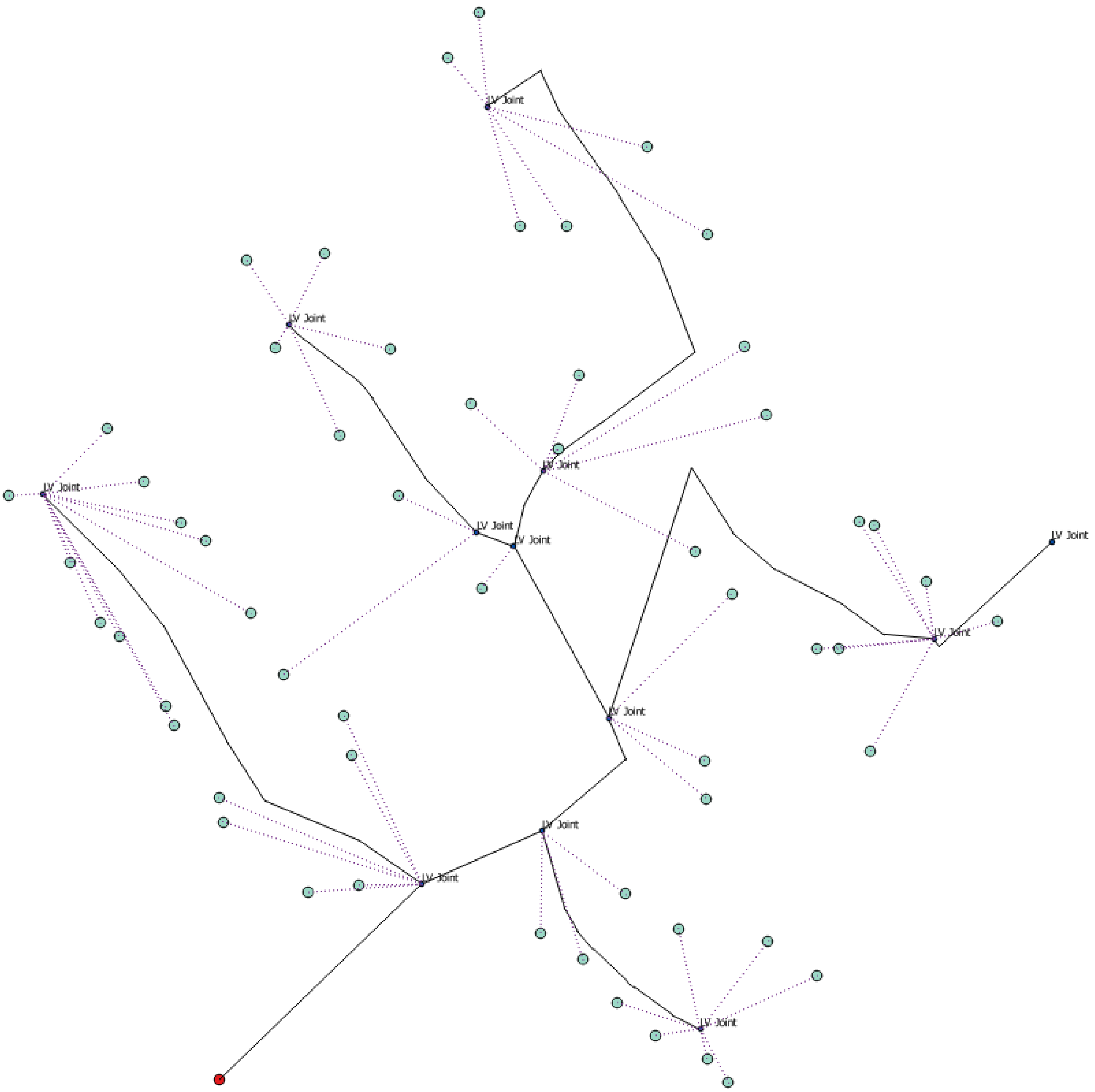

Figure 7: Example LV Feeder, with network approximations

Network approximations have been formulated for all 11 LV feeders that are being monitored.

The impact of these network approximations will be considered as next steps, when further development of the LV feeder loss estimation process resumes after the conclusion of work on HV feeders.

2.4.2 LV phase approximations

The phase allocations of single-phase customers will not generally be known for LV feeders that are not included in the measurement trials. Assuming that an accurate model for the demand is available, a method is therefore required for assigning phases to each single-phase customer and this introduces an inaccuracy into the loss estimation.

The extent to which the loss estimates are impacted by errors in the phase allocation has been studied by replacing the known phases with an arbitrarily assigned selection. This follows a simple counter, such that loads are assigned consecutive phases, incrementing in the order of their occurrence in the forward/backward sweep sequence. An exception to this process arises where multiple customers are assigned the same phase selection if they are served by a common single-phase lateral from the main feeder.

Approximating the actual phase allocations by using the sequential allocations has two consequences. Firstly, the aggregated currents will be different as the set of loads on each phase has been changed. Secondly, the mean power on each phase will change. The losses may reduce if the configuration is more balanced, but could also increase since assigning equal numbers of loads to each phase does not guarantee a balanced power.

The results of this investigation are shown in Table 4 where losses are calculated for January using the I^2R method.

	Mean power, kW		Percentage loss from I^2R method			
Feeder	Single-phase	Three-phase	Actual phase allocations	Sequential starting at L1	Sequential starting at L2	Sequential starting at L3
Pilot	9.52	0	0.38	0.38	0.38	0.38
Laxey	39.8	0	1.12	1.13	1.13	1.13
Ramsey	14.6	0.4	0.74	0.73	0.73	0.73
Tromode	43.4	0	2.28	2.04	2.04	2.03
Peel A	0	60.7	0.67	0.67	0.67	0.67
Peel B	0.2	66.0	1.79	1.80	1.80	1.79
Ballasalla	0.5	19.4	0.63	0.63	0.62	0.62
Braddan	1.0	29.8	1.17	1.17	1.18	1.18
Santon	6.1	0	0.64	0.67	0.67	0.67
Abbeylands	12.5	14.0	2.06	2.18	2.32	2.10
Ramsey	17.1	0.7	0.94	0.95	0.95	0.95

Table 4: I^2R loss percentages for actual and approximate phase allocations

In general, the percentage losses using the sequential phase allocations are very similar to those with the actual phase allocation. One feeder (Peel A) has no single-phase loads and so there is no impact of the approximated phase allocations. On several others (Peel B, Ballasalla and Braddan), the single-phase loads contribute a very small proportion of the total demand and so these feeders are also unaffected by the approximation.

There are two feeders for which the differences are slightly greater. Using the sequential phase allocations, the Tromode feeder has lower losses than with the actual phase allocations. The mean power at the substation using the actual phase allocations is L1: 8.8 kW, L2 20.9 kW, L3: 14.6 kW. The sequential phase allocations (starting on L1) give a better balance of L1: 16.6 kW, L2 13.9 kW, L3: 14.8 kW.

Conversely for the Abbeylands feeder, the mean power at the substation using the actual phase allocations is L1: 9.4 kW, L2 7.4 kW, L3: 10.8 kW. With the sequential phase allocations the mean unbalance is greater, with L1: 12.1 kW, L2 6.6 kW, L3: 8.9 kW. The network with the approximated phase allocations therefore has higher losses.

Table 4 also shows results for network models where the sequential phase allocations begin on phase L1, L2 or L3. The choice of the starting phase for the sequence has virtually no impact where all of the loads are single-phase as this simply moves the demand from one phase to another. The remaining differences are due to cable asymmetry and to the impact of using voltage measurements from different phases at the substation. However, where there are also three-phase demands on the network, changing the phase allocations causes different load currents to combine with the unbalanced three-phase loads, and the loss calculation does then depend on the phase assigned to each load. This situation arises with the Abbeylands feeder where the losses with the sequential phase allocations are noticeably different for the three different sequences.

A similar effect would occur if significant numbers of loads were connected on a single-phase spur of the network. This does not occur on the trials feeders and so the impacts of phase allocation errors with this form of topology are not included here.

Overall, the greatest error is the difference in percentage losses of 0.26% on the Abbeylands feeder. This is a change 12%. Otherwise, allocating phases according to a sequence rather than implementing the actual phase assignments tends to have very low impact on the percentage losses. When losses are estimated in the absence of measurement data, it seems likely that the errors due to the phase allocation approximation will be small in comparison to errors relating to the uncertainty in the demand.

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 %
HV Feeder Monitoring	£1,007	£771	£775	-£3	<-1%
LV Feeder monitoring	£496	£232	£222	£10	4%
Analysis	£425	£319	£331	-£12	-4%
Design & Project Management	£417	£314	£301	£13	4%
Contingency	£235	£0	£0	£0	0%
Total	£2,580	£1,636	£1,629	£8	<1%

Table 5: Progress Against Budget

3.2 Comments around variance

None.

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 3) Accurate modelling of losses with full information	**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 "I^2R" method (accurate modelling of the feeders). A snapshot of the Loss assessments for these feeders is shown in Appendix C.
4) Several models with limited data sets created and tested	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 progress with the development of this are described in Section 0 of this report. For LV feeders, initial assessment of key similarities and differences to the successful HV approach has been made. Work continues on an LV approach, and progress with development is described in Section 2.4 of this report.
5) Conclusion on level of information needed to accurately predict losses	Draft conclusions on the level of information required for HV feeders are available and will continue to be tested as the methodology is widely applied (expected Q2 2018). Conclusions on LV feeder specific loss estimation will follow.

Table 6: Progress towards project Success Criteria

5 Learning Outcomes

Selected learning from the period is noted in Table 7.

Area of Learning	Learning
HV loss analysis - Loss analysis using measurement data	• An analysis of the losses calculated using the I^2R method and with the power difference method shows that the difference in mean losses can be explained by relatively small tolerances applied to the current or voltage sensor readings. For the 11 HV trials feeders, the required correction factors were below 1% in most cases, and with only current sensor correction factor being over 2%. Although these correction factors are not necessarily the cause of the differences, the analysis shows that the agreement between the two methods is as close as could be expected given realistic tolerances on the measurement sensors. • Where the feeders include connected generation, the loss metrics need careful definition when defining the power input to the network. If the loss is simply expressed as a percentage of the power input at the primary, spurious results would be obtained if the net demand is zero, or if the feeder is exporting power upstream. Results are now presented where the loss power is expressed as a percentage of the total power imported to the feeder, either from the primary or from any of the distribution substations with a net export from the downstream side. • Similarly, the line loss factor figures (LLFs) need to be calculated carefully when the feeder includes generation. The LLF for a distribution transformer (the ratio of mean current in to the mean current out) must take account of changes in direction of the power flow on individual samples. Taking a simple example, with zero net demand (equal mean import and mean export power), the ratio of power on the HV side to that on the LV side would otherwise appear to be unity, whereas in practice there is a loss in each direction.
HV loss analysis - Network connectivity	• The loss estimation method requires input data to specify the network connectivity, and for estimation of losses on a regional scale, this network data must come from business-

Area of Learning	Learning
modelling	as-usual (BaU) databases. The BaU data has been found to be in close agreement with the project data as regards cable types, lengths, and the connection topology. • The BaU network data is not fully accurate in specifying the locations of open points. This affects the accuracy of the loss estimation as demand is either erroneously omitted or included and as the total transformer no-load losses are also incorrect. Within the set of 11 trials feeders, errors in the open point locations account for errors in the total feeder losses of around 5% of the loss power. • The cable impedances used by the DINIS software tool are around 5% lower than those estimated using for the project using finite element analysis. This difference is likely to be due to the omission of AC resistance effects in the DINIS data. This difference translates into a 5% reduction in the estimated cable losses (although not a 5% error in the total losses after allowing for the transformers). Feedback will be offered to the DINIS business owners • The loss estimation method is also impacted by errors in the number and location of customer connections, particularly where these are more heavily loaded half-hourly metered connections. In one of the HV trials feeders, differences between the BaU meter data and the project meter data accounted for a change in the estimated losses of 15%. However, the differences in meter data for other feeders caused a much lower impact. • It is expected that significant errors in the estimated demand due to inaccurate locations and assignments of customer connections can be detected as the scaling factor applied to the non-metered demand (such that the estimated primary substation current matches measurements) will be atypical. • Omitting the cable admittances has a negligible impact on the estimated losses. (However, including these effects was helpful when comparing the measured and calculated primary substation currents in order to verify that the simulations and measurement instrumentation were correctly deployed and consistent.) • The BaU DINIS network data includes a number of loops in the feeder topologies. In some cases these represent the actual operational state, but in others are due to the absence

Area of Learning	Learning
	of open points in the network data. There are also loops caused by limitations in the interpretation of the cable connectivity at substations, typically where physically separate junction nodes are assumed to be co-located. These erroneous loops are a constraint for unbalanced load-flow solvers where a radial topology is required. The loops can be easily resolved where planners might consider modelling individual feeders, but algorithmic methods are required for automated simulations on a regional scale. • The DINIS network files also have a number of inconsistencies such as branches defined with no end nodes, co-located nodes and duplicated site references. As with the feeder loops, these issues may be easily fixed when individual feeders are modelled by the planning teams, but difficulties arise when the network data is integrated with metering and transformer data. When these multiple BaU data sources are combined, the integrity of the data structures becomes more critical. • A number of the DINIS cable types have been found to have missing impedance data, such that voltage drops may be under-represented in BaU modelling. This information can be used as feedback to WPD network planning processes. Where necessary, approximations have been used for the project purposes.
LV loss analysis - Self-consumption of smart meters	• The self-consumption current of the smart meters used in the LV trials occurs on the DNO side of the meter (rather than on the customer side) and so contributes to the losses on the feeder. This adds a no-load loss factor which should be considered together with the I^2R losses of the feeder cables. • The losses for a whole-current single-phase meter (i.e. without a current transformer) have been measured using a test bench and found to be approximately 1.1 W. No significant additional impact has been observed relating to the processing or communications tasks involved in capturing and transmitting the high-resolution measurement data for the trials. • The meters also have a reactive power consumption of approximately 1.5 var at 50 Hz. The self-consumption current

Area of Learning	Learning
	is also highly distorted with approximately 20% current THD such that the meters have an apparent power of 2.8 VA. • The power consumption of the three-phase meters has not been comprehensively measured but initial tests have given similar results to the consumption of the single-phase meters. The trials analysis has therefore assumed that the same figures can be adopted for three-phase meters as for single-phase meters. • The smart meter active power loss figures are consistent with the data previously obtained from the manufacturer. The apparent power figures are also consistent, but the test bench results show that the reactive power is dominated by distortion, with lower reactive power at 50 Hz. • The self-consumption current due to the GridKey loggers (at substations in the LV trial and at primary and distribution substations in the HV trial) is very small relative to the measured loads and so have been neglected.
LV loss analysis - Accuracy of recorded power	• Detailed measurements of the active and reactive power obtained by the single-phase smart meters in the LV trial has shown that the recorded active power data is typically 5 W lower than would be expected based on differential measurements of the energy delivered. • Since the smart meters are designed and qualified as energy meters, and with the power measurements derived from the load surveys being a more unconventional use of this equipment, it has been decided to accept the energy readings as being more accurate. The accuracy of the energy readings is also verified in unit tests carried out by the manufacturer and in acceptance tests using the Manx Utilities test bench. • The reactive power measurements for single-phase meters also show a 5 W offset relative to the recorded reactive energy differences, but only for positive reactive power. • Three-phase meters with current transformers have a similar pattern of offsets in the recorded active power but with the differences being scaled from 5 W according to the current transformer ratio. • It is assumed that these differences are due to rounding of data processing issues within the load survey software

Area of Learning	Learning
	implementation. The fundamental measurement accuracies of current and voltage are consistent with the expected accuracy of the reported energy differences, but not with that of the reported power. • A key conclusion from the above is that the loss calculations using the power difference method are more reliable if the mean power over a period is derived from differential energy readings than by averaging the time series of power measurements. Clearly, the energy readings should be captured from each meter at the same time, although allowances can be made (using short term power readings) for any time offsets. • While the use of power and energy readings should theoretically give equivalent results, the recording of energy differences avoids any issues due to numerical handling of individual power readings. Although the offsets identified here may relate only to the specific meter types used in the trial, there is a general conclusion that smart meter measurement modes that are not conventionally used may be less well tested and qualified than those that are more closely aligned with their primary purpose.
LV loss analysis - Time synchronisation	• In addition to the impacts of offset in the recorded power data, the 1-minute loss calculations using the power difference have a greater spread due to residual differences in the clocks of each meter and the GridKey logger. Calculating the mean loss over a 10- minute period removes much of this spread, and gives results that are more closely in agreement with the results from the I^2R method.
LV loss analysis - Neutral current ratio	• The neutral currents on LV feeders from distribution substations in the HV trial in Milton Keynes can be substantial, both in absolute terms and relative to the mean phase current. For feeders with mean phase currents of over 100 A (averaged over time and over the three phases), there are many examples where the neutral current is 50% of the mean phase current. For feeders with mean phase currents between 50 and 100 A, the mean neutral current ranges up to 100% of the mean phase current. • This suggests a higher level of unbalance than was considered in previous analyses where an indicative figure of

Area of Learning	Learning
	35% was used as the ratio of neutral to phase currents. • Highly-loaded feeders on the LV trial in the Isle of Man have similar neutral current ratios. • LV feeders in the Isle of Man serving industrial customers are typically more balanced with neutral currents of around 10% of the mean phase current.
LV loss analysis - Estimation method	• If the actual phase allocation of single-phase customers is not known, the customer phases can be assigned using a sequential approach. For the LV trials feeders, this approximation introduces a relatively small error with up to 12% difference in the calculated losses using measurement data. • The estimated losses can either increase or reduce if estimated phase allocations are used in place of the actual data. Although the estimated phase allocations have equal numbers of customers on each phase, this may either over-estimate or under-estimate the unbalance if the mean demands for each customer are different.
HV loss analysis - Estimation method	• Where the feeder includes generation, either from metered connections, or in the non-metered demand, the estimation method must allow for net demand to be either positive or negative. The non-metered demand profiles can also be either positive or negative. Since only the magnitude of the primary substation current is known, there are two possible scaling factors of the non-metered profiles that would be consistent with the measured data. Good results for the trials feeders have been obtained by selecting the scaling factor closest to unity. • There are minor impacts on the estimated losses if the distribution transformer tap settings are not accurately known. Typically the transformers are assumed to be on a tap setting of 2, as has been found to be the case for most of the transformers on the HV trial, but the transformer load losses would be under-estimated if transformers were actually on tap 1 or over-estimated if a higher tap setting were used. • The model assumes constant power loads, and also assumes a constant voltage and current at the primary, and so inaccurate tap setting data causes no error to the estimated

Area of Learning	Learning
	cable losses or to the transformer no-load losses. • The estimation method is also unaffected if single-phase transformers were to be modelled as three-phase transformers, although this data is available from BaU processes and so this concern should not arise in practice. • The BaU network data does not indicate the phases to which single-phase transformers are assigned, or phases that are used to connect single-phase branches of the network into the three-phase feeders. An approach with the worst-case unbalance has been adopted in which all of the single-phase network is connected between the red and blue phases.

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.	15	• Adoption of Pilot approach. • Retention of both power difference and I^2R calculation methods. • Review of differences between the loss assessment of the two calculation methods	• Credible explanations of differences between calculation methods are within instrument tolerances. • Final checks on uncertainty in the overall methodology will be made once estimates of loss have been made for a wide range of feeders.
Unavailability of Distribution Transformer parameters /insufficiency of type values for loss assessment.	18	• Retention of both power difference and I^2R calculation methods as a cross-check to identify if transformer values are material issues.	• A first draft lookup table for transformer load and no-load loss values is currently being used where transformer-specific values are not available. • Additional work will be undertaken to further validate these values.
Time synchronisation of data available from different field devices is not adequate.	9	• 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.	9	• Adoption of Pilot approach. • Review of differences between the loss assessment of the two calculation methods	• Probable causes of differences between the loss assessment methods are due to apparent data inaccuracies in the meter load survey logging. • Correction factors have been drawn up and are in use.

Captured EDMI meter data cannot be adequately transmitted to a central data store for required roll out	6	• Project plan always included the implementation of a volume meter data collection system. • Collaborative testing of the proposed system.	• Volume data collection system is now undergoing final testing.

Table 8: Top five current risks (by rating)

Figure 8 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	1	1	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	6	2	0	0	**No of instances**
Total	8				No of live risks

Figure 8: Snapshot of Risk Register

Figure 9 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.

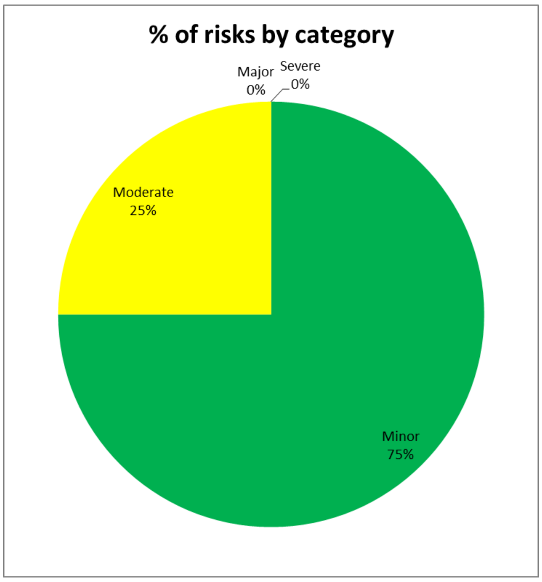

Figure 9: Graphical view of Risk Register by Risk Category

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[6]<<.

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.

[6] 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 I^2R 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 I^2R 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 I^2R calculation primarily based on current measurements at each downstream point on the networks. Additional information is needed for use with the I^2R 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 different tolerances in assessed losses arise from the two different methods, the I^2R 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 I^2R 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 10. 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.

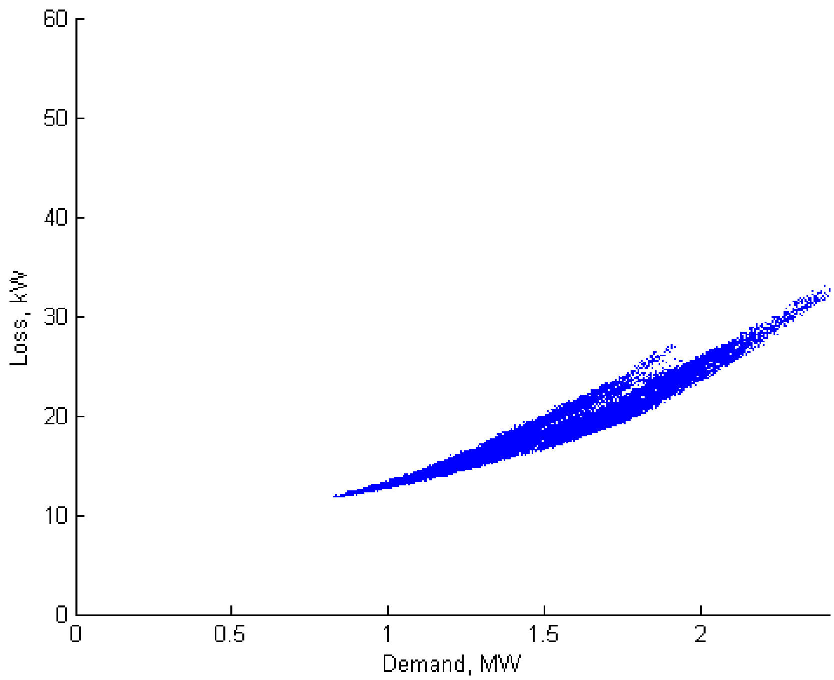

Figure 10: Pilot HV feeder losses for each 1 minute sample calculated with I^2R method

Using the I^2R 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 I^2R 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 11.

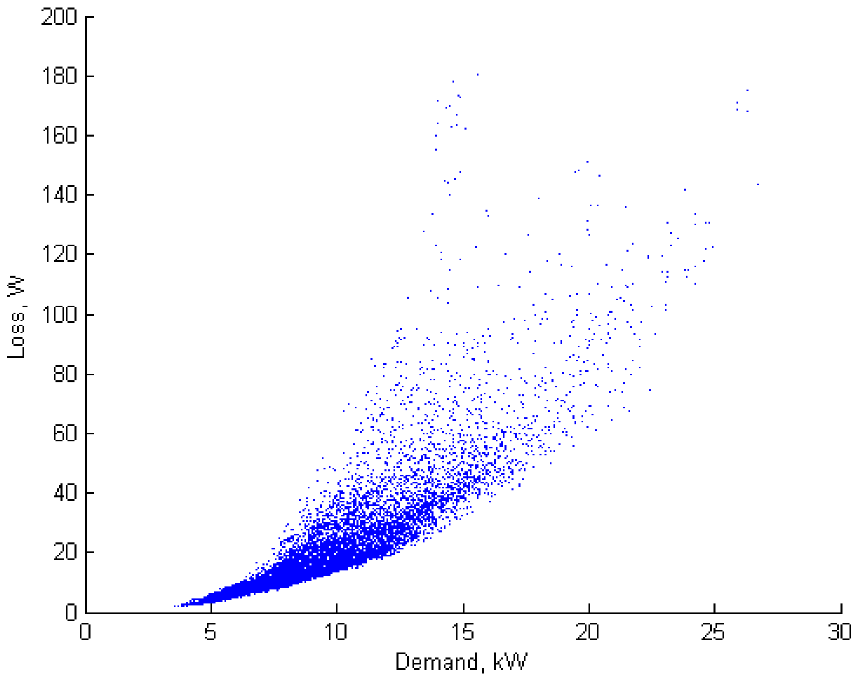

Figure 11: Pilot LV feeder losses for each 1 minute sample calculated with I^2R method

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 12 compares the loss calculations from the power difference and the I^2R 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 I^2R method is based on calculated component losses (i.e. modest percentages of small numbers). Therefore the I^2R method of loss calculation is fundamentally very much less sensitive to the same intrinsic instrument tolerances.

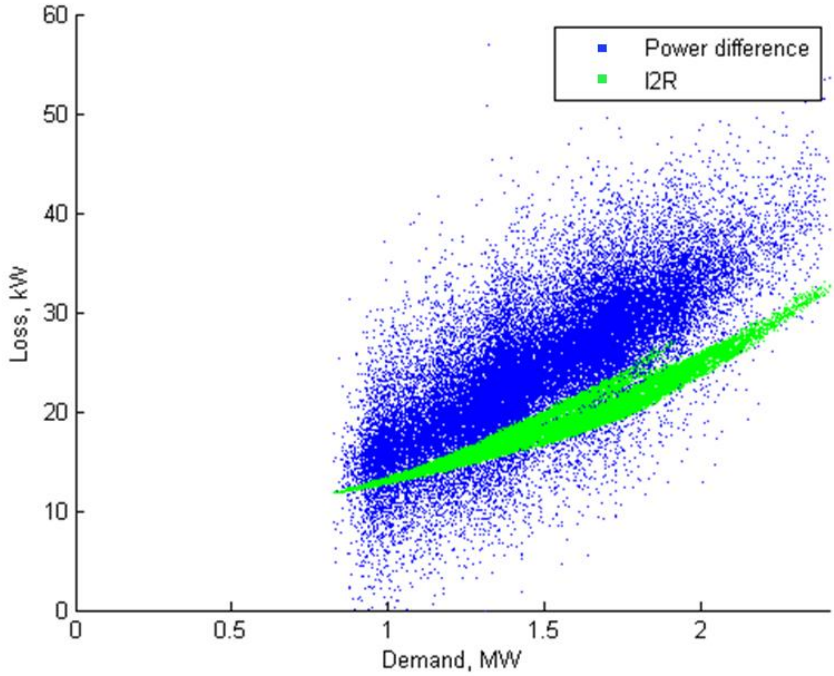

Figure 12: Pilot HV feeder losses for each 1 minute sample calculated with the power difference method and with the I^2R method

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 - 1*ϕ*	*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

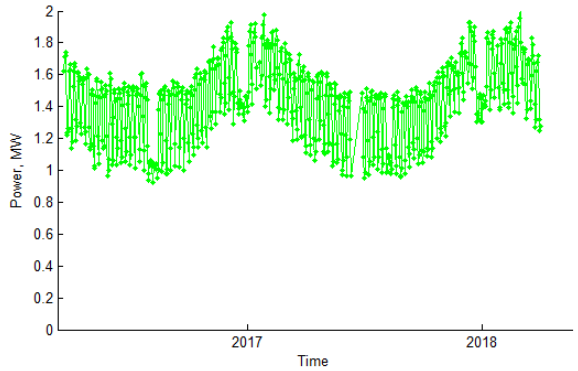

Figure 13: Long term mean daily feeder demand (Woodlands HV feeder)

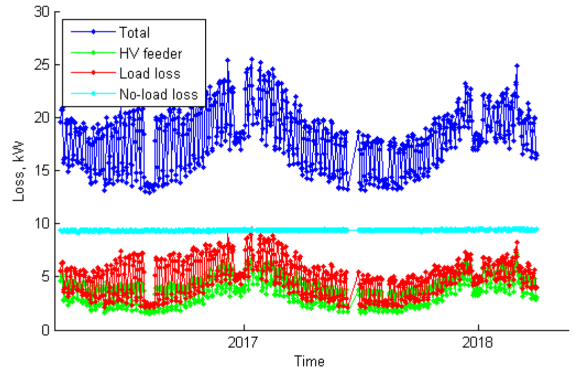

Figure 14: Long term mean daily (I^2R) loss (Woodlands HV feeder)

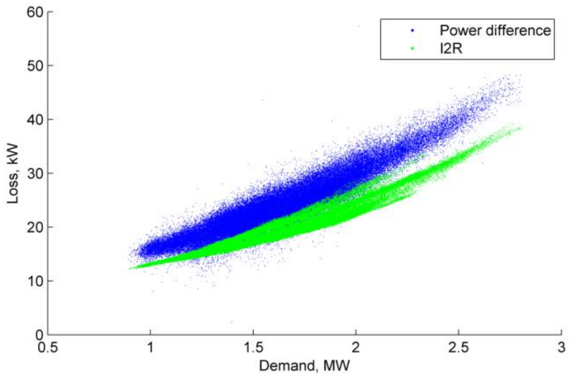

Figure 15: Feb & Mar 2018 2017 Loss, kW vs demand (Woodlands HV feeder)

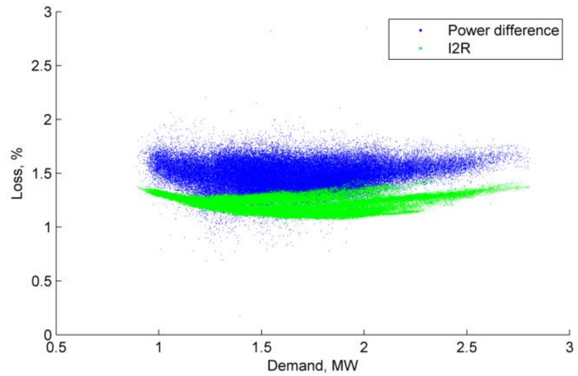

Figure 16: Feb & Mar 2018 2017 Loss, % vs demand (Woodlands HV feeder)

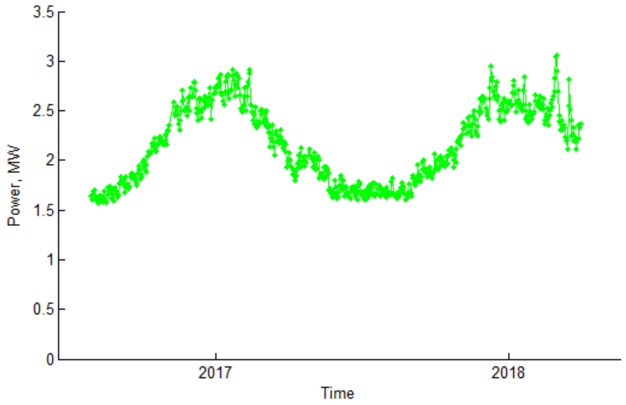

Figure 17: Long term mean daily feeder demand (Fox Milne Hotel HV feeder)

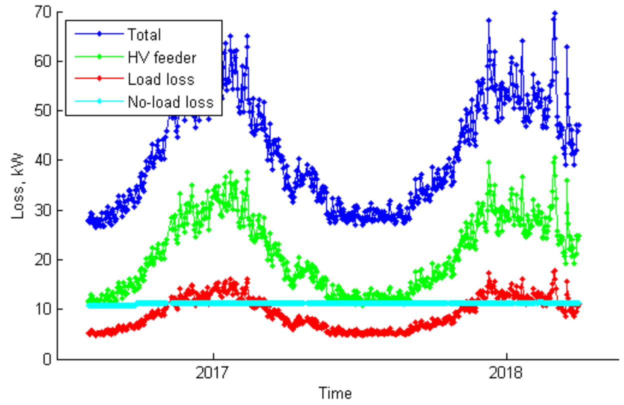

Figure 18: Long term mean daily (I^2R) loss (Fox Milne Hotel HV feeder)

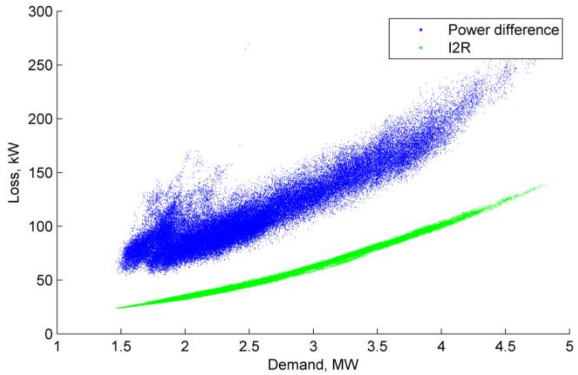

Figure 19: Feb & Mar 2018 Loss, kW vs demand (Fox Milne Hotel HV feeder)

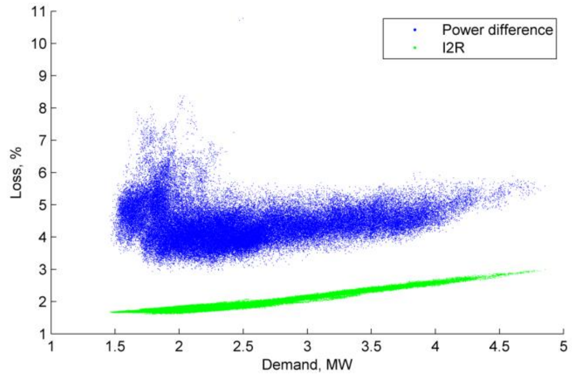

Figure 20: Feb & Mar 2018 Loss, % vs demand (Fox Milne Hotel HV feeder)

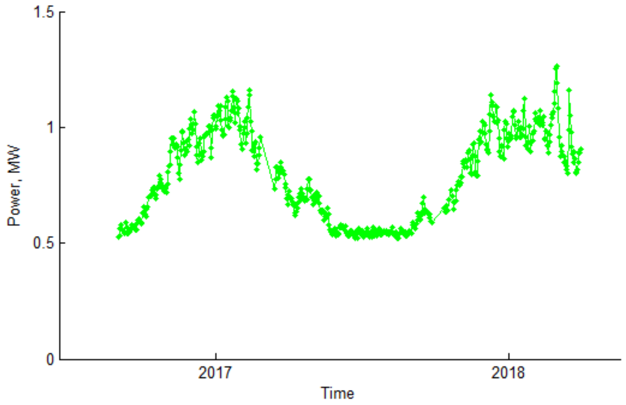

Figure 21: Long term mean daily feeder demand (Wavendon Gate Local HV feeder)

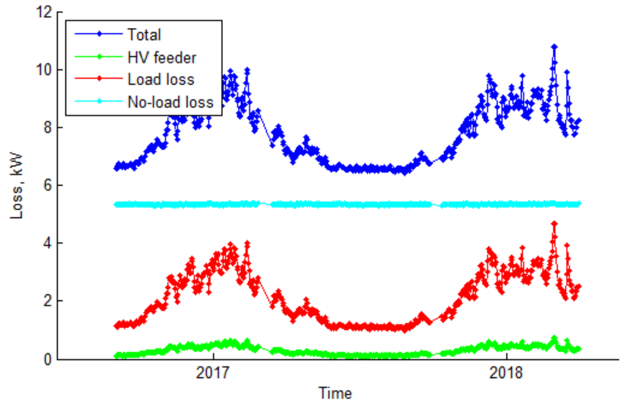

Figure 22: Long term mean daily (I^2R) loss (Wavendon Gate Local HV feeder)

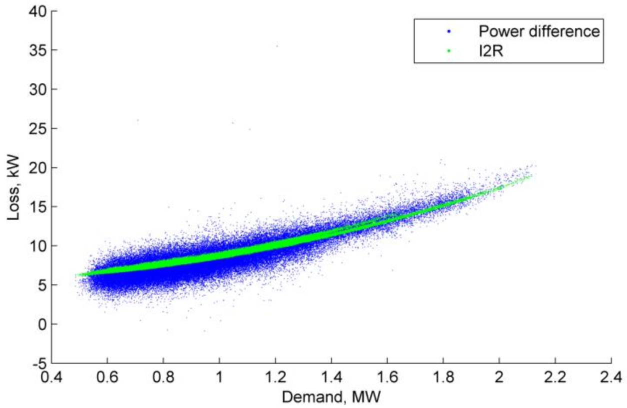

Figure 23: Mar & Apr 2018 Loss, kW vs demand (Wavendon Gate Local HV feeder)

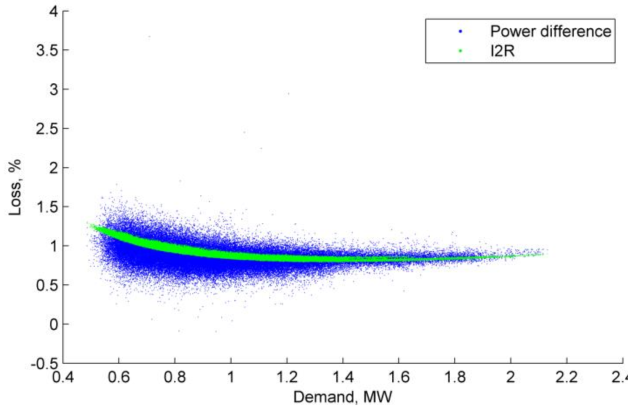

Figure 24: Mar & Apr 2018 Loss, % vs demand (Wavendon Gate Local HV feeder)

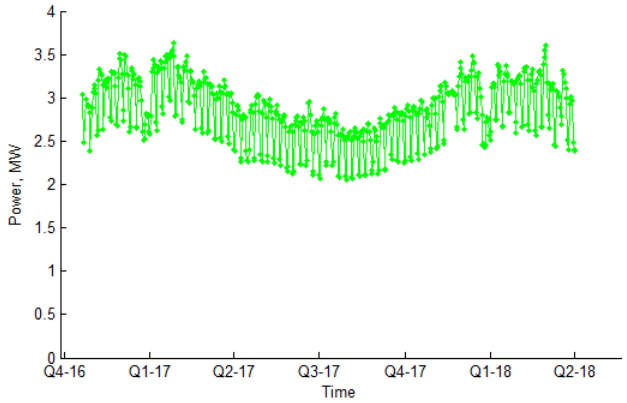

Figure 25: Long term mean daily feeder demand (Secondary School Walnut Tree HV feeder)

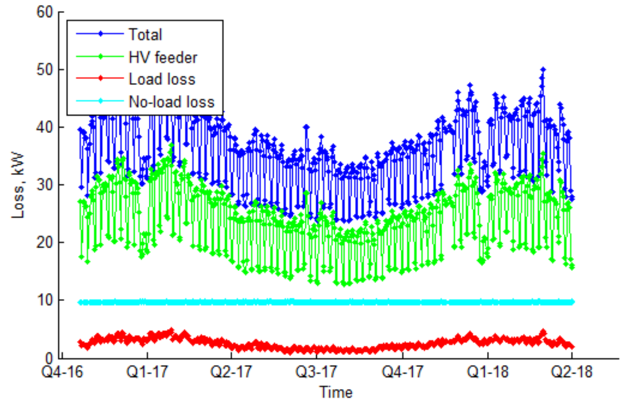

Figure 26: Long term mean daily (I^2R) loss (Secondary School Walnut Tree HV feeder)

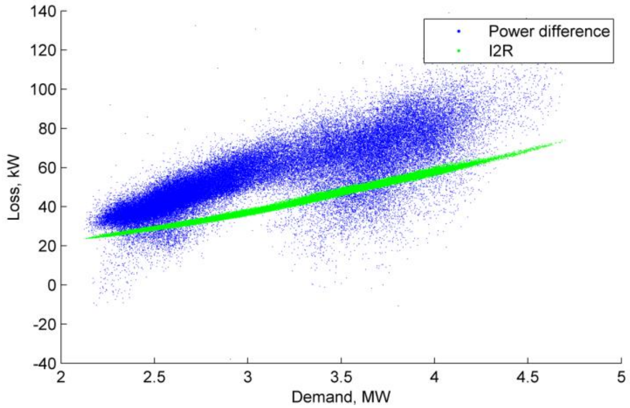

Figure 27: Mar & Apr 2018 Loss, kW vs demand (Secondary School Walnut Tree HV feeder)

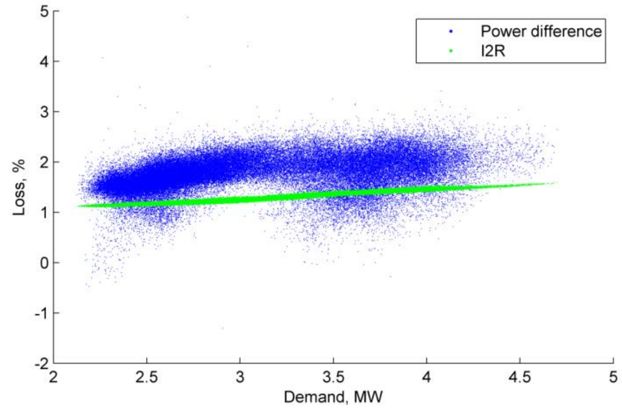

Figure 28: Mar & Apr 2018 Loss, % vs demand (Secondary School Walnut Tree HV feeder)

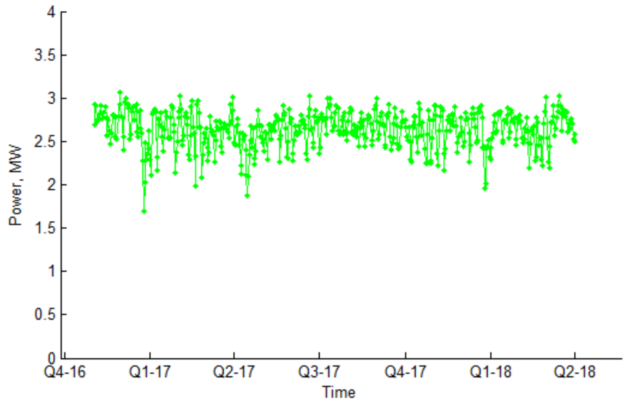

Figure 29: Long term mean daily feeder demand (Crawley Road Tee Howard Way HV feeder)

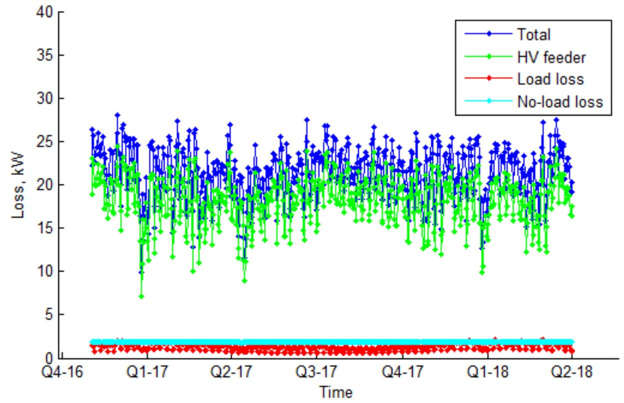

Figure 30: Long term mean daily (I^2R) loss (Crawley Road Tee Howard Way HV feeder)

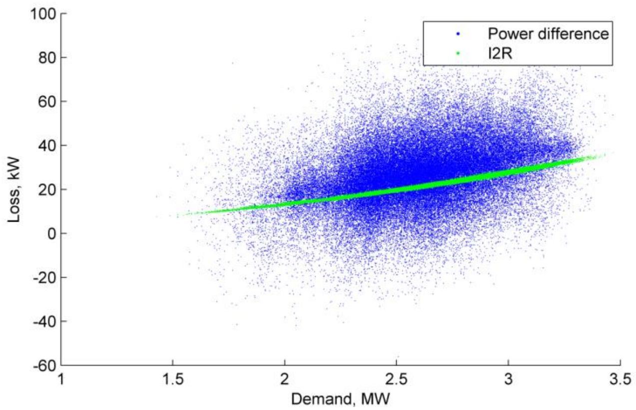

Figure 31: Mar & Apr 2018 Loss, kW vs demand (Crawley Road Tee Howard Way HV feeder)

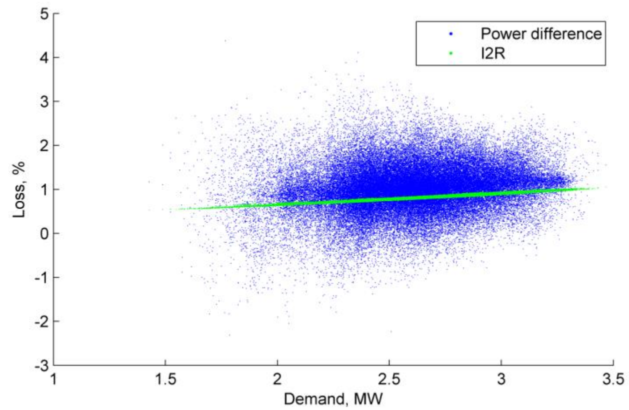

Figure 32: Mar & Apr 2018 Loss, % vs demand (Crawley Road Tee Howard Way HV feeder)

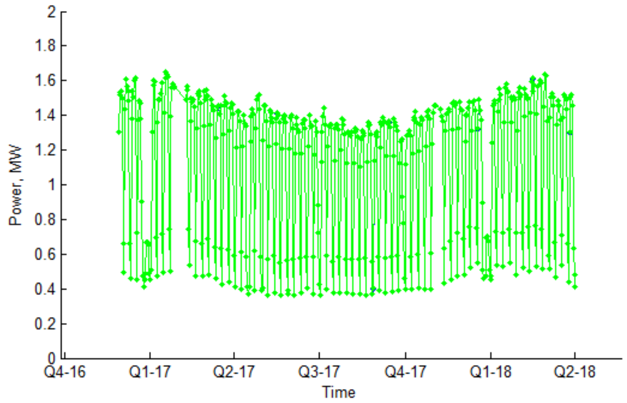

Figure 33: Long term mean daily feeder demand (Amway Tongwell HV feeder)

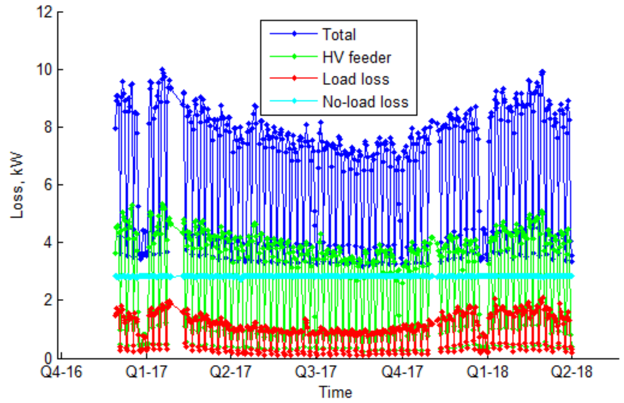

Figure 34: Long term mean daily (I^2R) loss (Amway Tongwell HV feeder)

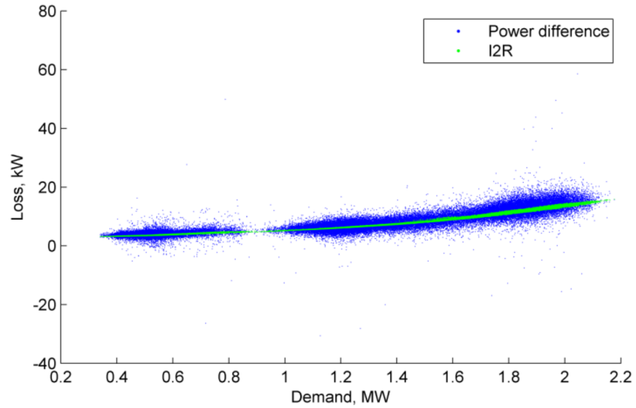

Figure 35: Mar & Apr 2018 Loss, kW vs demand (Amway Tongwell HV feeder)

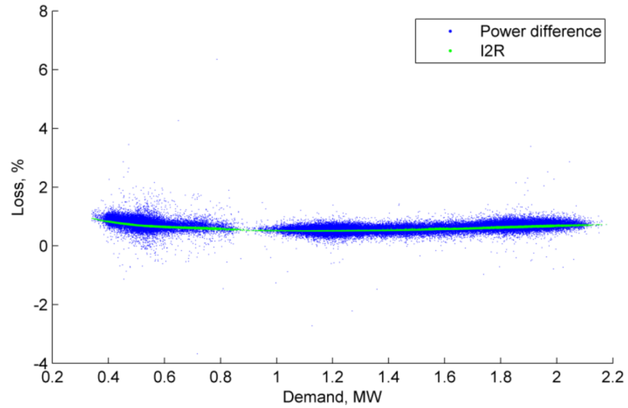

Figure 36: Mar & Apr 2018 Loss, % vs demand (Amway Tongwell HV feeder)

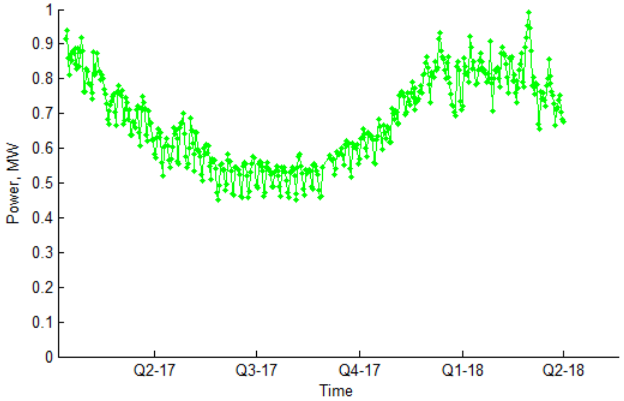

Figure 37: Long term mean daily feeder demand (Ackerman Tongwell Aldrich Drive Tee HV feeder)

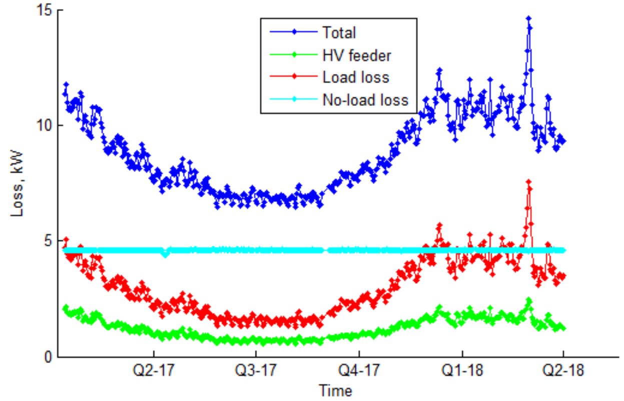

Figure 38: Long term mean daily (I^2R) loss (Ackerman Tongwell Aldrich Drive Tee HV feeder)

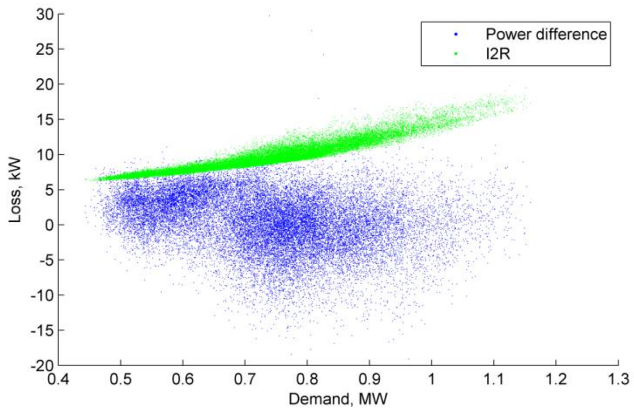

Figure 39: Mar & Apr 2018 Loss, kW vs demand (Ackerman Tongwell Aldrich Drive Tee HV feeder)

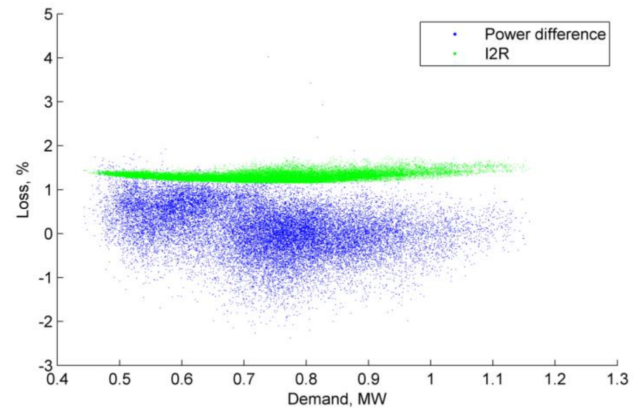

Figure 40: Mar & Apr 2018 Loss, % vs demand (Ackerman Tongwell Aldrich Drive Tee HV feeder)

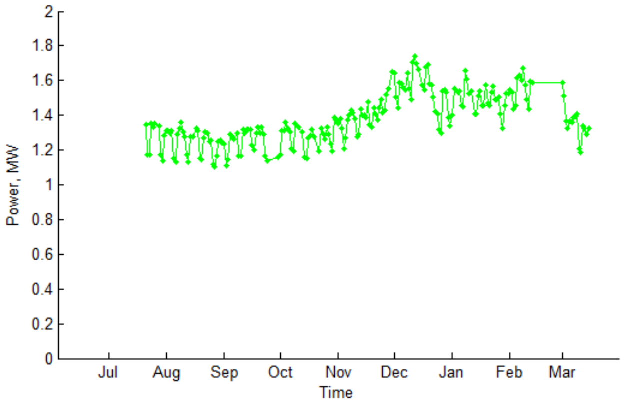

Figure 41: Long term mean daily feeder demand (The Avenue HV feeder)

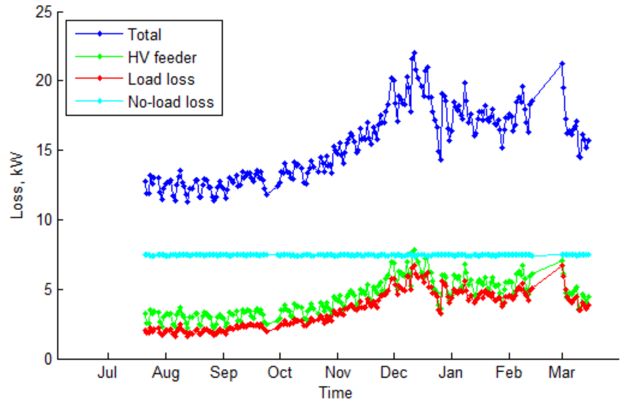

Figure 42: Long term mean daily (I^2R) loss (The Avenue HV feeder)

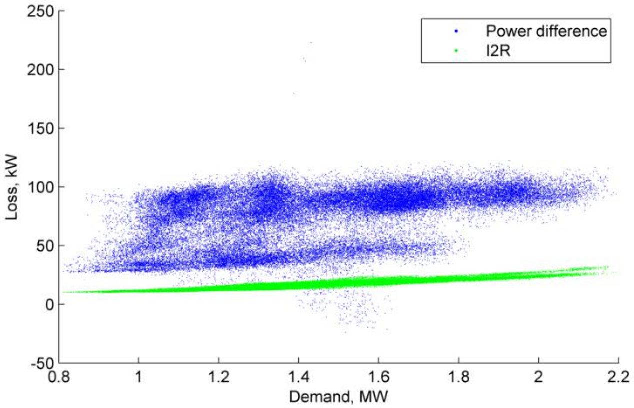

Figure 43: Mar & Apr 2018 Loss, kW vs demand (The Avenue HV feeder)

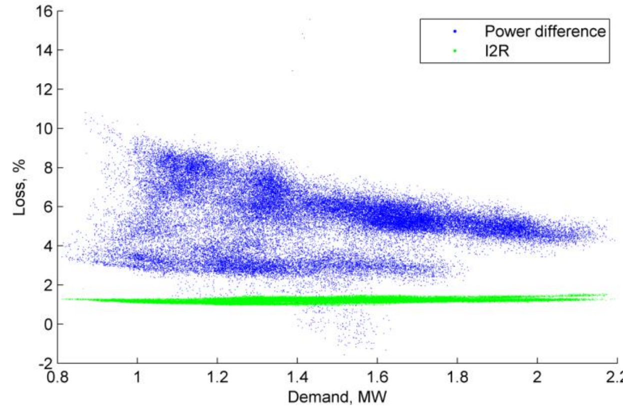

Figure 44: Mar & Apr 2018 Loss, % vs demand (The Avenue HV feeder)

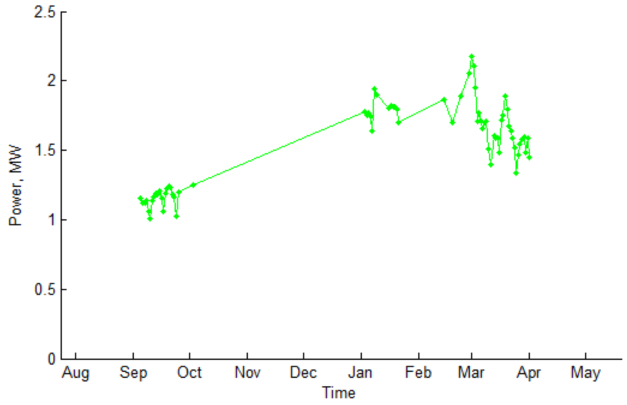

Figure 45: Long term mean daily feeder demand (Riverside Park HV feeder)

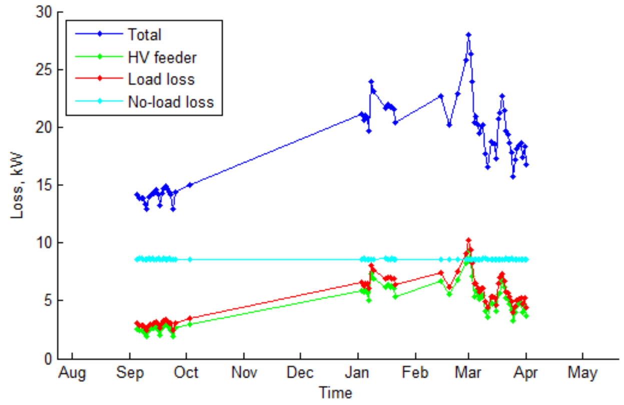

Figure 46: Long term mean daily (I^2R) loss (Riverside Park HV feeder)

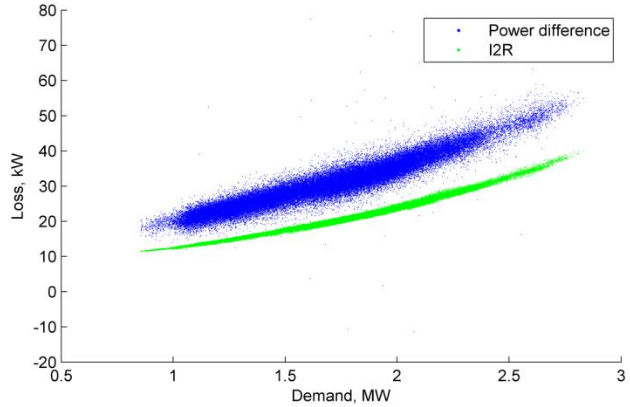

Figure 47: Mar & Apr 2018 Loss, kW vs demand (Riverside Park HV feeder)

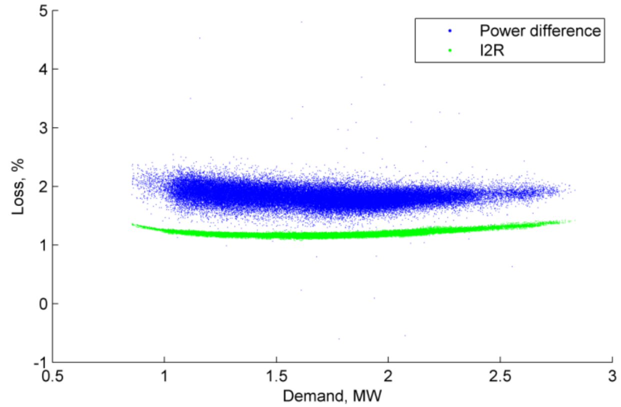

Figure 48: Mar & Apr 2018 Loss, % vs demand (Riverside Park HV feeder)

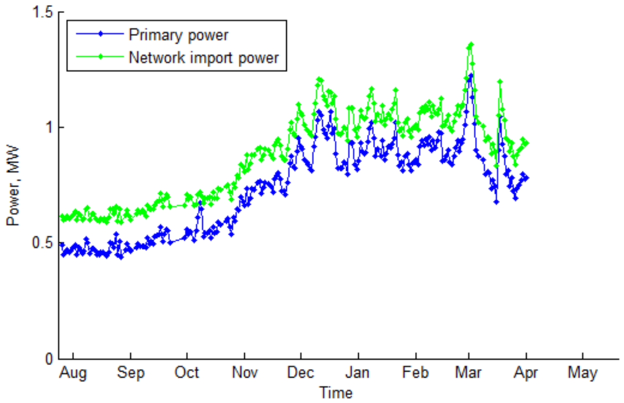

Figure 49: Long term mean daily feeder demand (Silver End HV feeder)

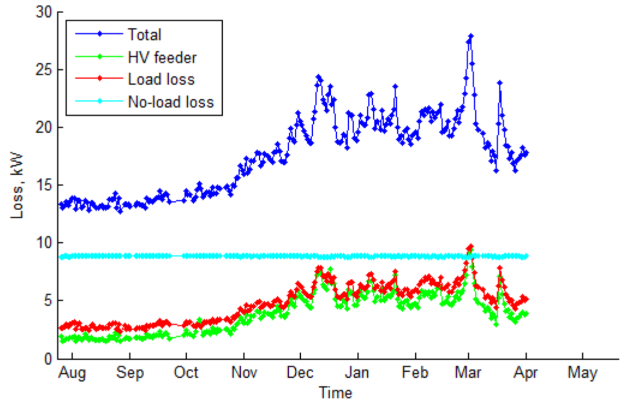

Figure 50: Long term mean daily (I^2R) loss (Silver End HV feeder)

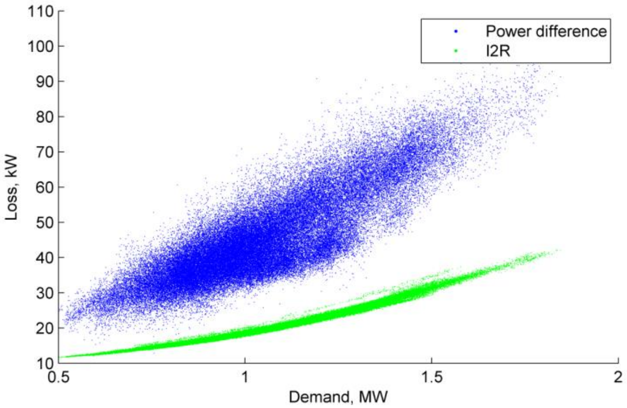

Figure 51: Mar & Apr 2018 Loss, kW vs demand (Silver End HV feeder)

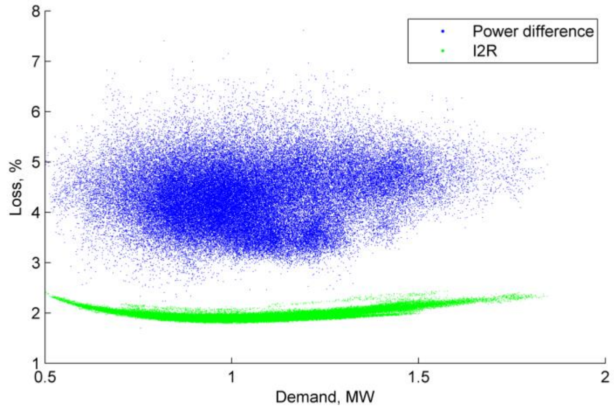

Figure 52: Mar & Apr 2018 Loss, % vs demand (Silver End HV feeder)

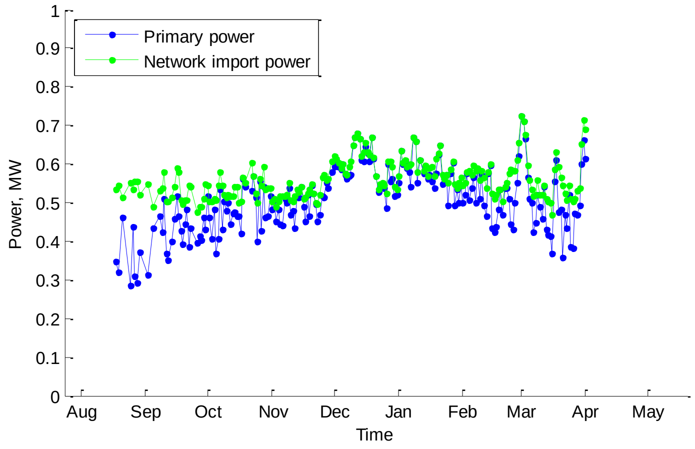

Figure 53: Long term mean daily feeder demand (Wolverton HV feeder)

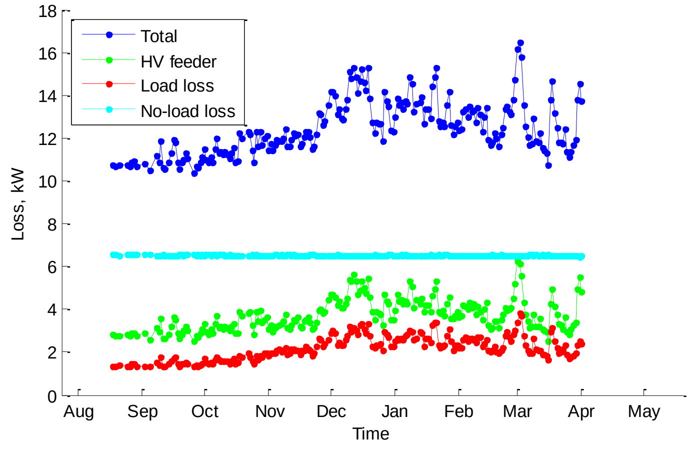

Figure 54: Long term mean daily (I^2R) loss (Wolverton HV feeder)

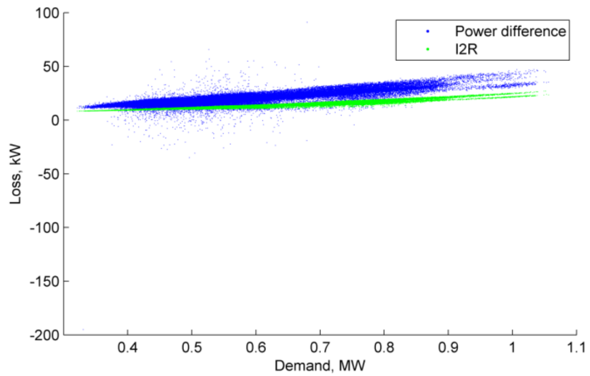

Figure 55: Mar & Apr 2018 Loss, kW vs demand (Wolverton HV feeder)

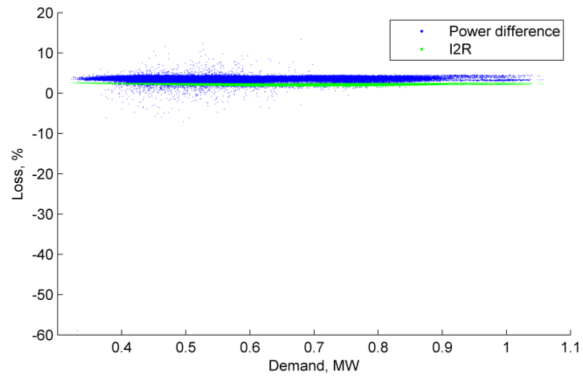

Figure 56: Mar & Apr 2018 Loss, % vs demand (Wolverton HV feeder)

Appendix C 2 LV feeders

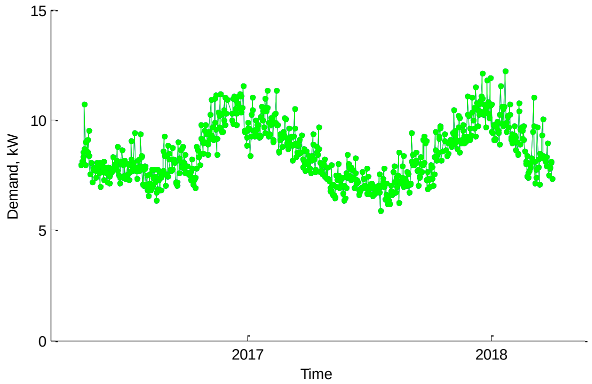

Figure 57: Long term mean daily feeder demand (Domestic Pilot LV feeder)

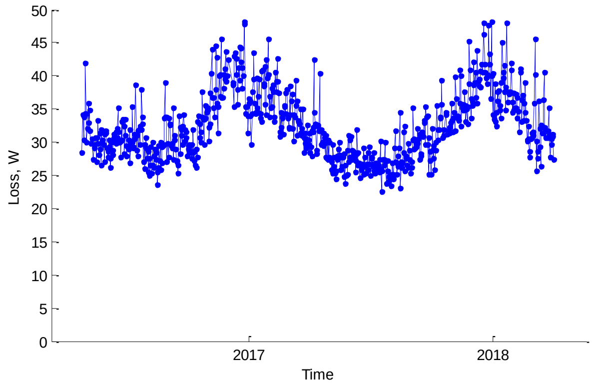

Figure 58: Long term mean daily (I^2R) loss (Domestic Pilot LV feeder)

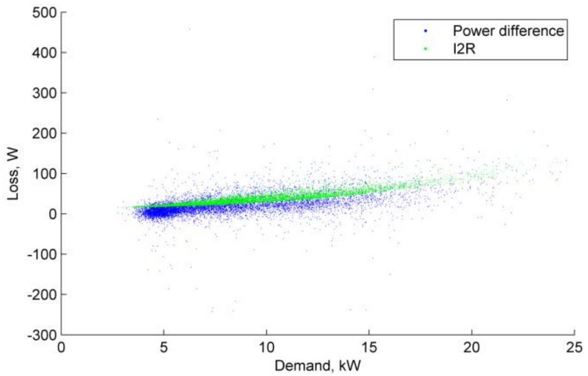

Figure 59: Mar & Apr 2018 Loss, kW vs demand, 10 min. av. (Dom. Pilot LV feeder)

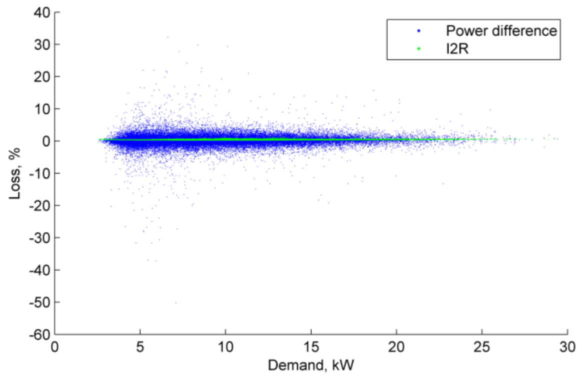

Figure 60: Mar & Apr 2018 2017 Loss, % vs demand, 1 min. av. (Dom.Pilot LV feeder)

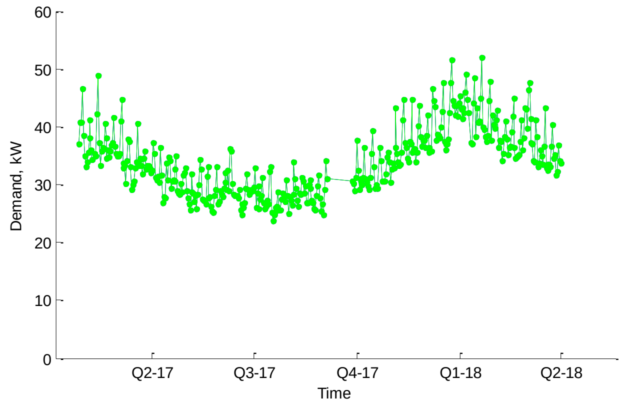

Figure 61: Long term mean daily feeder demand (Laxey Dom. LV feeder)

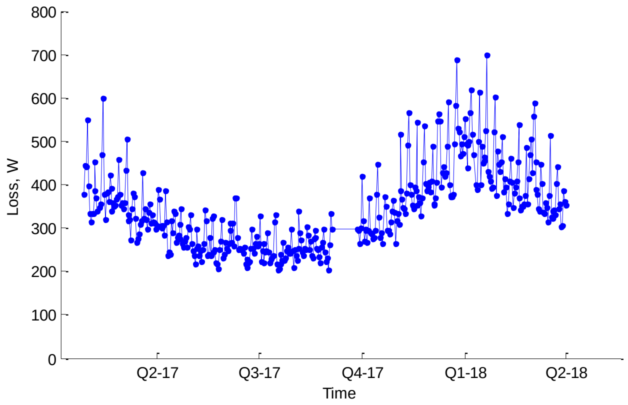

Figure 62: Long term mean daily (I^2R) loss (Laxey Dom. LV feeder)

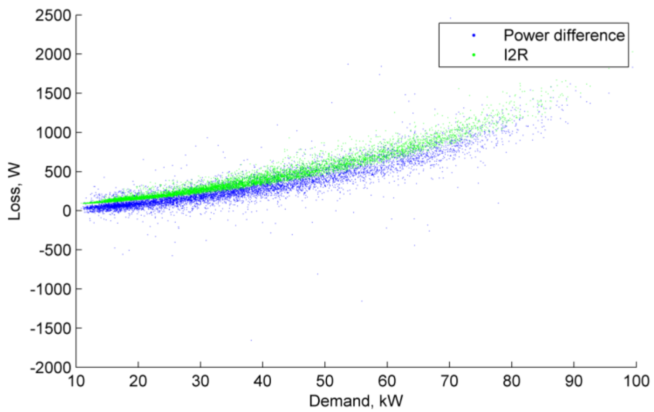

Figure 63: Mar & Apr 2018 Loss, kW vs demand, 10 min. av. (Laxey Dom. LV feeder)

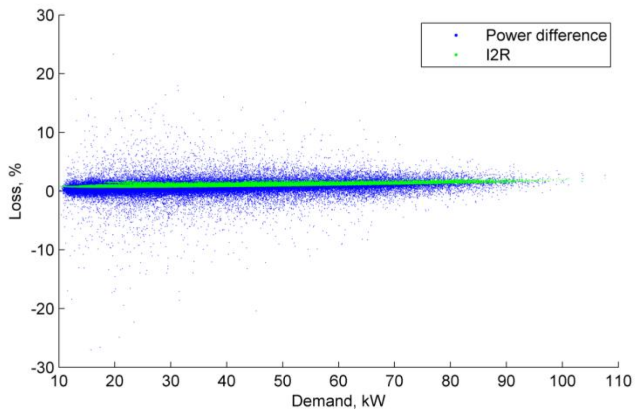

Figure 64: Mar & Apr 2018 Loss, % vs demand, 1 min. av. (Laxey Dom. LV feeder)

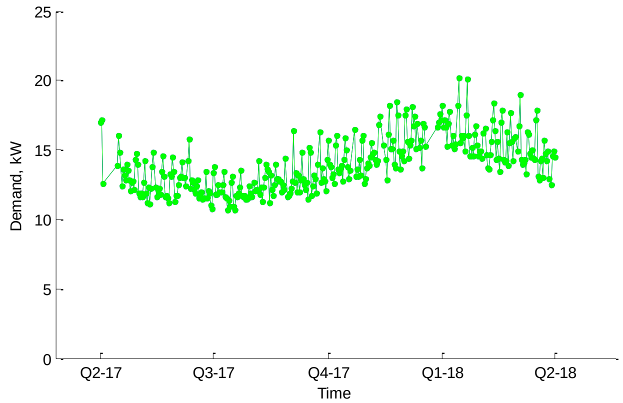

Figure 65: Long term mean daily feeder demand (Ramsey Dom. LV feeder)

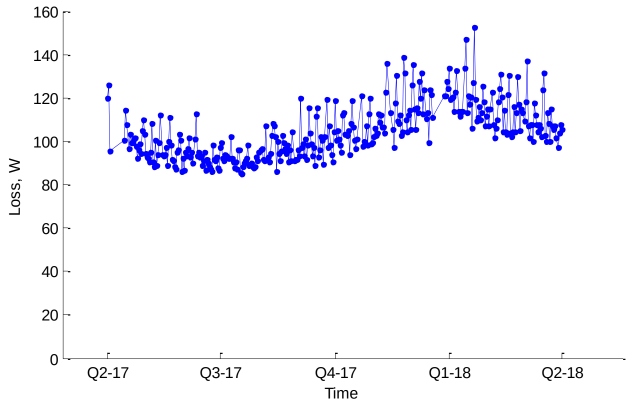

Figure 66: Long term mean daily (I^2R) loss (Ramsey Dom. LV feeder)

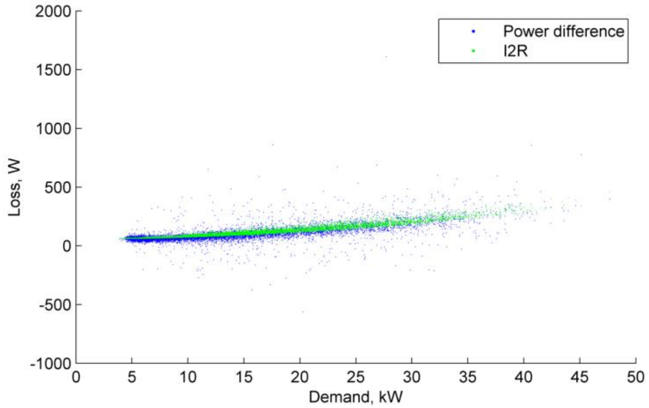

Figure 67: Mar & Apr 2018 Loss, kW vs demand, 10 min. av. (Ramsey Dom. LV feeder)

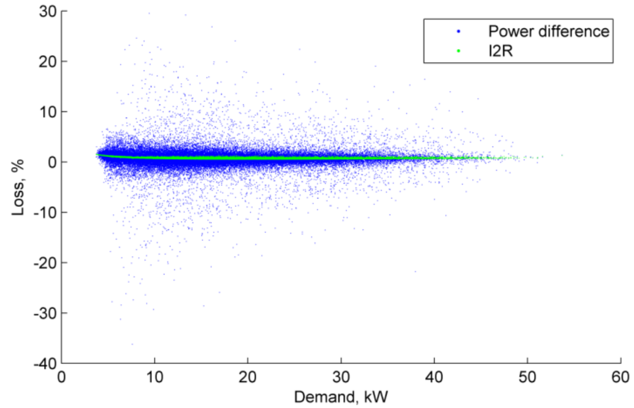

Figure 68: Mar & Apr 2018 Loss, % vs demand, 1 min. av. (Ramsey Dom. LV feeder)

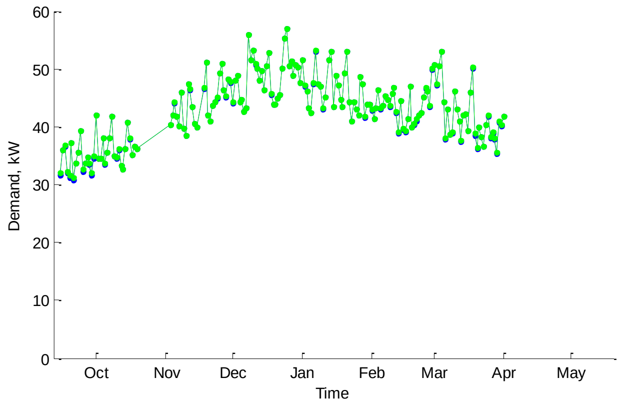

Figure 69: Long term mean daily feeder demand (Tromode Dom. LV feeder)

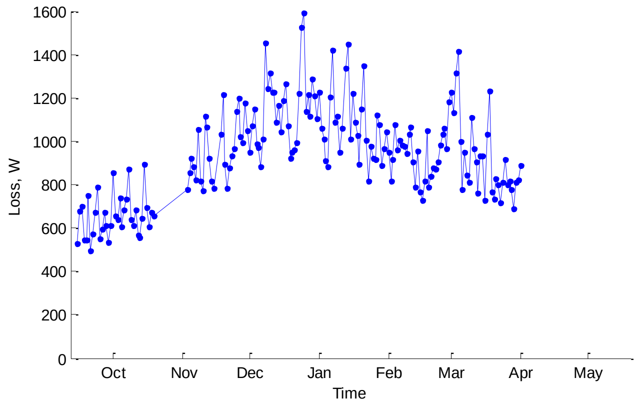

Figure 70: Long term mean daily (I^2R) loss (Tromode Dom. LV feeder)

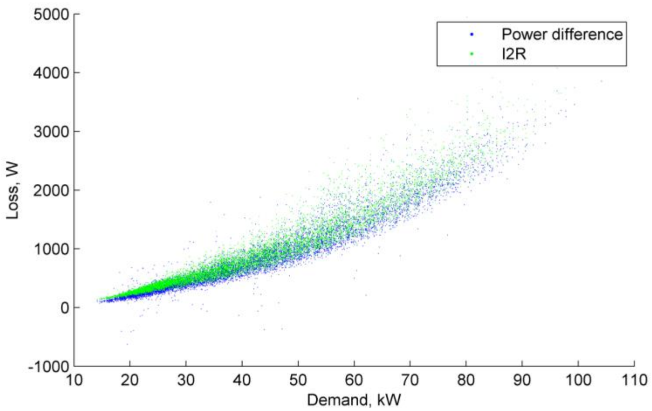

Figure 71: Mar & Apr 2018 Loss, kW vs demand, 10 min. av. (Tromode Dom. LV feeder)

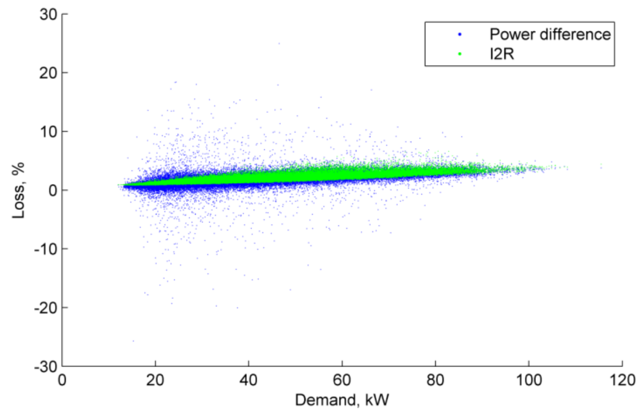

Figure 72: Mar & Apr 2018 Loss, % vs demand, 1 min. av. (Tromode Dom. LV feeder)

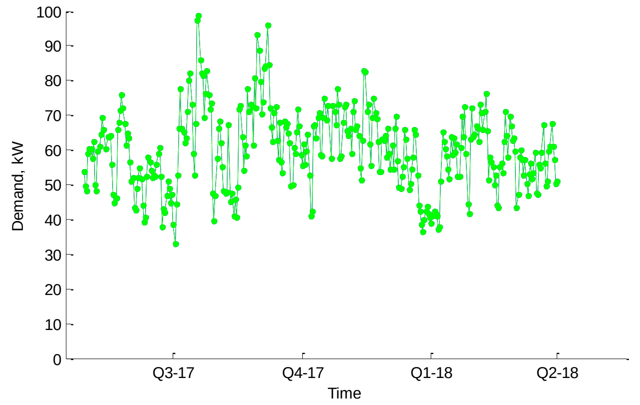

Figure 73: Long term mean daily feeder demand (Peel A I&C LV feeder)

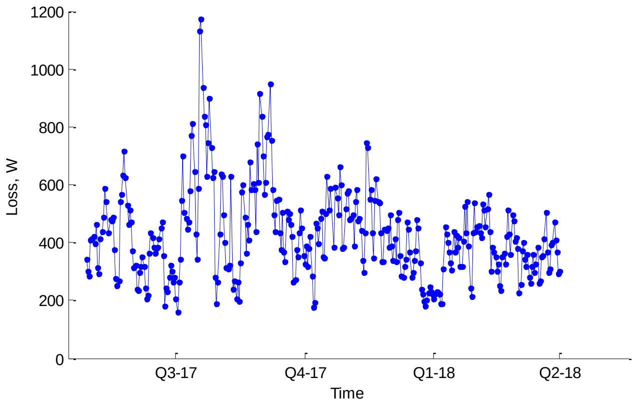

Figure 74: Long term mean daily (I^2R) loss (Peel A I&C LV feeder)

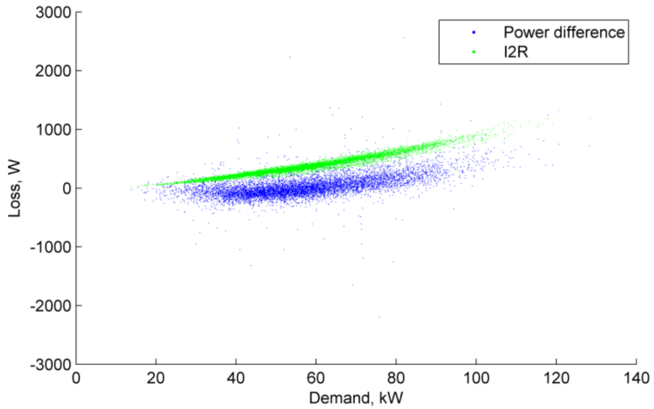

Figure 75: Mar & Apr 2018 2017 Loss, kW vs demand, 10 min. av. (Peel A I&C LV feeder)

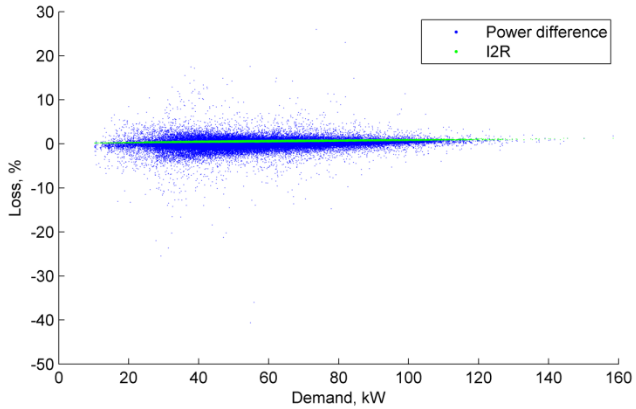

Figure 76: Mar & Apr 2018 Loss, % vs demand, 1 min. av. (Peel A I&C LV feeder)

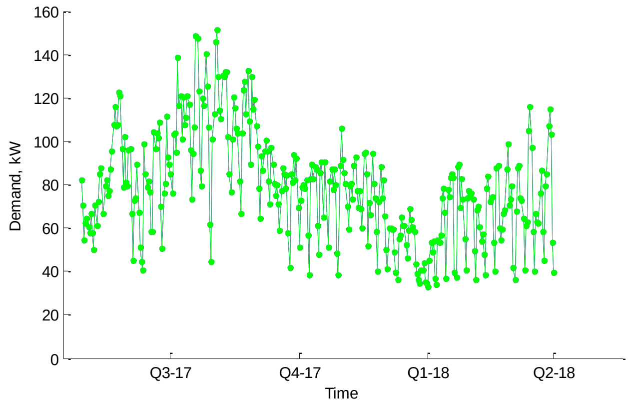

Figure 77: Long term mean daily feeder demand (Peel B I&C LV feeder)

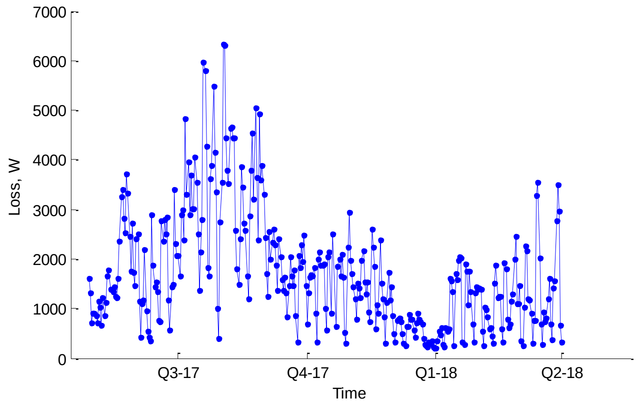

Figure 78: Long term mean daily (I^2R) loss (Peel B I&C LV feeder)

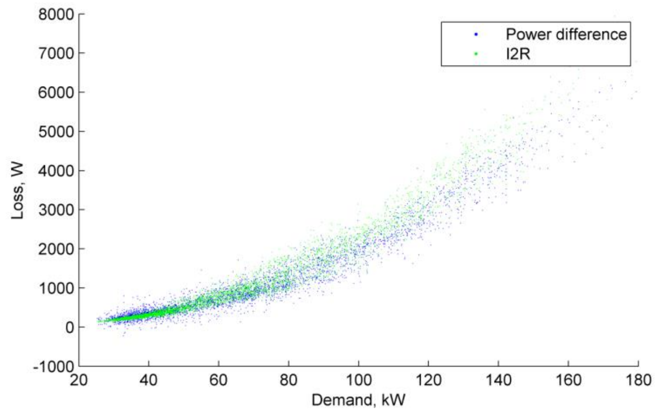

Figure 79: Mar & Apr 2018 Loss, kW vs demand, 10 min. av. (Peel B I&C LV feeder)

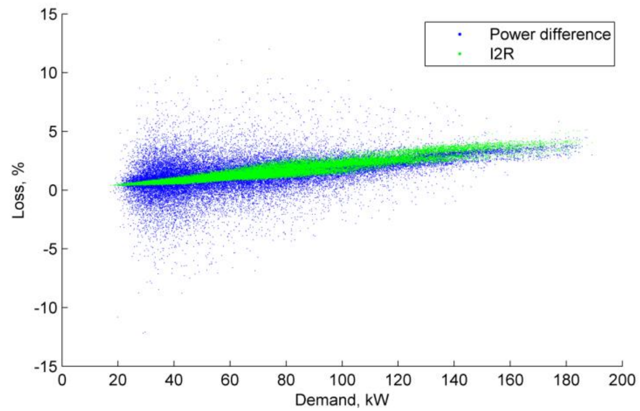

Figure 80: Mar & Apr 2018 Loss, % vs demand, 1 min. av. (Peel B I&C LV feeder)

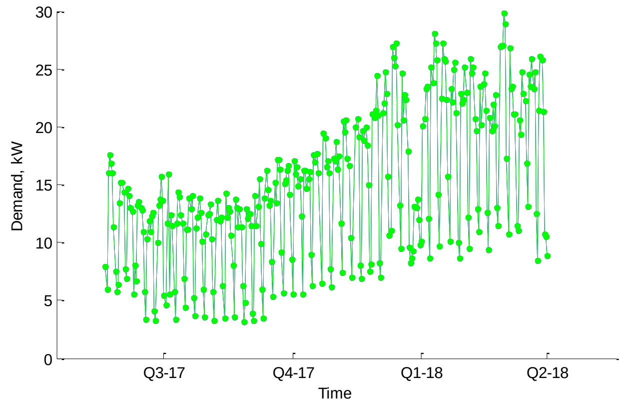

Figure 81: Long term mean daily feeder demand (Ballasalla I&C LV feeder)

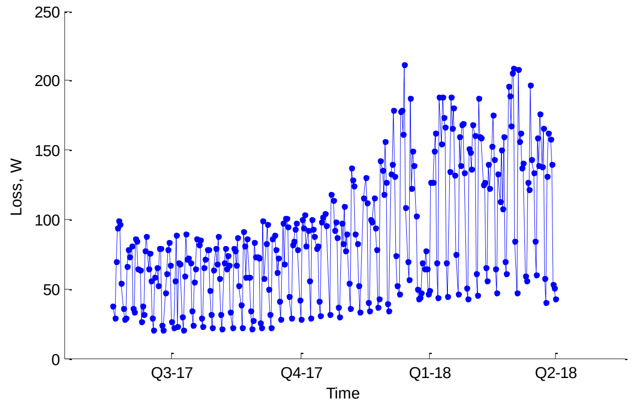

Figure 82: Long term mean daily (I^2R) loss (Ballasalla I&C LV feeder)

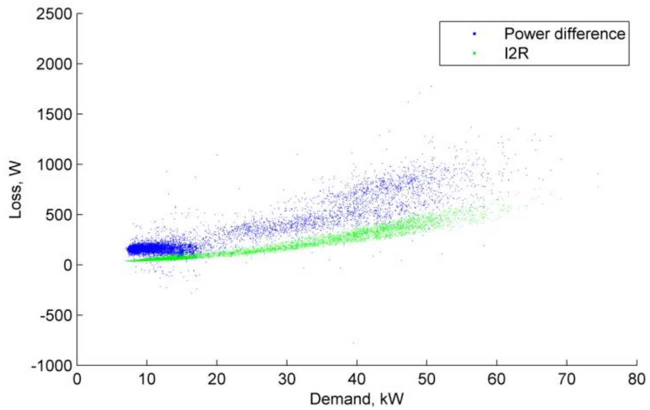

Figure 83: Mar & Apr 2018 Loss, kW vs demand, 10 min. av. (Ballasalla I&C LV feeder)

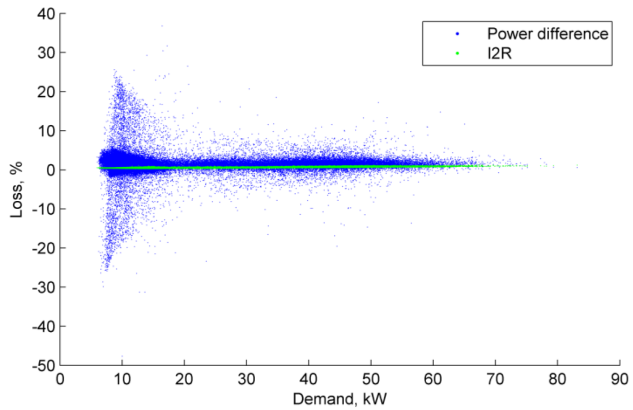

Figure 84: Mar & Apr 2018 Loss, % vs demand, 1 min. av. (Ballasalla I&C LV feeder)

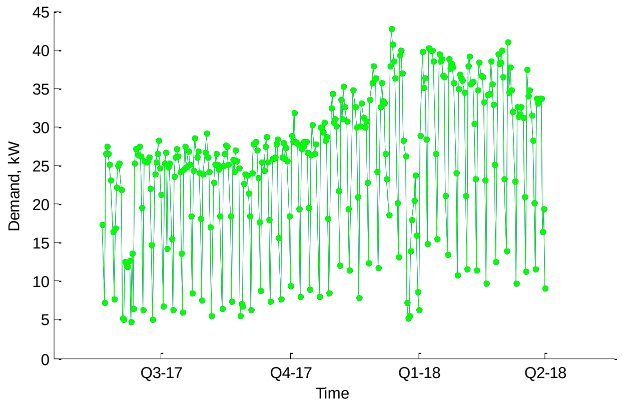

Figure 85: Long term mean daily feeder demand (Braddan I&C LV feeder)

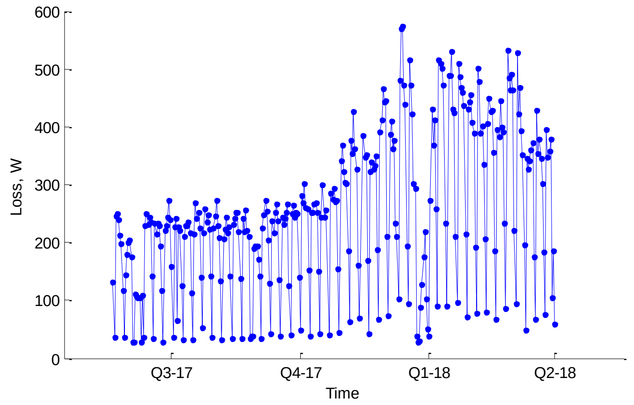

Figure 86: Long term mean daily (I^2R) loss (Braddan I&C LV feeder)

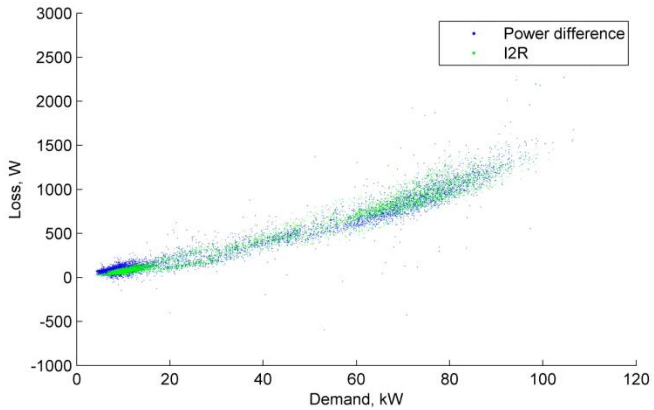

Figure 87: Mar & Apr 2018 Loss, kW vs demand, 10 min. av. (Braddan I&C LV feeder)

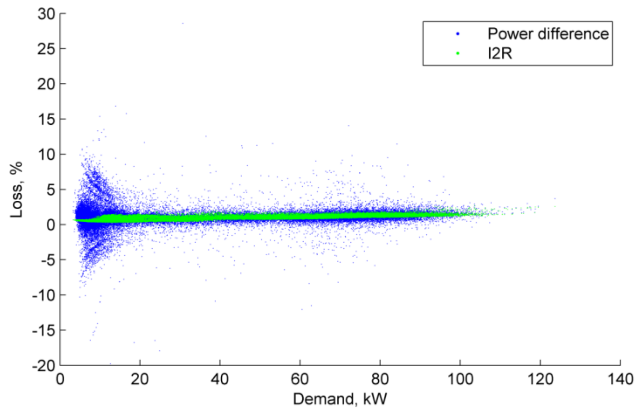

Figure 88: Mar & Apr 2018 Loss, % vs demand, 1 min. av. (Braddan I&C LV feeder)

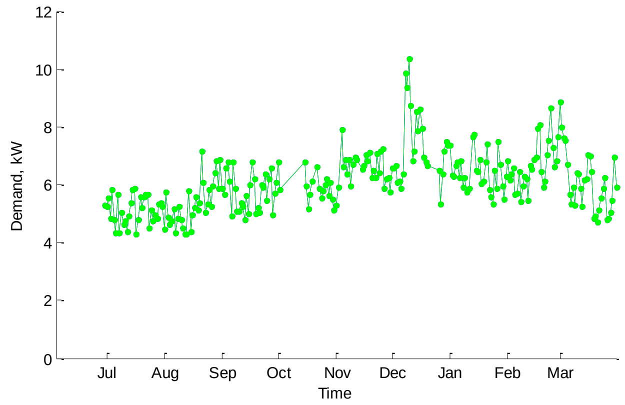

Figure 89: Long term mean daily feeder demand (Santon OH LV feeder)

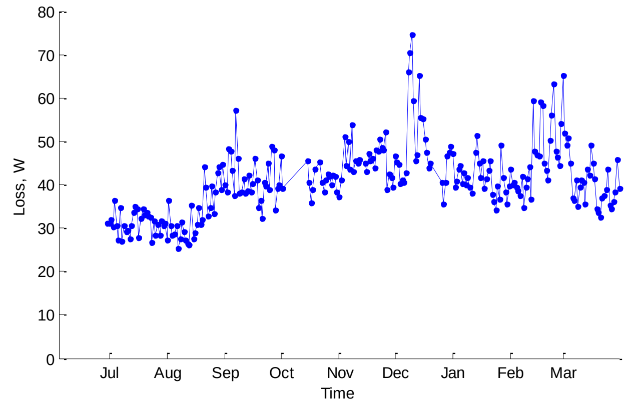

Figure 90: Long term mean daily (I^2R) loss (Santon OH LV feeder)

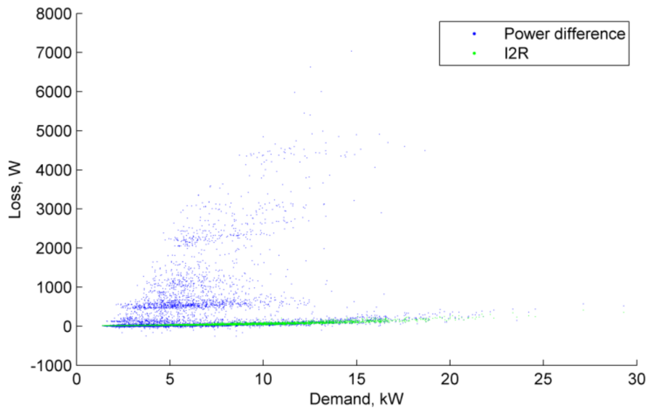

Figure 91: Mar & Apr 2018 Loss, kW vs demand, 10 min. av. (Santon OH LV feeder)

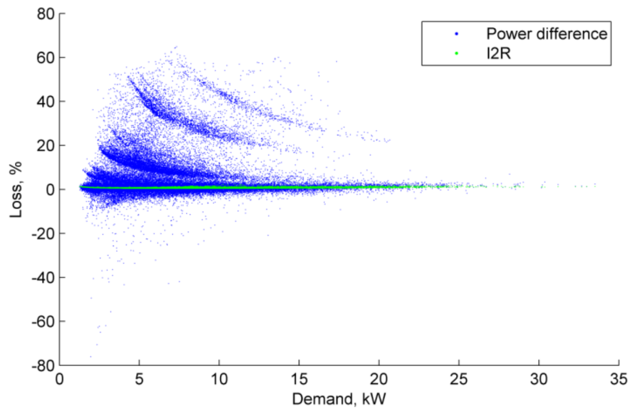

Figure 92: Mar & Apr 2018 Loss, % vs demand, 1 min. av. (Santon OH LV feeder)

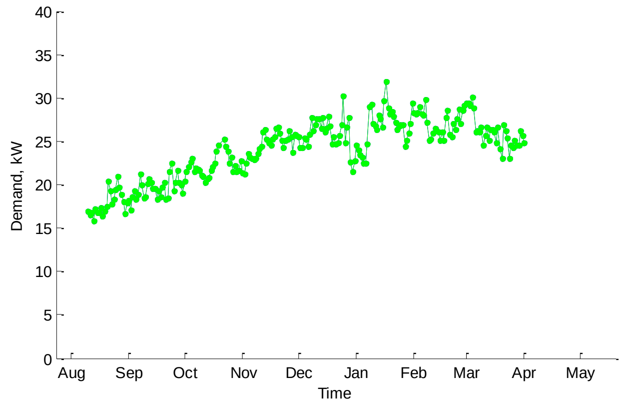

Figure 93: Long term mean daily feeder demand (Abbeylands OH LV feeder)

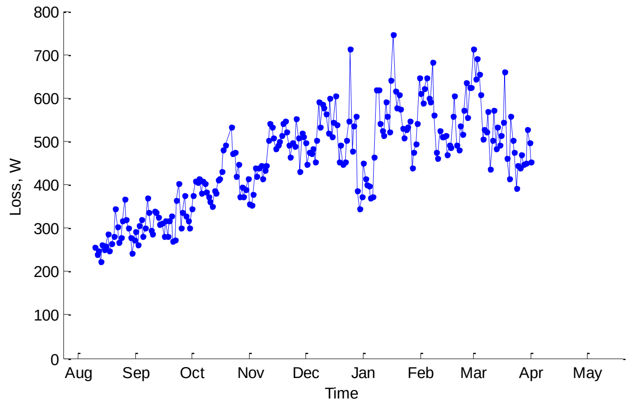

Figure 94: Long term mean daily (I^2R) loss (Abbeylands OH LV feeder)

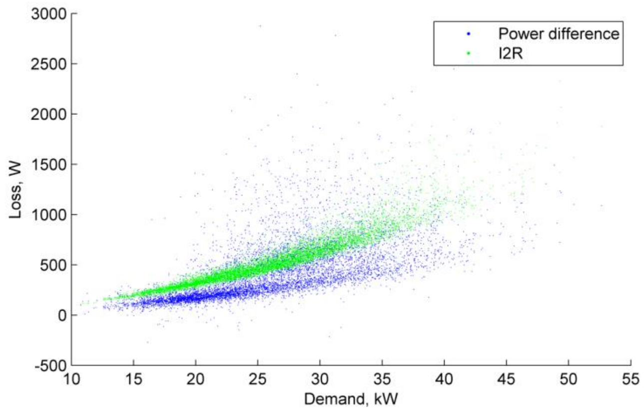

Figure 95: Mar & Apr 2018 Loss, kW vs demand, 10 min. av. (Abbeylands OH LV feeder)

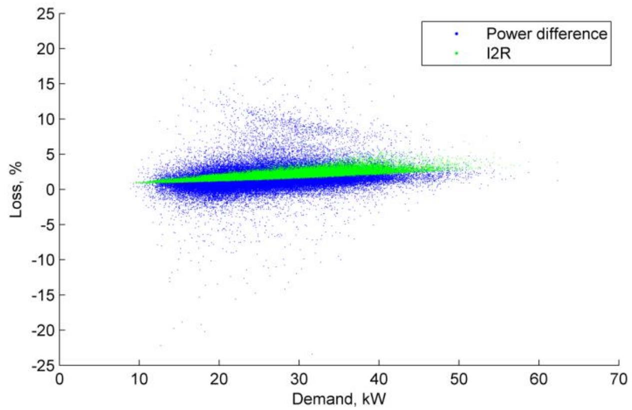

Figure 96: Mar & Apr 2018 Loss, % vs demand, 1 min. av. (Abbeylands OH LV feeder)

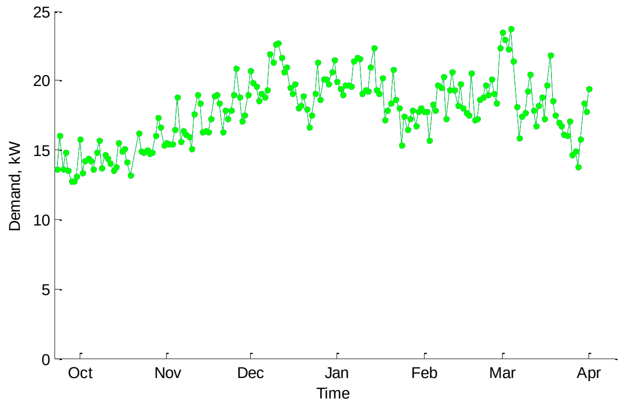

Figure 97: Long term mean daily feeder demand (Ramsey OH LV feeder)

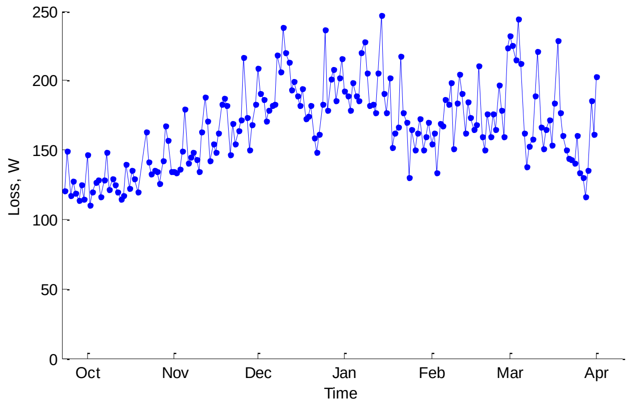

Figure 98: Long term mean daily (I^2R) loss (Ramsey OH LV feeder)

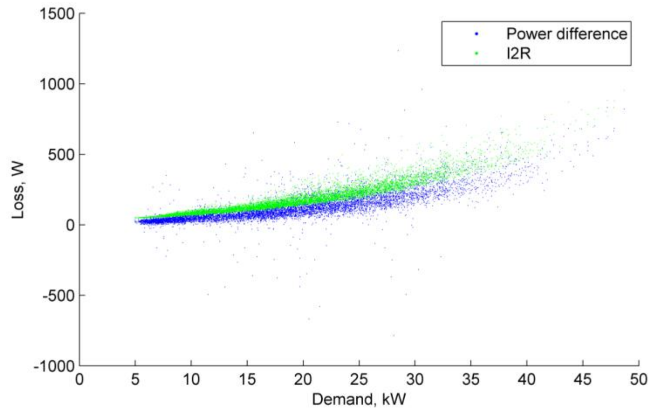

Figure 99: Mar & Apr 2018 Loss, kW vs demand, 10 min. av. (Ramsey OH LV feeder)

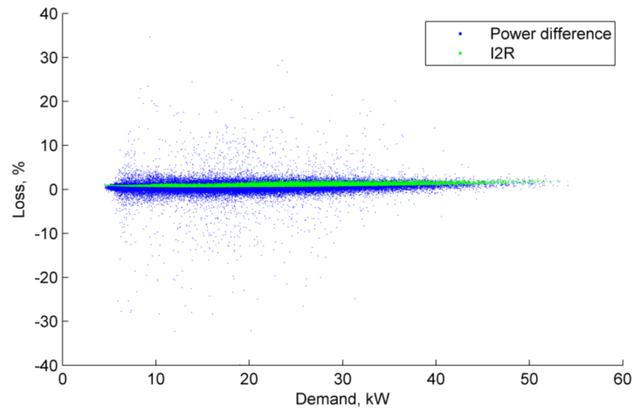

Figure 100: Mar & Apr 2018 Loss, % vs demand, 1 min. av. (Ramsey OH LV feeder)

Appendix D Review of Neutral Currents

Appendix D 1 Neutral current ratio

The neutral current ratio has been defined here as the ratio of the RMS neutral current to the RMS of the three phase currents. According to this definition, if all of the current were to be on one phase, then the RMS current would be equal to the phase current amplitude divided by the square root of 3, and so the neutral current ratio can appear to be greater than 1. Higher values can also occur due to harmonics, reactive power or, for very low currents, where the results are constrained by the accuracy of the GridKey readings. These points are omitted from the plots.

Only three-phase feeders have been included in the analysis since the neutral currents in single-phase feeders are not a form of unbalance that could potentially be mitigated.

Appendix D 2 LV feeders on HV trial in Milton Keynes

The data for the HV trial includes 390 three-phase LV feeders. There are a further 4 feeders for which the neutral current data is not available.

Figure 1 shows the RMS neutral and phase currents and Figure 2 shows the same current data expressed as a ratio.

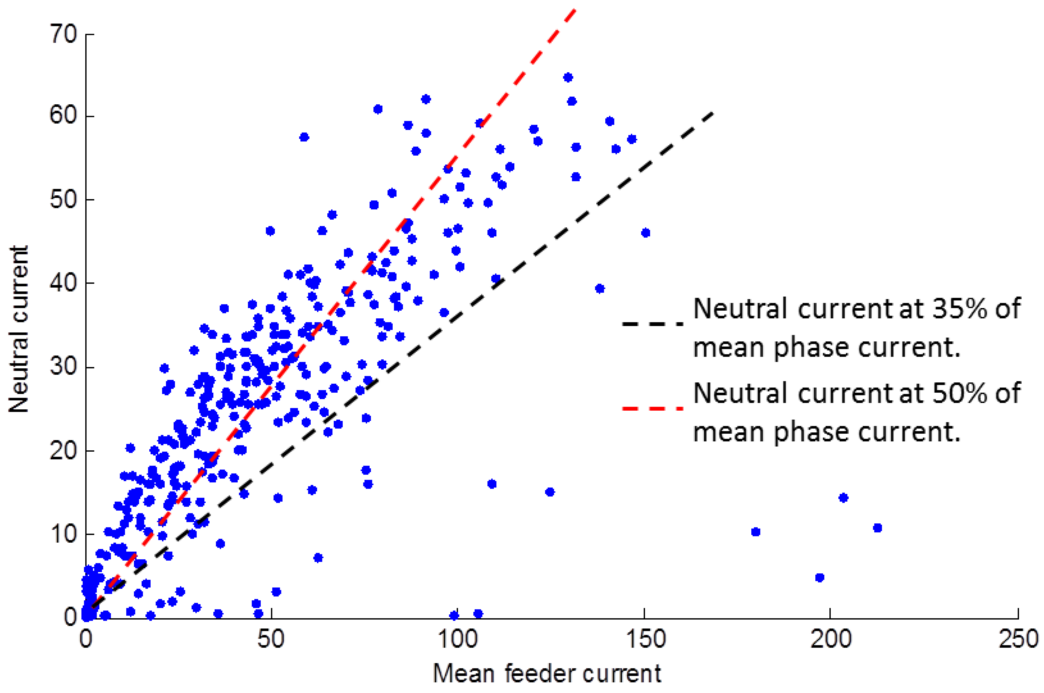

Figure 101: Neutral current vs. mean phase current for MK feeders

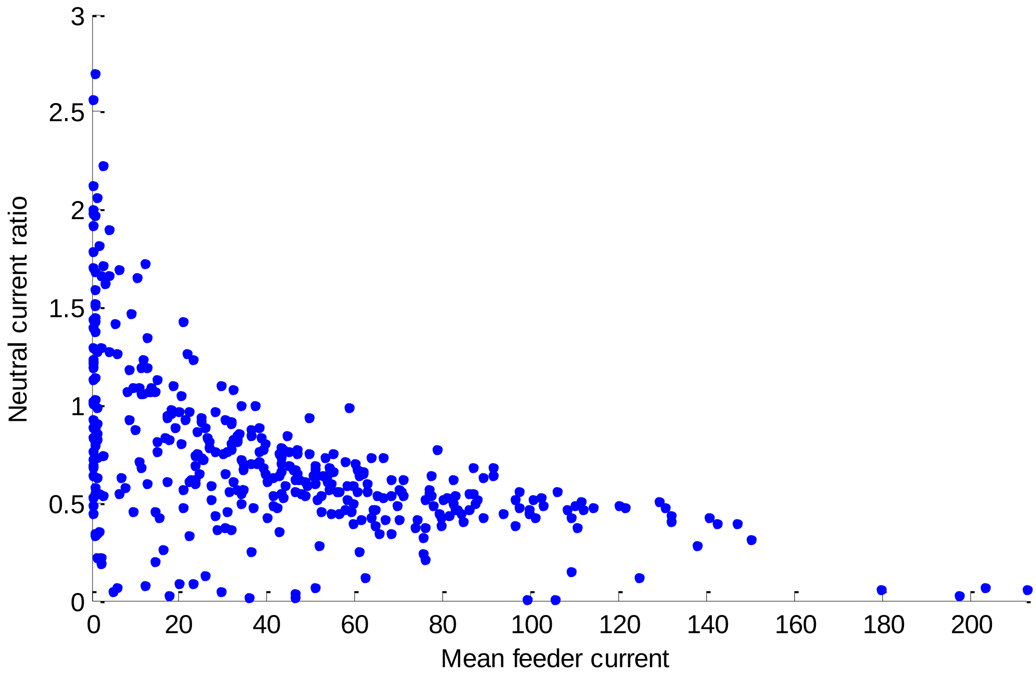

Figure 102: Neutral current vs. mean phase current for MK feeders

The neutral current ratio can be very high where the currents are low but the losses in these feeders are likely to be relatively low. However, there are many feeders with higher loading where the neutral current may be between 35% and 50% of the mean phase current. There are also a few feeders with low neutral current ratios, probably for industrial or commercial customers where the three-phase loads are well balanced.

Figure 3 shows the percentage of the year for which data is available. Instrumentation for the final four HV feeders in the trial was mostly completed between spring and summer 2017 and so these feeders have lower data availability.

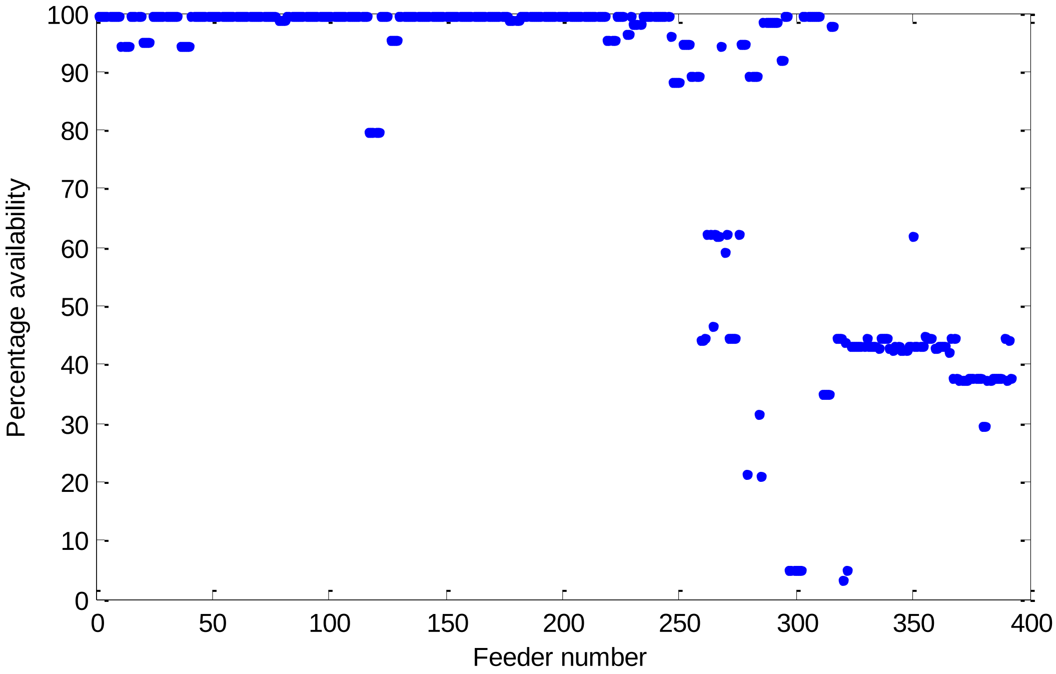

Figure 103: Neutral current data availability for MK feeders

Appendix D 3 LV feeders on the Isle of Man

A set of plots similar to those above are included below for the feeders in the Isle of Man LV feeder trial. There are only 11 feeders here and so the results are less representative of the LV network, but they appear to indicate the same general trends as above.

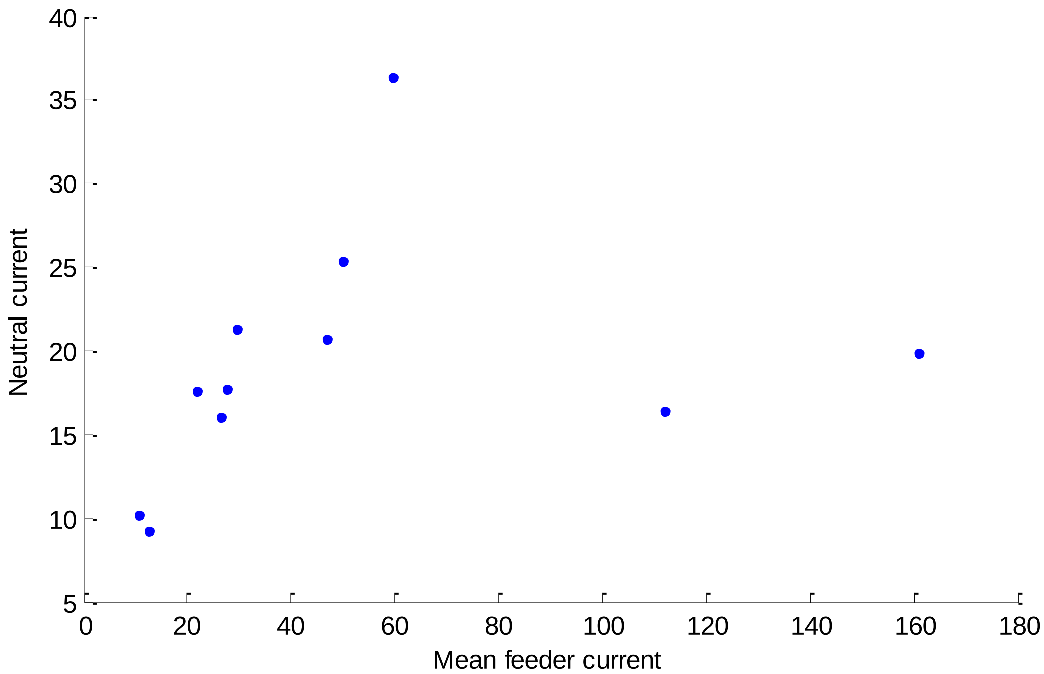

Figure 104: Neutral current vs. mean phase current for IoM feeders

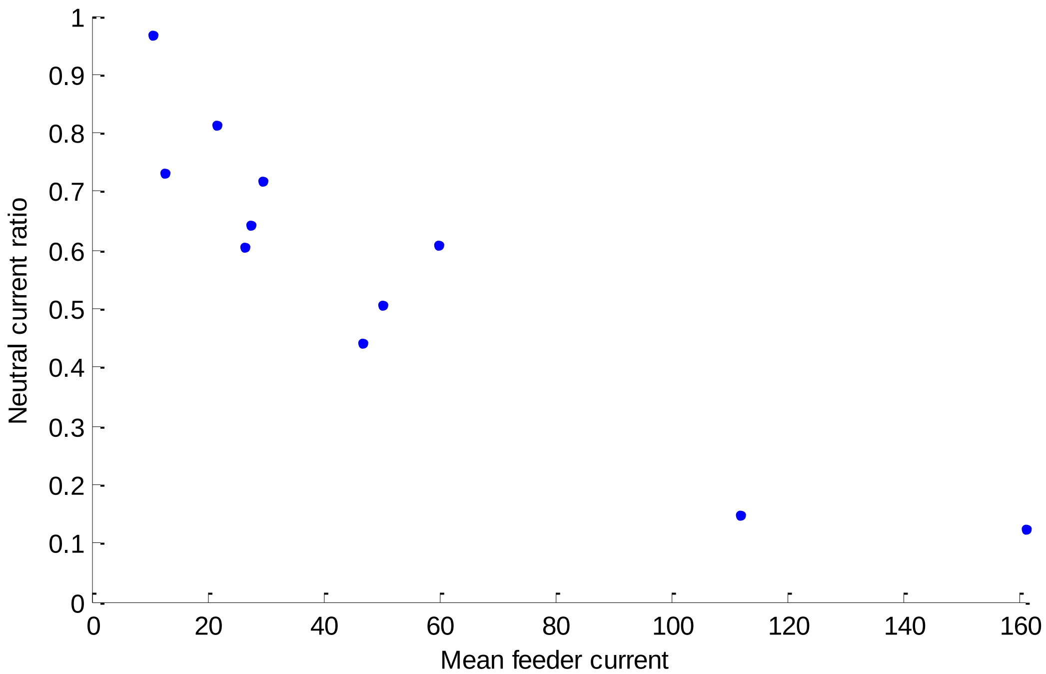

Figure 105: Neutral current vs. mean phase current for IoM feeders

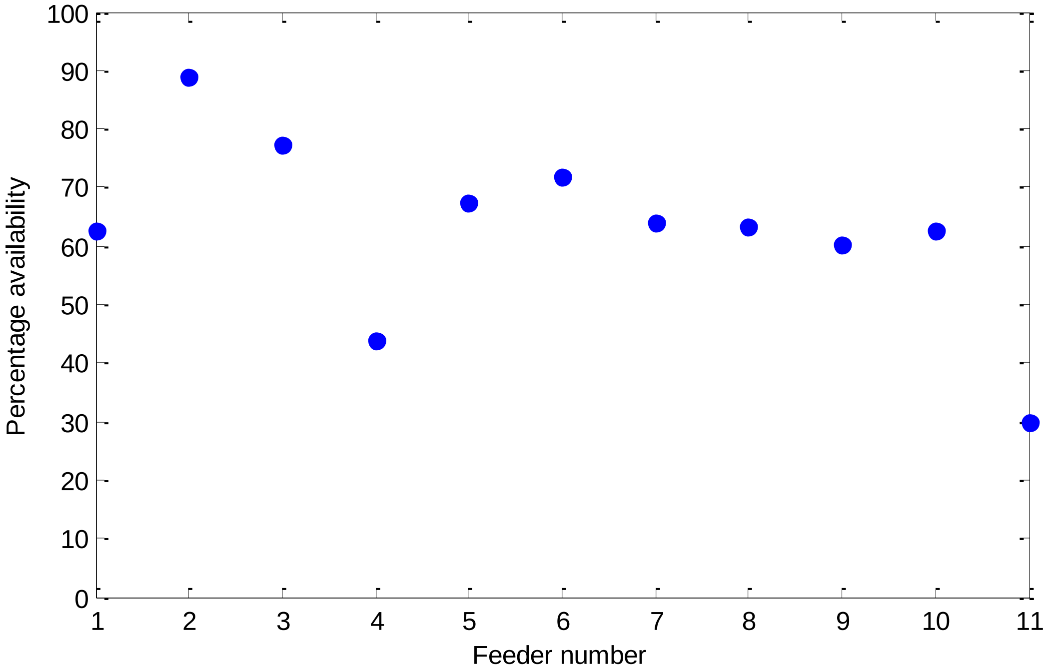

Figure 106: Neutral current data availability for IoM feeders