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Executive Summary

This project aims to assess the level of confidence in the ENWL distribution network model in IPSA for fault level studies and to provide a practical understanding of how close the simulated fault levels using network models are to the 'actual' values at the selected locations. The 'actual' fault levels are in fact the measured and predicted values by Fault Level Monitor (FLM) device manufactured by Outram Research Limited (ORL)[1] and installed at the selected locations. This device utilises information generated from voltage and current disturbances occurring naturally on the network, and not artificially generated.

The analysis has focused on four initial trial locations: Broadheath 11 kV, Denton West 6.6 kV, Irlam 6.6 kV and Wigan 33 kV.

A high level of confidence in modelling the ENWL network in the Denton West and Irlam areas in IPSA is observed. This is suggested by the small differences in the upstream RMS break fault values between the simulated results and the FLM results. The upstream fault values refer to the fault contribution coming from the wider (upstream) network for a fault applied at the Primary 6.6 kV. Larger differences are seen in the upstream peak make fault values.

The Broadheath results do not seem to follow the pattern seen at the other three locations, where differences in upstream RMS break are smaller than the peak make ones. For this location, the differences in RMS break between FLM and IPSA results are relatively high and could be explained by the possible inconsistency between the IPSA Master Network and the actual operating scheme of the 132 kV grid in Altrincham area during the period of measurements, the relatively modest disturbance energy seen by the device and the larger room for interpretation of the results in Pronto software compared to the other locations.

ENWL may wish to check the 132 kV network in Altrincham – Carrington area and the 400/275 kV National Grid topology in the area in the IPSA Master Network model and compare with the FLM results again if the IPSA Master Network model needs update.

The comparison of the IPSA and FLM results for Wigan location suggests that the 400/275 kV topology of wider National Grid transmission network feeding Wigan Grid in the network model may not be consistent with the actual operating scheme during the period of measurements. We recommend that ENWL check the 400/275 kV National Grid topology in this area and update the IPSA model if necessary in accordance with the latest National Grid week 42 data before making another comparison with the FLM results.

[1] http://www.outramresearch.co.uk/

It is recommended that ENWL update the National Grid transmission network topology and parameters in the IPSA Master Network model annually in accordance with the week 42 data provided by NG.

The review of the G74 induction machine representation in the IPSA model is an important aspect of the study. The G74 models are widely used in the industry by distribution network operators to simulate fault contribution from typical loads, when asynchronous motors forming part of the typical loads are not individually identifiable. Engineering Recommendation G74[2] and Engineering Technical Report 120[3] provide guidance on how to estimate fault level contribution of the typical loads and how to model the equivalent G74 motors.

The ENWL G74 models in IPSA generally follow the indicative guidelines but some small variations are observed. Recommendations are provided should ENWL wish to follow the guideline to a larger extent.

It should be noted that ER G74 methodology was developed in 1992 and since then the load mix and appliances used in commercial and industrial environments have changed to an extent. The results for these four locations consistently suggest that the peak make fault contribution from the equivalent G74 motors may be underestimated and that the ER G74 may need to be revised to reflect the change in load mix of today. This report provides useful information by studying a variation of the G74 model having a double fault contribution compared the one suggested by the guideline and currently used by ENWL.

The report is organized as follows: A short introduction to the subject is presented in the first section. Section 2 presents the review of the ENWL distribution network models. The most up-to-date ENWL 132/33 kV network model (received as the IPSA Master Network) is used in the studies. Any differences in the master network compared to the November 2015 annual revision of the Long Term Development Statement (LTDS)[4] in the selected locations are highlighted in Section 2.1. The ENWL HV (11 kV and 6.6 kV) networks (received in DINIS text format) of the Broadheath, Denton West and Irlam locations are reviewed in a high level analysis in Section 2.2.

A description of the G74 models together with a comparison against the industry guidelines and recommendations is presented in Section 3. The FLM results are summarised and commented upon in Section 4. The ENWL distribution network model is updated by combining the 132/33 kV network model with the 11 kV and 6.6 kV models of the selected network areas in Broadheath, Denton West and Irlam

[2] Energy Networks Association, 1992, Engineering Recommendation G74: Procedure to meet the requirements on IEC 909 for the calculation of short circuit currents, ENA, London, UK.

[3] Energy Networks Association, 1995, Engineering Technical Report 120: Calculation of fault currents in three-phase AC power systems (Application Guide to Engineering Recommendation G74), ENA, London, UK

[4] http://www.enwl.co.uk/about-us/long-term-development-statement

locations as detailed in Section 5. The model update ensures the network model in IPSA is representative for the network operation during the onsite measurement period. Accuracy and sources of errors of network modelling and fault level monitoring device are also discussed in the same section.

The calculated fault current results using the updated network model are compared to the fault level estimations provided by the FLM device. Differences between the IPSA and the FLM results are identified and potential reasons for the differences are analysed. Recommendations are made for further investigation and refinement of the ENWL distribution network models for fault calculations.

Definitions and abbreviations

Abbreviation	Description
AC	Alternating Current
BSP	Bulk Supply Point
CHP	Combined Heat and Power
CRMS	Control Room Management System
CT	Current Transformer
DC	Direct Current
DG	Distributed Generation
DINIS	Distribution Network Information System
DNO	Distribution network operator
EHV	Extra high voltage
ENWL	Electricity North West Limited
ER	Engineering Recommendation
ETR	Engineering Technical Report
ETYS	Electricity Ten Year Statement published by National Grid
FLA	Feeder Load Analysis
FLM	Outram Fault Level Monitor
GSP	Grid Supply Point
GT	Grid Transformer
HV	High Voltage
IEC	International Electrotechnical Commission
IPSA	Interactive Power System Analysis
LCNF	Low Carbon Networks Fund
LTDS	Long Term Development Statement
LV	Low Voltage
NER	Neutral Earthing Resistor
NG or NGET	National Grid Electricity Transmission plc
OFAF	oil forced air natural cooling system of transformer
ORL	Outram Research Limited
PDF	Probability Density Function
pu	per unit
PV	Photovoltaic
R	Resistance
RMS	Root Mean Square
SGT	Supergrid Transformer
SLD	Single line diagram
Tac	AC time constant
TNEI	TNEI Services Limited
VT	Voltage Transformer
X	Reactance
Z	Impedance

Definitions

Active power	The product of voltage and the in-phase component of alternating current measured in units of watts and standard multiples thereof
Cycle	A complete positive and negative wave of an alternating current. The number of cycles (per second) is a measure of the frequency of an alternating current
Fault Level	The product of the magnitude of the pre-fault voltage at a bus and the post-fault current, which would flow if that bus was shorted. The fault level or short circuit capacity is a measure of interconnections at any point in the power system network.
G74 model	In this study, it refers to the model of the equivalent machine that simulates the fault behaviour of the general load
Induction or Asynchronous Motor	An AC electric motor in which the electric current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field of the stator winding
Initial symmetrical fault (short circuit) current ($I_k^{"}$)	RMS value of the AC symmetrical component of a prospective (available) short-circuit current, applicable at the instant of short circuit if the impedance remains at zero-time value
Load	The Active, Reactive or Apparent Power, as the context requires, generated, transmitted or distributed
Peak make (peak short-circuit current)	The maximum instantaneous peak of the short circuit current waveform (occurring at approximately 10 ms or 1/2 cycle after the instant of fault)
Phase angle	Angle by which the voltage leads the current
Reactive Power	The product of voltage and current and the sine of the phase angle between them measured in units of volt-amperes reactive and standard multiples thereof
RMS break (symmetrical short-circuit breaking current)	RMS value of an integral cycle of the symmetrical AC component of the prospective shortcircuit current at the instant of contact separation of the first pole to open of a switching device

1 Introduction

TNEI Services Limited (TNEI) has been requested by Electricity North West Limited (ENWL) to carry out validation of their existing fault level models through comparison of the calculated fault levels to the onsite measurements. This work is to support the LCNF Tier 2 funded 'RESPOND' project for ENWL.

With increasing amounts of embedded generation in the distribution network, the corresponding increase in fault levels imposes significant challenges on secure operation of the distribution network. In order to control the fault levels within the design limits, new technologies are being deployed by DNOs.

The aim of the 'RESPOND' project is to utilise network models to perform fault calculations based on changes of the system in near real time and actively manage the network and fault levels. However it will be critical to ensure that there is a high level of confidence in the network models for fault calculations.

To make the comparison of calculated fault levels to onsite measurements, Outram Research Limited (ORL) provided fault level measurement equipment to be deployed to designated trial locations in the ENWL distribution network and perform the post-measurement fault level analysis. It was understood that 14 locations[5] in total in the ENWL distribution network will have fault level measured. This report refers to the first four measurement locations comprising Broadheath, Denton West, Irlam Primary Substations and Wigan Grid. A list of all the locations is presented in Appendix A.

Fault level calculations are performed for the four locations using an updated ENWL distribution network model in the format of IPSA2[6] power system software, and compared to the onsite measurements[7]. This report summarises findings of the studies.

[5] File 'Final Respond Site Selection V 7.3' provide by ENWL at the kick-off meeting dated 29/01/2016

[6] http://www.ipsa-power.com/

[7] File 'RESPOND Project for ENW Report #1inc Appendices V1' via e-mail from Kieran Bailey dated 01/04/2016 (Fwd Respond Project Report on 1 set of FLM sites)

2 Stage 1: Fault Level Modelling

2.1 Review of the 132/33 kV Network Models

2.1.1 Methodology

ENWL have provided the most up-to-date IPSA+ Master Network file[8] together with the corresponding database[9]. This network includes all EHV network (132 kV and 33 kV) and National Grid network equivalents. It has been confirmed by ENWL that this network includes more up-to-date information than the ENWL LTDS from November 2015 and is considered to be representative for the time period of the fault level measurements.

This section compares the electrical assets in the selected locations with the information provided in the LTDS. Any differences have been highlighted and commented on. A fault level study has then been undertaken by applying 3-phase faults in the selected locations and calculating:

- the peak make value (peak asymmetrical current) at 10 ms
- the symmetric RMS break value at 100 ms

The IPSA+ Master Network Model has been imported in IPSA2 and all the subsequent studies have been undertaken in IPSA2.

For the review of the network model, a 100 ms break time has been used, consistent with the break time listed in the ENWL LTDS. However, please note that for comparison with the FLM fault level results in Section 5, a 90 ms break time has been used, consistent with the setup of the Outram measurement device.

The option 'Apply Flat Start Voltages before a fault' has been maintained in the IPSA2 software, for consistency with the ENWL LTDS. In all other sections, the voltages resulted from the load flow have been taken into consideration, i.e. the option 'Apply Flat Start Voltages before a fault' has been unchecked in the IPSA2 software. All the other 'Advanced Settings' have been maintained as in the IPSA+ Master Network Model received from ENWL.

The fault level results have been compared with values listed in the LTDS from November 2015 ('*fault-levels.xlsx*'). Any mismatches have been highlighted in Table 2-1 to Table 2-4. We would expect the fault levels in the LTDS to generally match the IPSA2 simulated results where no updates have been applied to the selected network areas. The LTDS provides fault level values for the buses/electrical nodes equipped with circuit breakers only.

[8] File 'Authorised Master v68-01Mar16.iif' via e-mail from Kieran Bailey dated 01/03/2016 (FW TNEI - IPSA+ Model)

[9] File 'CMM Database v8.idf' via e-mail from Kieran Bailey dated 11/02/2016 (IPSA+ data base)

The IPSA Master Network Model and the ENWL LTDS do not include network information for the HV and LV networks (11 kV and below) so these are not assessed here.

2.1.2 Description of the EHV Models in the Selected Locations

This section describes the selected network locations as received via the IPSA Master Network Model.

There are no reactors or capacitor banks connected in selected locations.

2.1.2.1 Broadheath

Broadheath Primary is supplied by Altrincham BSP via two 33/11 kV 11.5/23 MVA OFAF Dyn11 (‘altrin_t11’ and ‘altrin_t13’) transformers and one 33/11 kV 10/15 MVA Dyn11 OFAF (‘altrin_t12’) transformer. Altrincham BSP is in turn supplied by Carrington GSP via two 132/33 kV 90 MVA transformers.

Altrincham BSP also supplies Bowdon Primary 33/11 kV and Green Lane Primary 33/11 kV. In addition, Green Lane Primary is connected to Gatley Primary in Moss Nook area, via a normally open circuit line.

The boundary of the selected location has been considered to be the 132 kV terminals of the Altrincham BSP transformers. A snapshot from the IPSA Master Network Model is shown in Figure 2-1.

No generators have been identified in the selected location, at 33 kV.

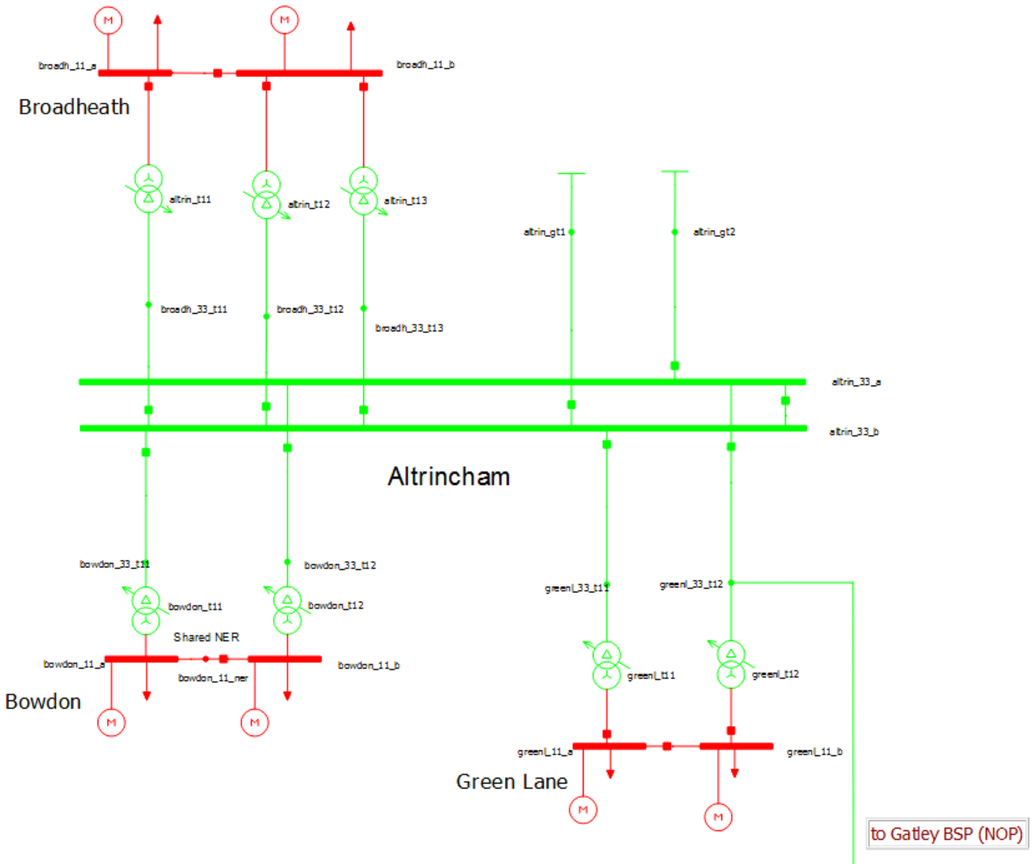

Figure 2-1 Broadheath Primary/Altrincham BSP Location

2.1.2.2 Denton West

Denton West Primary is supplied by Droylsden BSP via two 33/6.6 kV 11.5/23 MVA OFAF Dyn11 transformers (‘dentwe_t11’ and ‘dentwe_t12’). Droylsden BSP is in turn supplied by Stalybridge GSP via two 132/33 kV 90 MVA transformers.

Droylsden BSP also supplies Denton East Primary 33/6.6 kV, Openshaw Primary 33/6.6 kV, Droylsden East Primary 33/6.6 kV and Snipe Primary 33/6.6 kV. In addition, Denton West Primary and Droylsden BSP are also connected to Longsight BSP and Saint St. BSP respectively, via normally open circuit lines.

The boundary of the selected location has been considered to be the 132 kV terminals of the Droylsden BSP transformers. A snapshot from the IPSA Master Network Model is shown in Figure 2-2.

No generators have been identified in the selected location, at 33 kV.

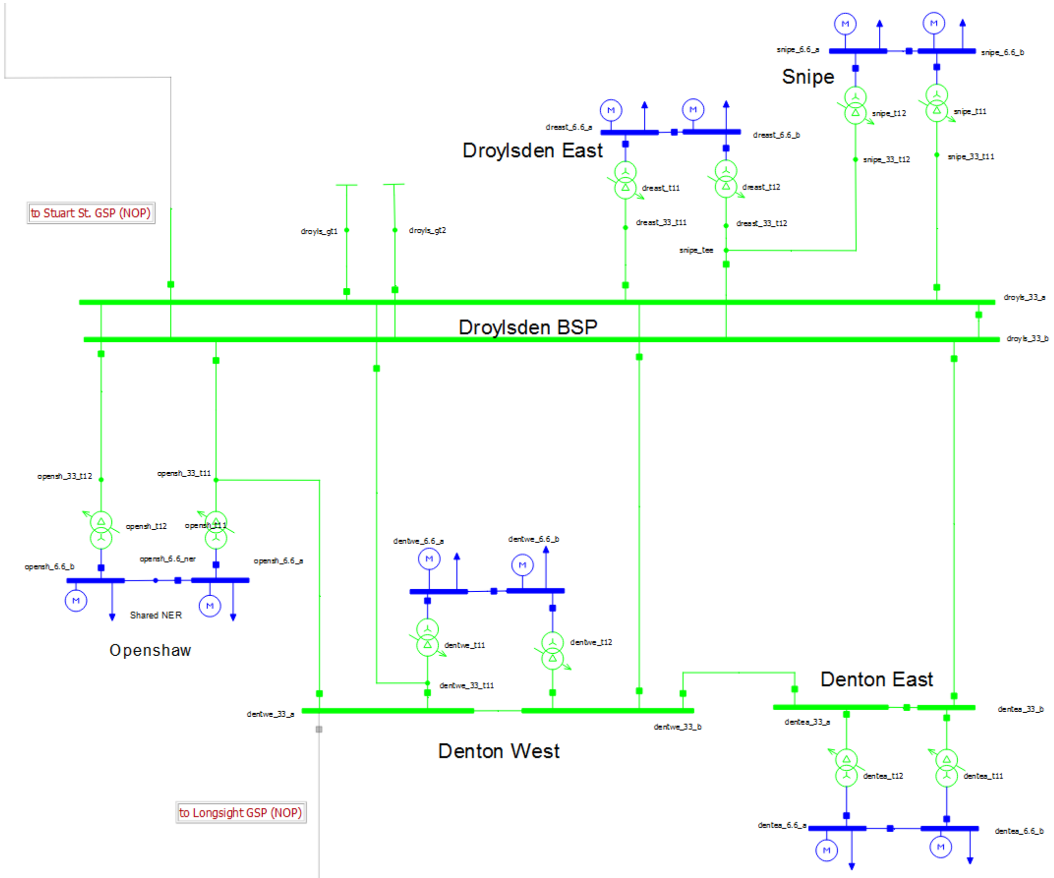

Figure 2-2 Denton West Primary / Droylsden BSP Location

2.1.2.3 Irlam

Irlam Primary is supplied by Carrington BSP via two 33/6.6 kV 23 MVA Dyn11 transformers (‘irlamp_t11’ and ‘irlamp_t12’). Carrington BSP is in turn supplied by Carrington GSP via two 132/33 kV 60 MVA transformers. Carrington BSP also supplies NWGB Partington 33/6.6 kV Primary and Air Products 33/6.6 kV Primary.

According to the IPSA Master Network Model, Air Products Primary contains one 0.325 MW generator.

Manchester Rd Short Term Operating Reserve (STOR) with a rated generation capacity of 20 MW is due to connect in the following months via a loop-in connection in the Carrington BSP – National Grid British Gas circuit no. 1, after the completion of the fault level measurements. This generator has been maintained disconnected from the rest of the network to reflect the actual operating and running configuration. Please note that the network changes to facilitate this generation connection in the Carrington BSP – National Grid British Gas circuit no. 1 have been considered.

The boundary of the selected location has been considered to be the 132 kV terminals of the Carrington transformers. A snapshot from the IPSA Master Network Model is shown in Figure 2-3.

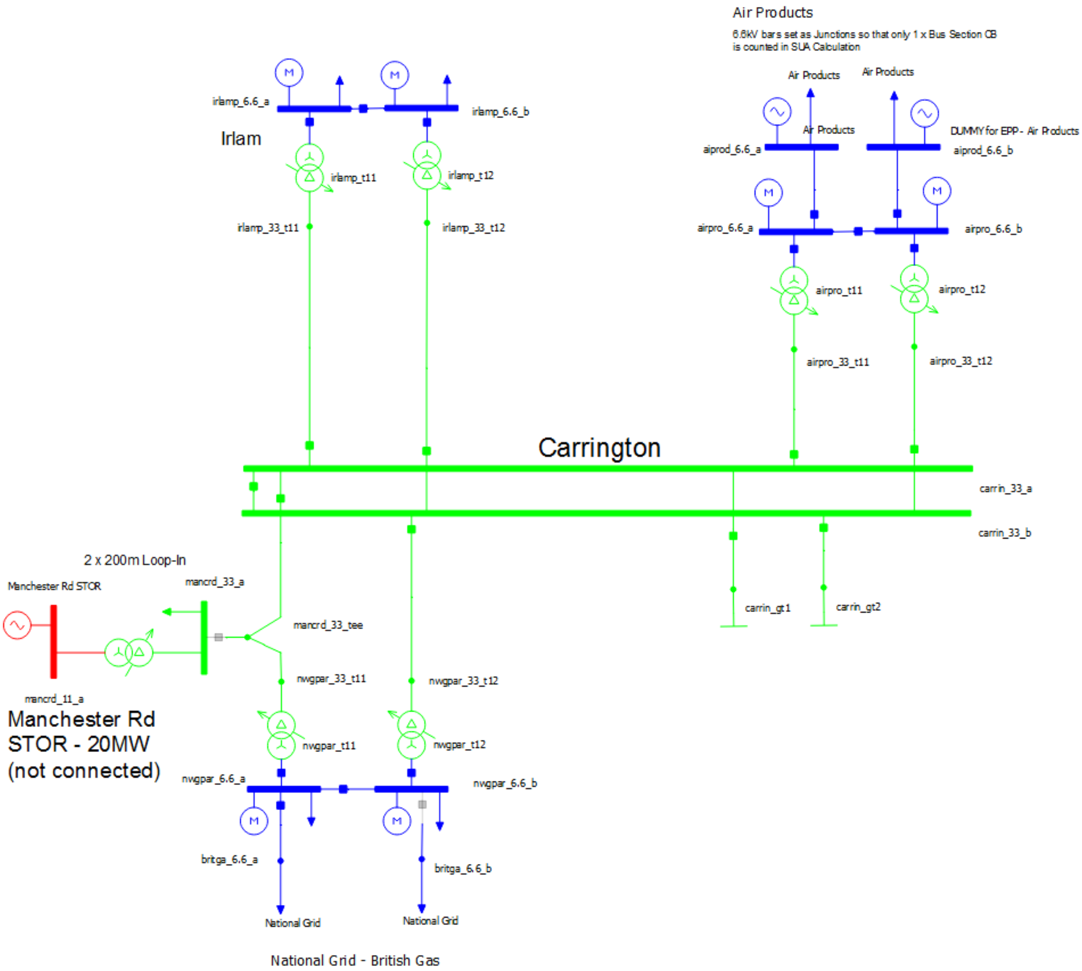

Figure 2-3 Irlam Primary / Carrington BSP Location

2.1.2.4 Wigan

Wigan Grid is supplied by Washway Farm GSP and Kirkby GSP via two 132/33 kV 90 MVA OFAF YnD1 (‘wigan_gt1’ and ‘wigan_gt2’).

Wigan Grid supplies Gidlow Primary 33/6.6 kV, Green Street T12 & T13 33/6.6 kV and Worsley Mesnes 33/6.6 kV. There are also connections with Lamberhead, Kit Gren, Golborne, Green Street T11/Westhoughton and Hindley Green, via normally open points.

The boundary of the selected location has been considered to be the 132 kV terminals of by Washway Farm and Kirkby transformers feeding the Wigan Grid. Two snapshots from the IPSA Master Network Model are shown in Figure 2-4 and Figure 2-5, one showing the Wigan Grid area and the second one showing the wider network.

No generators have been identified in the selected location, at EHV or HV.

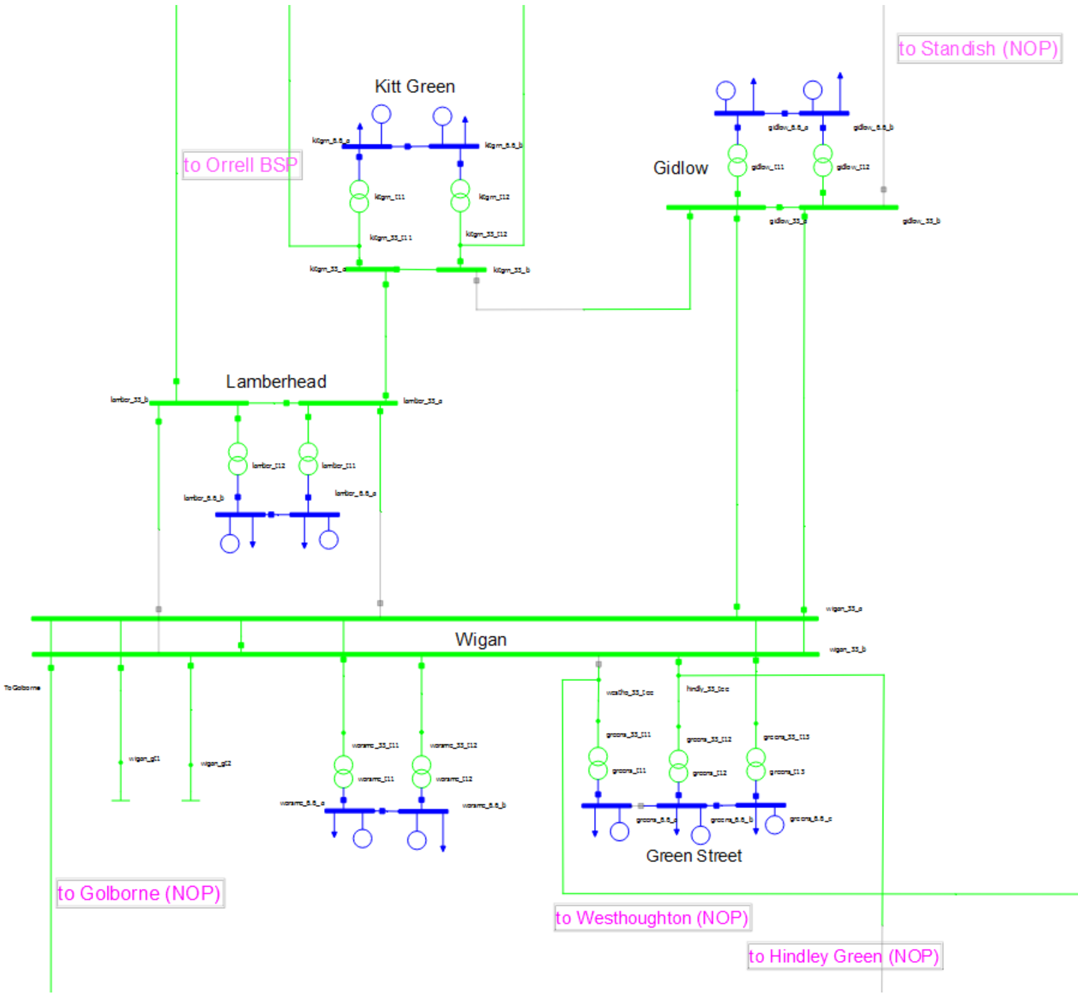

Figure 2-4 Wigan Grid Location

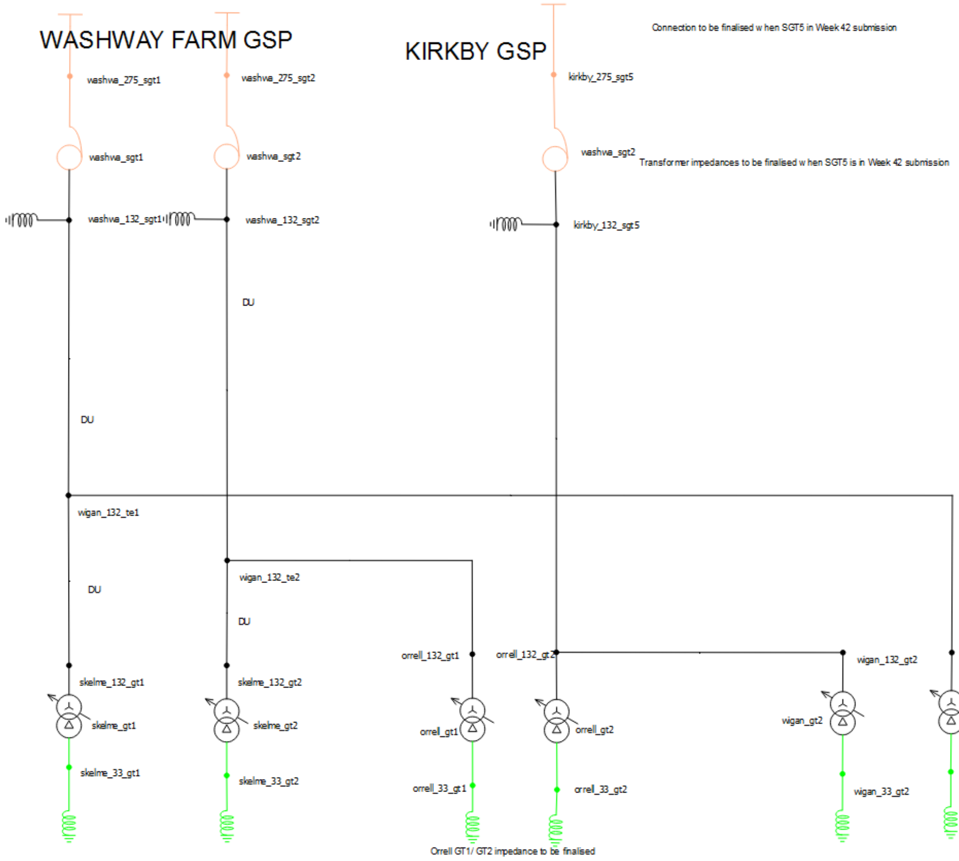

Figure 2-5 Wigan Grid Transformers and the Wider Network

2.1.3 Modelling of Loads and General Load Fault Infeed

Any load supplied by the HV busbar of a Primary substation is generally represented by an equivalent passive load model in the ENWL IPSA Master Network Model.

The fault contribution from the load, however, is represented by an equivalent G74 induction machine connected to the HV busbar in accordance with the Engineering Recommendation G74 methodology. A description of the G74 models together with a comparison against the industry guidelines is presented in Section 3.

2.1.4 Asset Parameters Comparison against LTDS Data

The asset (transformers, cables, overhead lines) parameters in the provided IPSA Master Network Model for the selected network locations were compared with those listed in the LTDS from November 2015. The comparison focused on:

- Positive sequence resistance, reactance and susceptance, in p.u. on 100 MVA base for circuits
- Positive sequence resistance and reactance in p.u. on 100 MVA base, typically nameplate rating (MVA), minimum and maximum taps (%) for transformers

- Active power (MW) and reactive power (MVAr) for loads
- Presence of local generation
- Network topology

Differences are summarised below for each selected network location. Appendix B shows the comparison in detail, highlighting in red the differences higher than 10 % for impedance values. All the values in percentage are related to the LTDS values.

The ratings given in the LTDS indicate the nameplate ratings of the transformers at each location and these have been compared against ratings of the transformer types extracted from the database in the IPSA Master Network Model.

Please note that the zero impedance elements (e.g. bus couplers) and Neutral Earthing Resistors (NERs) have not been shown in the results tables.

Both the maximum loads corresponding to 2014-2015 period and the maximum forecasted 2015-2016 loads have been extracted from LTDS. The 2015-2016 loads have been compared with the loads in the IPSA Master Network Model.

2.1.4.1 Broadheath Location

The parameters of the 33 kV lines in the area in the IPSA Master Network Model generally match with the values listed in the LTDS, with minor differences in the Altrincham to Bowdon circuits and in one of the Altrincham to Green Lane circuits, where a 11 % reduction in susceptance is seen (Table B.1.1, Appendix B1).

No changes in the topology of the network have been observed.

The transformer parameters comparison shows some differences (Table B.1.2, Appendix B1) summarised below:

- Higher reactance of the two Green Lane 33/11 kV transformers in the IPSA Master Network Model (up to 16 %)
- Smaller reactance of the Broadheath 33/11 kV transformer (‘altrin_t12’) in the IPSA Master Network Model (up to 13 %)

The loads comparison is shown in Table B.1.3, Appendix B1. Loads are smaller in the IPSA Master Network Model (up to 3.8 % difference).

2.1.4.2 Denton West Location

Two changes in the topology of the network are observed in this selected location:

- In the IPSA Master Network Model and also in the 33 kV schematics dated 15/10/2015 from LTDS (‘33kv-diagram-sheet.pdf’), the Droylsden to Openshaw feeder 1 includes a feed to the Denton West BSP (bus A) via a tee-off, while the circuit data table in the LTDS (‘33kv-circuit-data-nov2015-published.xlsx’) suggests that this tee-off connects Stuart St. instead

- In the IPSA Master Network Model, only two direct feeders connect Denton West (A and B) to Droylsden BSP while in the circuit data table from the LTDS ('33kv-circuit-data-nov2015-published.xlsx'), there is a third feeder that connects Denton West A to Droylsden BSP
- These two network changes above are also listed in the single line diagram of the IPSA Master Network Model and this re-configuration is due to changes in the Stuart St - Bloom St interconnector scheme and due to amendments in the Droylsden - Denton West & East circuits

Comparison of the 33 kV lines parameters in the IPSA Master Network Model against LTDS data (Table B.2.1, Appendix B2) shows some differences, some of them being related to the network changes listed above:

- Large differences in the parameters of the Droyslden to Openshaw T11 circuit, most likely related to its revised connection, i.e. mainly an increase in reactance of 98.2 %.
- Large differences in the parameters of the Droyslden to Openshaw T12 circuit, i.e. mainly an increase in reactance of 80.9 %.
- Differences in the parameters of the Droyslden to Denton West circuits, i.e. mainly an increase in reactance of 13.9 % in the circuit going to Denton West B and of 22.9 % in the circuit going to Denton East A.
- Difference in parameters of the Droyslden to Denton East circuit, i.e. an increase of 9.9 % in resistance, of 32.5 % in reactance and a decrease in susceptance of 12.8 %.

The transformer parameters comparison shows some differences (Table B.2.2, Appendix B2) specified below:

- Differences in the reactance of some 33/6.6 kV transformers in Denton East, Droylsden East and Snipe, values in the IPSA Master Network Model being lower and with a maximum difference of 3.8 %.

The loads comparison is shown in Table B.2.3, Appendix B2. Loads are smaller in the IPSA Master Network Model (up to 3.5 % difference).

2.1.4.3 Irlam Location

Comparison of asset parameters in the IPSA Master Network Model to the LTDS data (Table B.3.1, Appendix B3) shows some differences, summarised below:

- The resistance and reactance of the Carrington to Irlam 33 kV feeder no. 1 are 34 % lower and 7 % higher respectively, compared with the LTDS data; Carrington to Irlam 33 kV feeder no. 2 parameters are slightly changed (1.1 % difference); this parameter update is also highlighted in the Single Line Diagram (SLD) of the IPSA Master Network Model
- Difference in the Carrington to NWGB Partington feeder no. 1 due to inclusion via a loop-in connection of the future Manchester Rd STOR 20 MW

(an increase of impedance of more 100 %). The generator is not yet connected, however the IPSA Master Network Model provided has the network changes incorporated

The transformer parameters comparison shows some differences (Table B.3.2, Appendix B3) summarised below:

- The resistance of the 'nwgpar_t11' transformer increases by 25 %, while the reactance of both NWGB Partington 33/6.6 kV transformers reduces by about 4 %
- Carrington 'carrin_gt2a' 132/33 kV transformer in the transformer data table in the LTDS ('transformer-data-nov2015-published.xlsx') has 30 MVA rating instead of 60 MVA
- Air Products 33/6.6 kV transformers parameters are not included in the LTDS

The loads comparison is shown in Table B.3.3, Appendix B3. NWGB Partington and Air Products loads are not shown in the 33 kV load data table from LTDS ('33kv-substation-load-data-nov2015-published'). Loads are generally smaller in the IPSA Master Network Model (up to 4.0 % difference).

2.1.4.4 Wigan Location

Wigan 33 kV and 6.6 kV areas

Comparison of asset parameters in the IPSA Master Network Model to the LTDS data (Table B.4.1, Appendix B4) shows some differences, summarised below:

- Minor differences in the resistance and reactance of the Wigan to Green Street feeder, the parameters being maximum 2.4 % higher in the IPSA Master Network Model
- Minor differences in the resistance and reactance of the Wigan to Worseley Mesnes T12 33 kV feeder, the parameters being roughly 1.2 % higher in the IPSA Master Network Model

The transformer parameters comparison (Table B.4.3, Appendix B4) shows that the reactance of the 'greens_t13' transformer increased by 2.0 %.

The loads comparison is shown in Table B.4.5, Appendix B4. Loads are generally smaller in the IPSA Master Network Model (up to 3.4 % difference).

Wigan 132 kV area

Comparison of asset parameters in the IPSA Master Network Model to the LTDS data (Table B.4.2, Appendix B4) reveals no difference. Please note that the circuits connecting Orrell 132 kV to Kirkby and Wigan have not been identified in LTDS ('132kv-circuit-data-nov2015-published.xlsx'), as this file most likely not contains the most up-to-date network configuration in the area.

The transformer parameters comparison shows some differences (Table B.4.4, Appendix B4) summarised below:

- In the IPSA Master Network Model, the 'kirkby_275_sgt5' 180 MVA transformer in Kirkby connects to 'kiby22' bus and feeds the Wigan – Orrell area, while the Electricity Ten Year Statement (ETYS) 2015[10] suggests that this transformer with a rated capacity of 240 MVA is connected to 'KIBY21' bus; the resistance of this transformer is 23 % higher in the IPSA Master Network Model
- The resistance and reactance of the SGT2 transformer in Washway Farm decreases by 0.51 % and 1.72 % respectively, when compared against ETYS 2015 data

2.1.5 Comparison of the Fault Level Results against LTDS Data

2.1.5.1 Broadheath Location

The fault level results comparison is shown in Table 2-1. It can be noted that the fault levels are generally slightly higher in IPSA Master Network Model. The generally higher values are most likely caused by the recent IPSA update of the 132 kV circuits.

The maximum difference in peak make is 0.94 % at Bowdon 11 kV while the maximum difference in RMS break is 0.58 % at Altrincham 33 kV.

2.1.5.2 Denton West Location

The fault level results comparison is shown in Table 2-2. The fault levels are generally slightly smaller in IPSA Master Network Model. The generally smaller values are most likely caused by the change in parameters of Droylsden to Openshaw, Denton East and West circuits.

The maximum difference in peak make is 3.30 % while the maximum difference in RMS break is 2.73 %, both at Denton East 33 kV.

2.1.5.3 Irlam Location

The fault level results comparison is shown in Table 2-3. The fault levels are generally slightly smaller in IPSA Master Network Model and this can be explained by the slight reduction of the fault level in Carrington 132 kV area.

The maximum difference in peak make is 2.99 % while the maximum difference in RMS break is 2.86 %, at Irlam 6.6 kV.

[10] http://www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/Electricity-ten-year-statement/

2.1.5.4 Wigan Location

The fault level results comparison against LTDS is shown in Table 2-4. The fault levels in the Wigan Grid area match the ones in LTDS (highest difference of 0.08 %). The fault level results in Wigan 132 kV area are not listed in LTDS. The ETYS 2015 fault level results show a peak make of 74.08 kA and RMS break of 26.45 kA at ‘kiby22’ busbar, higher than the IPSA results (66.77 kA and 23.65 kA respectively). Please note that the RMS break listed in ETYS corresponds to a break time of 50 ms. Differences are seen between IPSA and ETYS 2015 in Kirkby area and this is expected if the normal arrangement in the area has changed from November 2015.

Table 2-1 Fault Level Comparison Results for Broadheath

IPSA	LTDS		IPSA		LTDS		Difference (%)	
S/S or Busbar Name	S/S or Busbar Name	Voltage Level (kV)	Peak Make (kA)	RMS Break (kA)	Peak Make (kA)	RMS Break (kA)	Peak Make	RMS Break
altrin_33_a	ALTRINCHAM	33	32.27	11.26	32.10	11.20	0.50%	0.58%
altrin_33_b	ALTRINCHAM	33	32.27	11.26	32.10	11.20	0.50%	0.58%
broadh_11_a	BROADHEATH	11	32.91	11.13	33.03	11.11	-0.37%	0.19%
broadh_11_b	BROADHEATH	11	32.91	11.13	33.03	11.11	-0.37%	0.19%
bowdon_33_t11	BOWDON T11	-	21.32	9.45	-	-	-	-
bowdon_33_t12	BOWDON T12	-	21.17	9.43	-	-	-	-
greenl_33_t11	GREEN LANE T11 - Altrincham	-	22.40	9.85	-	-	-	-
greenl_33_t12	GREEN LANE T12 - Altrincham	-	20.41	8.85	-	-	-	-
bowdon_11_a	BOWDON	11	23.58	7.99	23.36	7.98	0.94%	0.13%
bowdon_11_b	BOWDON	11	23.58	7.99	23.36	7.98	0.94%	0.13%
greenl_11_a	GREEN LANE-Altrincham	11	21.27	7.21	21.31	7.21	-0.17%	0.12%
greenl_11_b	GREEN LANE-Altrincham	11	21.27	7.21	21.31	7.21	-0.17%	0.12%
altrin_132_gt1	Altrincham 1	-	26.74	10.83	-	-	-	-
altrin_132_gt2	Altrincham 2	-	26.58	10.78	-	-	-	-
broadh_33_t11	BROADHEATH T11	-	32.24	11.20	-	-	-	-
broadh_33_t12	BROADHEATH T12	-	32.24	11.20	-	-	-	-
broadh_33_t13	BROADHEATH T13	-	32.25	11.20	-	-	-	-

Table 2-2 Fault Level Comparison Results for Denton West Location

IPSA	LTDS		IPSA		LTDS		Difference (%)	
S/S or Busbar Name	S/S or Busbar Name	Voltage Level (kV)	Peak Make (kA)	RMS Break (kA)	Peak Make (kA)	RMS Break (kA)	Peak Make	RMS Break
droyls_132_gt2	Droylsden 2	-	16.44	5.93	-	-	-	-
droyls_132_gt1	Droylsden 1	-	21.29	8.26	-	-	-	-
droyls_33_b	DROYLSDEN	33	38.04	13.07	38.08	13.10	-0.10%	-0.21%
droyls_33_a	DROYLSDEN	33	38.04	13.07	38.08	13.10	-0.10%	-0.21%
opensh_6.6_a	OPENSHAW	6.6	38.79	13.39	39.14	13.48	-0.90%	-0.69%
opensh_6.6_b	OPENSHAW	6.6	38.79	13.39	39.14	13.48	-0.90%	-0.69%
snipe_33_t11	SNIPE T11	-	25.15	10.67	-	-	-	-
snipe_6.6_a	SNIPE	6.6	40.17	13.86	40.15	13.87	0.06%	-0.04%
dreast_33_t11	DROYLSDEN EAST T11	-	35.47	12.65	-	-	-	-
dreast_33_t12	DROYLSDEN EAST T12	-	35.01	12.58	-	-	-	-
dreast_6.6_a	DROYLSDEN EAST	6.6	42.36	14.40	42.23	14.40	0.30%	-0.04%
dreast_6.6_b	DROYLSDEN EAST	6.6	42.36	14.40	42.23	14.40	0.30%	-0.04%
opensh_33_t11	-	-	26.50	10.90	-	-	-	-
dentwe_33_a	DENTON WEST	-	28.50	11.59	29.24	11.88	-2.51%	-2.41%
dentwe_33_b	DENTON WEST	-	28.50	11.59	29.24	11.88	-2.51%	-2.41%
dentea_33_b	DENTON EAST	33	27.00	11.17	27.92	11.48	-3.29%	-2.72%
dentea_33_a	DENTON EAST	33	27.00	11.17	27.92	11.48	-3.30%	-2.73%
dentea_6.6_a	Denton East	6.6	39.68	13.51	39.58	13.60	0.24%	-0.62%
dentea_6.6_b	Denton East	6.6	39.68	13.51	39.58	13.60	0.24%	-0.62%
dentwe_33_t11	DENTON WEST A	-	28.49	11.59	-	-	-	-
dentwe_6.6_b	Denton West	6.6	39.88	13.78	40.05	13.86	-0.44%	-0.54%

IPSA	LTDS		IPSA		LTDS		Difference (%)	
S/S or Busbar Name	S/S or Busbar Name	Voltage Level (kV)	Peak Make (kA)	RMS Break (kA)	Peak Make (kA)	RMS Break (kA)	Peak Make	RMS Break
dentwe_6.6_a	Denton West	6.6	39.88	13.78	40.05	13.86	-0.44%	-0.54%
opensh_33_t12	OPENSHAW T12	-	23.16	10.01	-	-	-	-
snipe_33_t12	SNIPE T12	-	25.54	10.76	-	-	-	-
snipe_6.6_b	SNIPE	6.6	40.17	13.86	40.15	13.87	0.06%	-0.04%

Table 2-3 Fault Level Comparison Results for Irlam Location

IPSA	LTDS		IPSA		LTDS		Difference (%)	
S/S or Busbar Name	S/S or Busbar Name	Voltage Level (kV)	Peak Make (kA)	RMS Break (kA)	Peak Make (kA)	RMS Break (kA)	Peak Make	RMS Break
irlamp_6.6_a	IRLAM	6.6	34.88	11.88	35.96	12.23	-2.99%	-2.86%
irlamp_6.6_b	IRLAM	6.6	34.88	11.88	35.96	12.23	-2.99%	-2.86%
carrin_33_a	CARRINGTON	33	30.60	10.89	30.87	10.91	-0.88%	-0.23%
carrin_33_b	CARRINGTON	33	30.60	10.89	30.87	10.91	-0.88%	-0.23%
irlamp_33_t11	IRLAM T11	-	21.08	8.90	-	-	-	-
irlamp_33_t12	IRLAM T12	-	21.25	8.54	-	-	-	-
nwgpar_33_t11	NWGB PARTINGTON T11	-	21.49	9.20	-	-	-	-
nwgpar_33_t12	NWGB PARTINGTON T12	-	26.04	10.11	-	-	-	-
airpro_33_t11	AIR PRODUCTS T11	-	30.37	10.79	-	-	-	-
airpro_33_t12	AIR PRODUCTS T12	-	30.24	10.77	-	-	-	-
nwgpar_6.6_a	NWGB PARTINGTON	6.6	36.63	13.03	36.61	13.04	0.05%	-0.06%
nwgpar_6.6_b	NWGB PARTINGTON	6.6	36.63	13.03	36.61	13.04	0.05%	-0.06%
carrin_132_gt1	Carrington GT1	-	49.27	17.35	-	-	-	-

IPSA	LTDS		IPSA		LTDS		Difference (%)	
S/S or Busbar Name	S/S or Busbar Name	Voltage Level (kV)	Peak Make (kA)	RMS Break (kA)	Peak Make (kA)	RMS Break (kA)	Peak Make	RMS Break
carrin_132_gt2	Carrington GT2	-	49.45	17.41	-	-	-	-
airpro_6.6_a	-	-	40.47	14.28	-	-	-	-
airpro_6.6_b	-	-	40.47	14.28	-	-	-	-
britga_6.6_a	-	-	36.62	13.03	-	-	-	-

Table 2-4 Fault Level Comparison Results for Wigan Location

IPSA	LTDS		IPSA		LTDS		Difference (%)	
S/S or Busbar Name	S/S or Busbar Name	Voltage Level (kV)	Peak Make (kA)	RMS Break (kA)	Peak Make (kA)	RMS Break (kA)	Peak Make	RMS Break
wigan_33_a	WIGAN	33	23.94	8.23	23.96	8.23	-0.08%	-0.03%
wigan_33_b	WIGAN	33	23.93	8.23	23.96	8.23	-0.08%	-0.03%
gidlow_33_a	GIDLOW	33	21.19	7.69	21.19	7.69	0.01%	-0.02%
gidlow_33_b	GIDLOW	33	21.19	7.69	21.19	7.69	0.01%	-0.02%
gidlow_6.6_a	GIDLOW_6.6	6.6	36.35	12.26	36.37	12.26	-0.05%	0.00%
gidlow_6.6_b	GIDLOW_6.6	6.6	36.35	12.26	36.37	12.26	-0.05%	0.00%
worsme_33_t11	-	-	20.36	7.73	-	-	-	-
worsme_33_t12	-	-	20.37	7.73	-	-	-	-
greens_33_t13	-	-	23.10	8.04	-	-	-	-
worsme_6.6_a	WORSLEY MESNES	6.6	35.54	12.30	35.53	12.30	0.03%	-0.01%
worsme_6.6_b	WORSLEY MESNES	6.6	35.54	12.30	35.53	12.30	0.03%	-0.01%
greens_6.6_b	GREEN ST (T12+T13)	6.6	36.91	12.46	36.92	12.46	-0.02%	0.00%

IPSA	LTDS		IPSA		LTDS		Difference (%)	
S/S or Busbar Name	S/S or Busbar Name	Voltage Level (kV)	Peak Make (kA)	RMS Break (kA)	Peak Make (kA)	RMS Break (kA)	Peak Make	RMS Break
greens_6.6_c	GREEN ST (T12+T13)	6.6	36.91	12.46	36.92	12.46	-0.02%	0.00%
greens_33_t12	-	-	23.13	8.04	-	-	-	-
wigan_132_te2	-	-	17.33	6.23	-	-	-	-
wigan_132_te1	-	-	17.16	6.15	-	-	-	-
washwa_132_sgt1	-	-	17.28	6.18	-	-	-	-
washwa_132_sgt2	-	-	17.38	6.26	-	-	-	-
skelme_132_gt1	-	-	16.81	6.04	-	-	-	-
skelme_132_gt2	-	-	17.04	6.12	-	-	-	-
wigan_132_gt1	-	-	9.97	4.09	-	-	-	-
wigan_132_gt2	-	-	11.03	4.28	-	-	-	-
kirkby_132_sgt5	-	-	16.56	5.98	-	-	-	-
kirkby_275_sgt5	-	-	66.77	23.65	-	-	-	-
orrell_132_gt1	-	-	12.83	4.90	-	-	-	-
orrell_132_gt2	-	-	14.29	5.10	-	-	-	-
orrell_33_gt1	-	-	26.44	9.21	-	-	-	-
orrell_33_gt2	-	-	26.44	9.21	-	-	-	-

2.1.6 Conclusions and Recommendations

The following main conclusions can be drawn from the comparison of asset parameters and fault level results produced by the ENWL IPSA Master Network Model and those in the November 2015 LTDS:

- Some of the differences in Denton West and Irlam locations are due to recent updates on the IPSA Master Network Model between November 2015 and March 2016 (following publication of the 2015 LTDS)
- 'altrin_t12' 33/11 kV transformer in Broadheath Primary has a significantly smaller reactance in the IPSA Master Network Model (up to 13 %)
- The fault levels in the Wigan Grid location areas match the ones listed in the LTDS
- Some of the differences in the peak make values could be explained by the load differences between the two sources which triggers variation of the G74 models parameters. The G74 model is limited to 1 MVA increments thus a variation of e.g. 0.2 MVA can result in a 1 MVA variation initial symmetrical fault contribution

A slight difference in load values are expected as the IPSA network works with observed demand, while the values listed in the yearly LTDS are weather corrected and also the distributed generation is subtracted.

ENWL may wish to fully automate the export of the transformer data from IPSA in the specified LTDS format. It is believed that application of the automation will reduce time for data conversation and minimize risk of errors.

Some inconsistencies between the IPSA Master Network and NGET ETYS 2015 are noticed in the Wigan – Kirkby - Orrell – Washway Farm 132 kV area. This suggests that the two sources of information are not correlated.

The fault contribution to the DNO distribution network is mainly from large generators connected to the NG transmission network and the equivalent NG transmission network impedance at the interface points between NG transmission network and ENWL distribution network plays an important role to accurate calculation of fault currents in the ENWL distribution network. It is thus recommended that ENWL update the NG transmission network topology and parameters in the IPSA Master Network model annually in accordance with the week 42 data provided by NG.

2.2 Review and Update of 11 kV and 6.6 kV Network Models for Broadheath, Denton West and Irlam Locations

2.2.1 Methodology

In the ENWL IPSA Master Network Model, load demands on all feeders at each Primary substation are aggregated into an equivalent passive model load connected to the HV busbar. For the purpose of this project, the load demands at those specific locations are modelled at HV/LV substations of the feeders. This creates a more accurate representation of loading of each HV feeder, compared to the existing HV busbar model.

This method makes possible for the distributed generators to be modelled as connected to the actual connection point on the 11 kV or 6.6 kV network. This allows a more accurate fault level calculation compared to the existing IPSA Master Network Model in which HV generator connections are not modelled or could be modelled with an equivalent circuit.

ENWL have provided the most up-to-date DINIS files[11] for the three network locations to be studied, together with the corresponding DINIS Line Code file[12]. These files include all the 11 kV and 6.6 kV networks, together with the 33 kV network information of the corresponding BSPs.

The three DINIS text files have been converted to IPSA2 software via an in-house script, preserving the geographical position of the nodes.

A parameter review was then undertaken to check the network in the IPSA format and several amendments have been made in certain areas, following comparison with Control Room Management System (CRMS) data with the help of ENWL. The changes are described in the following sections, for each selected location.

Please note that this section does not refer to the Wigan 33 kV location, for which DINIS HV data has not been used. The 132/33 kV Wigan Grid does not feed directly HV and LV consumers but via three Primaries: Gidlow, Green Street T12 & T13 and Worsley Mesnes 33/6.6 kV.

2.2.1.1 Broadheath Location

Twelve radial feeders are connected to the 11 kV bus of the Broadheath Primary. Broadheath area also has 6.6 kV networks, fed via two 11/6.6 kV transformers in Woodcote Rd Auto and Epsom Ave respectively. The list of the feeder names is presented in Appendix C.1.

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[11] Files 'Broadheath.txt', 'Dentonwest.txt' and 'irlam.txt', via e-mail from Kieran Bailey dated 04th February 2016 (RE DINIS File)

[12] File 'TlTab.Type' via e-mail from Kieran Bailey dated 10th March 2016 (FW Line Codes)

A snapshot of the Broadheath Primary area from the converted IPSA model is shown in Figure 2-6.

The corresponding DINIS file contains all the network elements from the entire Altrincham BSP. These elements, together with the Broadheath Primary 33/11 kV transformers, have been excluded, prior to combining the Broadheath HV network with the IPSA Master Network Model.

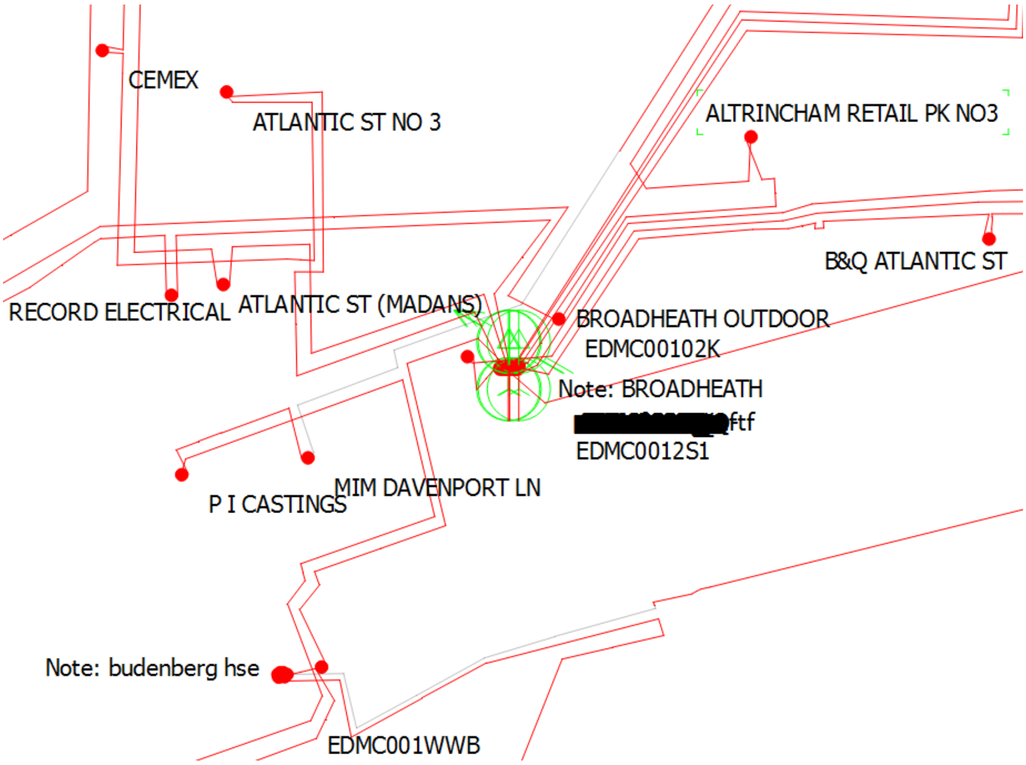

Figure 2-6 IPSA Snapshot of Broadheath Primary diagram indicating 11 kV feeders and secondary substations (segment)

Some amendments have been made to the Broadheath HV network, following discussions with ENWL, listed below:

- Unicorn coupler opened to allow the separation of the ‘L2243 THE FLEET’ and ‘L2242 BROADHEATH O/D’ feeders
- Parameters of the two 11/6.6 kV transformers in the area have been updated from (0.001+j0.01) MVA to (0.167+j1.42) MVA, as advised by ENWL

2.2.1.2 Denton West Location

Ten radial feeders are normally connected to the 6.6 kV bus of the Denton West Primary. The list of the feeder names is presented in Appendix C.2.

A snapshot of the Denton West Primary area from the converted IPSA model is shown in Figure 2-7.

The corresponding DINIS file contains all the network elements from the entire Droylsden BSP. These elements, together with the Denton West Primary 33/6.6 kV transformers, have been excluded, prior to combining the Denton West HV network with the IPSA Master Network Model.

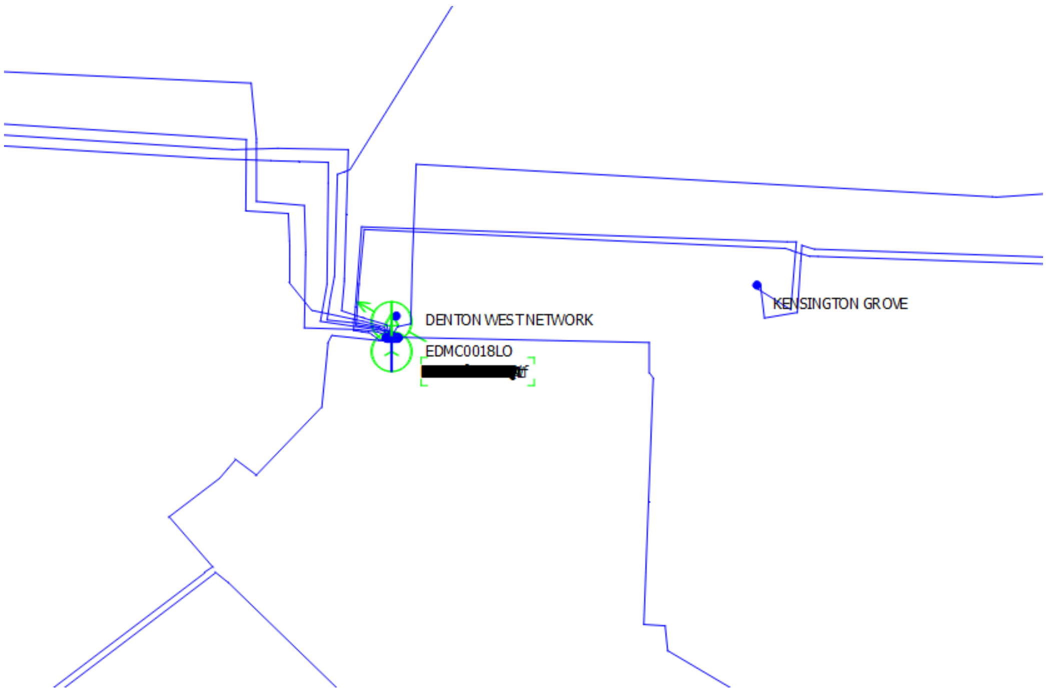

Figure 2-7 IPSA Snapshot of Denton West Primary diagram indicating 11 kV feeders and secondary substations (segment)

2.2.1.3 Irlam Location

Eleven radial feeders are normally connected to the 6.6 kV bus of the Irlam Primary. The list of the feeder names is presented in Appendix C.3.

A snapshot of the Denton West Primary area from the converted IPSA model is shown in Figure 2-8.

The corresponding DINIS file contains all the network elements from the entire Carrington BSP. These elements, together with the Irlam Primary 33/6.6 kV transformers, have been excluded, prior to combining the Irlam HV network with the IPSA Master Network model.

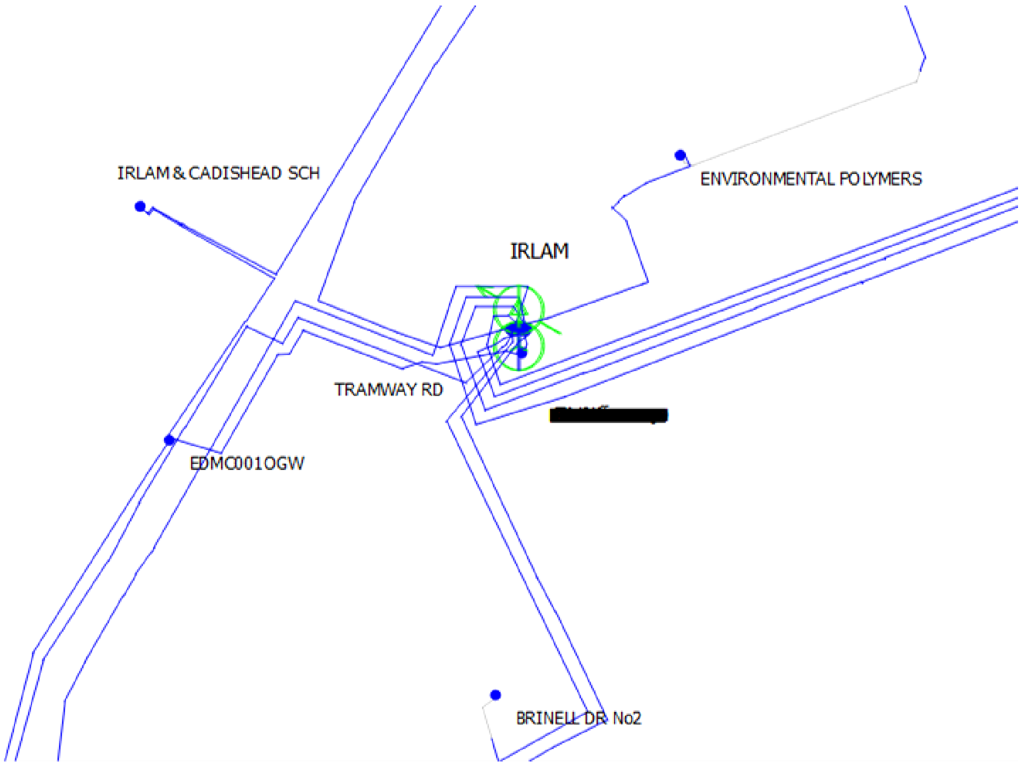

Figure 2-8 IPSA Snapshot of Irlam Primary diagram indicating 11 kV feeders and secondary substations (segment)

2.2.2 Loads Modelling

Loads are characterised in the DINIS files via three different values: rating (kVA), actual load (kVA), TDI (kVA) and a power factor value. TNEI understands that the load values and the corresponding power factor values provided in the DINIS files are not necessarily representative of the actual peak loading of the feeders.

In order to model and simulate different load profiles representative for the period of measurements, Feeder Load Analysis (FLA) data provided by ENWL has been used to scale each load based on the rating given via the DINIS file. This methodology is described in Section 5.2.

A total of about 32 loads did not have the rating specified in DINIS files and the values have been replaced with transformer rating values from Control Room Management System (CRMS) or have been assumed, where information was not sufficient. A detailed table is presented in Appendix D, for each selected location.

2.2.3 Distributed Generation Modelling

The distributed generators (DG) are modelled as connected to the actual connection point on the 11 kV and 6.6 kV network. This allows a more accurate fault level calculation compared to the existing IPSA Master Network Model in which HV generator connections are not modelled or could be modelled with an equivalent circuit.

ENWL have provided information on HV distributed generation (DG) larger than 200 kW connected in the selected locations, at TNEI's request. General information is listed in Table 2-5.

Table 2-5 Distributed Generation General Information

Scheme name	Postcode	Plant Cap kW	Substation No.	Substation	Primary
The Winery Fairhills Rd Irlam **(PV)**	M44 6BD	250	166594	CWS BOTTLING	IRLAM
Urban Splash **(Mini CHP)**	WA14 4ET	210	177710	BUDENBERG HOUSE	BROADHEATH

Irlam HV network in the ENWL DINIS file already contains one generator: Whiteparish Landfill. According to ENWL, at this time, the customer only has one operational generator, Electricity North West Butchersfield Generation Substation (166877), 1 x 150 kW LV synchronous generator. It has been communicated that the generator impedance already included in the DINIS file is not necessarily representative for this site and because the generator rating is less than 150 kW, the Whiteparish Landfill generating unit has been excluded from the study, i.e. disconnected from the rest of the grid.

The Winery Fairhills Rd Irlam (PV)

The Winery Fairhills Rd Irlam (PV) site is comprised of eight PowerOne Trio 27.6 TL inverters. The information about the generator transformer was not available, thus generic data has been used. ENWL have provided TNEI with available information, including the SLD and the inverter general datasheet[13].

In the absence of data, all connecting circuits within the site have been omitted from the model.

According to the datasheet, one PowerOne Trio 27.6 TL has a rated AC power of 27.6 kW and AC rated grid voltage of 0.4 kV. More detailed information is shown in Appendix E.1. Table 2-6 shows the fault contribution considered in the studies. The PowerOne Trio datasheets provides the maximum fault contribution of the inverter to be 45 A and this has been assumed to correspond to the RMS break contribution. The peak make current has been assumed based on in-house information of inverter of similar structure.

Typically, the short circuit behaviour of inverters indicates a controlled current source where the maximum short circuit is governed by the inverter's control algorithm usually at the end of the first cycle after inception of the fault. It is however, assumed that inverter's algorithm is not capable of controlling fault

[13] Files 'Kingsland Wines line diagram' and 'PowerOne Trio-27.6' via e-mail from Kieran Bailey dated 14/03/2016 (The Winery data) and e-mail 'HV Generator data' from Kieran Bailey dated 14/03/2016

contribution immediately after inception of the fault. Two separate models, i.e. equivalent synchronous machines with constant voltage source and fixed equivalent impedance, have been applied to calculate fault contribution from the inverters for peak make and break fault contributions.

Table 2-6 Winery Fairhills Rd Irlam PV Fault Contribution for a Three-Phase Fault (400 V)

Definition		Current for one 27.6 kW inverter		Total Current of Site
		p.u.*	A	A
Maximum peak short circuit current @10ms	ip	2.62	113.5	908
Maximum RMS symmetrical short-current @90ms	$I_{k(90)}$	1.04	45	360

* rated current of 43.3 A, calculated for a maximum power of 30 kW

Urban Splash (Mini CHP)

The Urban Splash combined heat and power site is comprised of two T100 100 kW LV Micro Turbines connected via a 1.25 MVA Dyn11 6 % impedance voltage transformer. ENWL have provided TNEI with relevant information, including the site layout and the turbine description[14].

In the absence of data, all connecting circuits within the site have been omitted from the model.

The T100 turbine has a rated apparent power of 120 kW and the power from the generator is rectified and converted to the grid frequency. More detailed information is shown in Appendix E.2.

According to the manufacturer datasheet, when the T100 turbine is connected in parallel with the utility grid, the power electronics is controlled as a current source. The output current is limited by the control system, mainly in order to protect the power electronics. For long-term operation, the maximum rated current of 195 A is allowed by the control system.

No other information has been provided about the fault level contribution of these turbines thus a 90 ms RMS break current contribution of 195 A and a peak make contribution of 2.62 times the rated current, i.e. 453.8 A have been assumed. This approximation of the peak value is based on the fact that the peak current in p.u. is expected to be similar to other generating units connected to grid via power electronics e.g. as for the Winery Fairhills Rd Irlam.

[14] Files '2595PE01 Layout1 (1)', 'D11234 02 Electrical Protection' and 'Microturbina_T100_Detailed_Specifications1' via e-mail from Kieran Bailey dated 14/03/2016 (Urban Splash Data) and e-mail 'HV Generator data' from Kieran Bailey dated 14/03/2016

Table 2-7 shows the fault contribution considered in the studies.

Table 2-7 Urban Splash T100 Turbine Fault Contribution for a Three-Phase Fault (400 V)

Definition		Total Current	
		p.u.*	A
Maximum peak short circuit current @10ms	ip	2.62	453.8
Maximum RMS symmetrical short-current @90ms	$I_{k(90)}$	1.13	195

* rated current of 173.2 A, calculated for an apparent power of 120 kVA

3 ER G74 General Load Fault Infeed Model Comparison

3.1 ER G74 Theory on Fault Infeed from General Load

This section comments upon the validity of the ENWL G74 model in relation with the following guidelines:

- Engineering Recommendations G74: Procedure to meet the requirements on IEC 909[15] for the calculation of short circuit currents in three-phase AC power systems, Energy Networks Association, London, UK, 1992
- Engineering Technical Report 120: Calculation of fault currents in three-phase AC power systems (Application Guide to Engineering Recommendation G74), Energy Networks Association, London, UK, 1995

The ER G74 procedure was intended to set out 'good industry practice' for a computer-based method for calculating short-circuit currents which can be used as an alternative to the methods presented in IEC 909 where higher precision is required.

The ETR 120 aims to represent an application guide to assist the Electricity Industry staff engaged in applying ER G74 to evaluate short circuit currents in transmission and distribution networks and in generating station auxiliary systems.

Section 9.5 of ER G74 provides guidance for modelling asynchronous motors forming part of the general load. These motors, which are not individually identifiable, may be modelled as a lumped equivalent motor connected at the 33 kV busbar that supplies them. ER G74 indicates that ideally the impedances and time constants for the equivalent motor (G74 model) should be obtained by measurement. Where measurements are not available, it provides indicative values that may be used for calculating the fault contribution. These indicative values are shown in Table 3-1.

Table 3-1 ER G74 Indicative Figures

Fault infeed allowance for motors connected at 50 < V ≤ 1000	Initial symmetrical fault contribution of 1 MVA per MVA of aggregated winter demand
Fault infeed allowance for motors connected at voltages > 1000 V	Initial symmetrical fault contribution of 2.6 MVA per MVA of aggregated winter demand
X/R ratio	2.76
AC time constant	40 ms
Contribution to three-phase faults at times > 120 ms following fault inception	Negligible

[15] International Electrotechnical Commission (IEC), 2001, *IEC 60909: Short-circuit currents in three-phase a.c. systems*

Engineering Technical Report (ETR) 120 provides further guidance on calculating the equivalent machine to represent aggregated asynchronous machines forming part of the general load. ETR 120, paragraph 4.5.6 states that the negative sequence reactance of the equivalent machine can be taken to be equal to the sub-transient positive sequence reactance and that this remains constant with time:

$$X2_{eqm} = X''_{eqm}$$

Using these figures above the impedances for the equivalent machine representing asynchronous machines in the general load may be calculated using the equations:

$$Z''eqm\ (pu) = \frac{MVA(base)}{MVA\ (infeed)}$$

$$R''\mathrm{eqm\ (pu)} = \mathrm{Z}''eqm \sin \tan^{-1}\frac{R}{X}$$

$$X''eqm\ (pu)\ = Z''eqm \cos \tan^{-1}\frac{R}{X}$$

Where the lumped equivalent machine is connected at an 11 kV busbar, ETR 120 paragraph 4.5.5 states that the equivalent machine impedances may be estimated by subtracting the interconnection impedance (Z_{int}) between the 11 kV busbar and a notional 33 kV busbar.

$$Z''\mathrm{eqm\ 11kV} = \mathrm{Z}''eqm\ 33kV - Zint$$

As before, advice in ETR 120 is to base the interconnection impedance upon local knowledge of the network being studied. The worked example in ETR 120 uses an interconnection impedance of (4 + 60j) % on a 100 MVA base.

The guidelines do not make any reference for the case when the lumped equivalent machine is connected at a 6.6 kV busbar. It is understood that the same methodology can be used as for the 11 kV case.

3.2 Comparison of ENWL IPSA Model with ER G74 Guidelines

3.2.1 Calculated Values

The equations used by the IPSA2 fault level model for induction machines are as follows:

$$Yac\ = \left(\frac{1}{X''}\right)e^{\frac{-t}{T''}}$$

$$Ydc\ = \left(\frac{1}{X''}\right)e^{\frac{-t}{T_a}}$$

$$T''\ = \frac{X''}{2\,\pi\,f\,R_{rotor}}$$

$$T_a\ = \frac{X''}{2\,\pi\,f\,(R_{stator}\ +\ R_{external})}$$

$$X" = X_{external} + X_{stator} + \frac{(X_{rotor,\ standstill}\, X_{magnetising})}{(X_{rotor,\ standstill} + X_{magnetising})}$$

$$Z_{external} = R_{external} + j\, X_{external}$$

$Z_{external}$ being the system impedance between the machine terminals and the fault point.

Values were calculated for an IPSA induction machine (standstill), using the ER G74 guidelines and indicative values discussed above for a 33 kV and an 11 kV fault infeed.

Values for 33 kV fault infeed:

$$Z"eqm\ (pu) = \frac{100\ MVA}{1\ MVA\ (infeed)} = 100$$

$$R"\text{eqm (pu)} = 100 \sin \tan^{-1} \frac{1}{2.76} = 34.06$$

$$Rrotor\ (running\ slip = 0) = \frac{94.02}{2\pi f \times 0.04} = 7.48$$

$$Rstator(pu) = 34.06 - 7.48 = 26.58$$

$$Xstator\ (pu) = X"eqm\ (pu) = 100 \cos \tan^{-1} \frac{1}{2.76} = 94.02$$

Values for 11 kV fault infeed:

$$Z"eqm\ (pu) = \frac{100\ MVA}{1\ MVA\ (infeed)} = 100$$

$$R"\text{eqm (pu)} = 100 \sin \tan^{-1} \frac{1}{2.76} = 34.06$$

$$X"eqm\ (pu) = 100 \cos \tan^{-1} \frac{1}{2.76} = 94.02$$

$$R"\text{eqm 11kV (pu)} = 34.06 - 0.04 = 34.02$$

$$Xstator\ (pu) = X"\text{eqm 11kV (pu)} = 94.02 - 0.6 = 93.42$$

$$Rrotor\ (running\ slip = 0) = \frac{93.42}{2\pi f \times 0.04} = 7.43$$

$$Rstator(pu) = 34.02 - 7.43 = 26.59$$

These values are compared with those in the ENWL database fault infeed models in Table 3-2. The shaded cells in the table represent the values that would be entered into an IPSA induction machine component.

Table 3-2 Comparison of ENWL and ER G74 Calculation for 1 MVA Fault Infeed (Initial Symmetrical Fault Contribution) Model from General Load

	ENWL 33kV	G74 33kV	ENWL 11kV	G74 11kV
X_{stator} (pu)	**67.39**	**94.02**	**67.07**	**93.42**
R_{stator} (pu)	**8.99**	**26.58**	**8.94**	**26.59**
X_m (pu)	**2097.5**	**n/a**	**2087**	**n/a**
X_{rotor} (pu)	**26.97**	**n/a**	**26.84**	**n/a**
R_{rotor} (pu)	**25.08**	**7.48**	**24.96**	**7.43**
Z" (pu)	100	100	99.52	99.42
X" (pu)	94.02	94.02	93.57	93.42
R_{total} (pu)	34.07	34.06	33.9	34.02
X/R	2.76	2.76	2.76	2.76
Tac (s)	0.01	0.04	0.01	0.04

As can be seen from Table 3-2, the calculated values of Z", X", Rtotal and X/R values using the indicative values in G74 are comparable to those in the ENWL IPSA models. This suggests that the ENWL database G74 infeed models have been generally calculated in accordance with the principles of ER G74. The breakdown of the values which are entered into the IPSA induction machine component suggest that, due to the presence of magnetising reactance (X_m), the ENWL models may have been calculated based upon the parameters of a known or typical machine.

It is questioned whether the R_{stator} and R_{rotor} values have been transposed in the ENWL models, as these appear to be reversed when compared to those calculated during this study. The effect of this reversal is to lower the time constant, T_{ac}, as shown in Table 3-2.

The indicative $Z_{internal}$ suggested in ER G74 is (0.04 + 0.60j) pu, in the ENWL model this is calculated as (0.17 + 0.48j) pu. A value of Z = 0.5 pu is reasonable for two 33/11 kV transformers connected in parallel in the ENWL network, although the resistance figure seems high for two such transformers. The resistance may be intended to represent the resistance in circuits between the 33 kV and 11 kV busbars, if the load infeed is modelled at a busbar remote from the 11 kV BSP primary busbar.

It is also worth commenting that the ENWL G74 fault infeed database components represent 1 MVA fault contributions, or typical fault infeed from 1 MVA of connected LV demand. Using these components the network modeller is limited to 1 MVA increments and a decision needs to be made if the connected demand is e.g. 1.5 MVA.

3.2.2 Fault Infeeds

Several induction machines were modelled in IPSA using the calculated parameters for a 1, 3 and 5 MVA fault infeed and the ENWL database components. The resulting fault contributions are shown in Table 3-3, Table 3-4 and Table 3-5 respectively. These results show that the initial symmetrical and peak fault contributions from both models are comparable.

The contribution from the ENWL model at break time (90 ms) is negligible, whereas the model calculated using the indicative G74 parameters has a contribution to fault currents at break time. This difference is a result of the smaller time constant in the ENWL model discussed earlier. The ENWL model produces slightly smaller peak contribution values than the model using the G74 indicative parameters.

Table 3-3 Resulting Fault Contribution from 1 MVA Fault Infeed Models

Value\Model	33kV		11kV	
	ENWL (kA)	G74 (kA)	ENWL (kA)	G74 (kA)
Symmetrical RMS at 0.00 s	0.018	0.018	0.053	0.054
Symmetrical RMS at 0.04 s	0.000	0.007	0.000	0.021
Symmetrical RMS at 0.09 s	**0.000**	**0.002**	**0.000**	**0.006**
Symmetrical RMS at 0.24 s	0.000	0.000	0.000	0.000
Asymmetrical RMS at 0.01 s	0.021	0.018	0.062	0.054
Peak at 0.01s	**0.029**	**0.031**	**0.089**	**0.093**
Value\Model	**ENWL (MVA)**	**G74 (MVA)**	**ENWL (MVA)**	**G74 (MVA)**
Symmetrical RMS at 0.00 s	1.013	1.023	1.018	1.030
Symmetrical RMS at 0.04 s	0.000	0.389	0.000	0.392
Symmetrical RMS at 0.09 s	**0.000**	**0.112**	**0.000**	**0.113**
Symmetrical RMS at 0.24 s	0.000	0.003	0.000	0.003
Asymmetrical RMS at 0.01 s	1.183	1.016	1.189	1.021
Peak at 0.01s	**1.686**	**1.759**	**1.694**	**1.767**

Table 3-4 Resulting Fault Contribution from 3 MVA Fault Infeed Models

Value\Model	33 kV		11 kV	
	ENWL (kA)	G74 (kA)	ENWL (kA)	G74 (kA)
Symmetrical RMS at 0.00 s	0.053	0.054	0.160	0.164
Symmetrical RMS at 0.04 s	0.000	0.020	0.000	0.062
Symmetrical RMS at 0.09 s	**0.000**	**0.006**	**0.000**	**0.018**
Symmetrical RMS at 0.24 s	0.000	0.000	0.000	0.000
Asymmetrical RMS at 0.01 s	0.062	0.053	0.187	0.162
Peak at 0.01s	**0.088**	**0.092**	**0.267**	**0.281**
Value\Model	ENWL (MVA)	G74 (MVA)	ENWL (MVA)	G74 (MVA)
Symmetrical RMS at 0.00 s	3.038	3.070	3.053	3.126
Symmetrical RMS at 0.04 s	0.000	1.168	0.000	1.190
Symmetrical RMS at 0.09 s	**0.000**	**0.336**	**0.000**	**0.343**
Symmetrical RMS at 0.24 s	0.000	0.008	0.000	0.008
Asymmetrical RMS at 0.01 s	3.549	3.048	3.567	3.090
Peak at 0.01s	**5.057**	**5.276**	**5.082**	**5.342**

Table 3-5 Resulting Fault Contribution from 5 MVA Fault Infeed Models

Value\Model	33 kV		11 kV	
	ENWL (kA)	G74 (kA)	ENW (kA)	G74 (kA)
Symmetrical RMS at 0.00 s	0.089	0.090	0.267	0.277
Symmetrical RMS at 0.04 s	0.000	0.034	0.000	0.105
Symmetrical RMS at 0.09 s	**0.000**	**0.010**	**0.000**	**0.030**
Symmetrical RMS at 0.24 s	0.000	0.000	0.000	0.001
Asymmetrical RMS at 0.01 s	0.103	0.089	0.312	0.273
Peak at 0.01s	**0.147**	**0.154**	**0.445**	**0.472**
Value\Model	ENWL (MVA)	G74 (MVA)	ENWL (MVA)	G74 (MVA)
Symmetrical RMS at 0.00 s	5.064	5.117	5.088	5.272
Symmetrical RMS at 0.04 s	0.000	1.946	0.000	2.009
Symmetrical RMS at 0.09 s	**0.000**	**0.560**	**0.000**	**0.579**
Symmetrical RMS at 0.24 s	0.000	0.013	0.000	0.014
Asymmetrical RMS at 0.01 s	5.915	5.080	5.945	5.198
Peak at 0.01s	**8.428**	**8.793**	**8.470**	**8.978**

3.3 Validity of ENWL G74 Model in Relation with the Guidelines

The modelling information provided in ER G74 is based on fundamental principles. The ENWL database G74 infeed models have been generally calculated in accordance with the principles of ER G74 with a few differences discussed above. If ENWL wish to follow the guidelines to a higher extent, we recommend the indicative figures provided in G74 and reproduced in Table 3-1. The parameters of the equivalent induction machines representing the G74 model can be replaced by the values provided by TNEI in Table 3-2.

It is also worth commenting that the ENWL G74 fault infeed database components represent 1 MVA fault contributions, or typical fault infeed from 1 MVA of connected LV demand. Using these components the network model is limited to 1 MVA increments and a decision needs to be made if the connected demand is e.g. 1.5 MVA. ENWL may wish to increase the accuracy of the G74 model fault contribution by reducing the MVA increment. Some examples are presented below:

- the G74 model parameters can be calculated for each load either via an automated process or via spreadsheets; the values can then be pasted in the IPSA Master Network Model
- the fault level study can be undertaken via a script that reads the load at each bus and automatically calculates the fault contribution of the G74 models

4 Summary of Outram Fault Level Monitor (FLM) Device Results and Discussion

Outram FLM devices have been installed on the secondary side of the transformers in the selected substations, attached to the measurement Current Transformers CT and Voltage Transformer VT circuits (Figure 4-1).

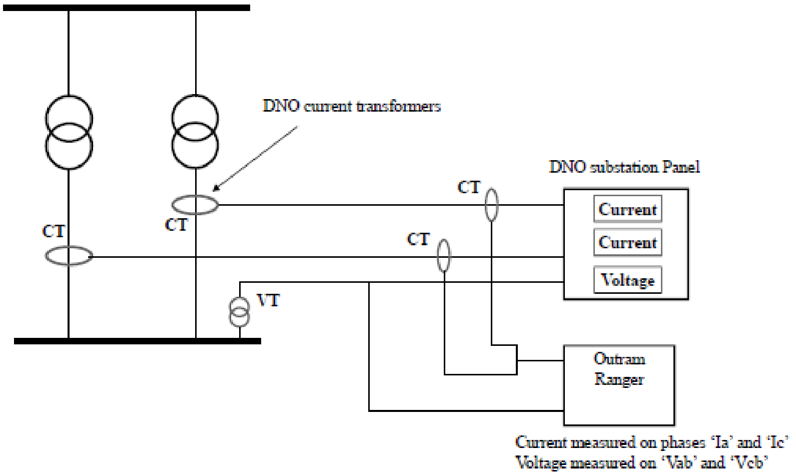

Figure 4-1 Simplified Schematics of the FLM Connection (example)

ENWL have provided TNEI with both the raw measurements files[16] and the Outram initial Fault Level Report[17]. An updated Outram report was later provided that included a CT ratio correction of the Wigan measurements[18].

On the initial trial the connection to Phase C current sensor was faulty and the current on phase C was not recorded correctly in Broadheath. All connections were corrected on a subsequent trial. The report refers to this second recording of Broadheath. The Outram report[19] was updated to include these measurements.

The raw measurements (MDM) files have been downloaded into the Pronto Data Analysis and Presentation software, and the Fault Level Analysis module has been used.

Table 4-1 shows the recording periods for the selected locations, as presented in the Outram report.

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[16] Corresponding *.MDM files from Kieran Bailey

[17] File 'RESPOND Project for ENW Report #1inc Appendices V1' via e-mail from Kieran Bailey dated 01/04/2016 (Fwd Respond Project Report on 1 set of FLM sites)

[18] File 'RESPOND Project for ENW Report #1inc Appendices D5x125.docx' via e-mail from Kieran Bailey dated 03/05/2016 (FW Supplementary note to ENW re Wigan etc.msg)

[19] File 'RESPOND Project for ENW Report #1inc Appendices V3.docx' via e-mail from Kieran Bailey dated 21/07/2016 (RE FL Reprot.msg)

Table 4-1 Recording Period for Selected Locations

Location	Recording Start Date	Recording End Date
Broadheath (100134)	11/03/2016	16/06/2016
Denton West (100111)	13/01/2016	08/03/2016
Irlam Primary (100615)	05/01/2016	07/03/2016
Wigan (200421)	24/12/2015	09/03/2016

4.1 Description of the FLM Device and its Operation Algorithm

This section provides a short description of the device based on the information of PM7000FLM Operating Procedure document[20] provided by Outram and other Outram documents publicly available.

The PM7000 Fault Level Monitor (FLM) is designed by Outram to obtain Fault Level estimation for three phase and single phase systems on radial or interconnected networks. If the network is interconnected, the device must be installed on a radialised section.

The monitor utilises information generated from voltage and current disturbances that occur normally on the network, or from disturbances generated artificially, to produce three distinct fault level results:

- Peak Upstream Fault Level at ½ cycle (10 ms at 50 Hz)
- RMS Upstream Fault Level at typically 90 ms (selectable)
- Peak Downstream (motor) contribution at ½ cycle (10 ms)

The FLM operates as a passive device, without affecting the network.

A downstream change like a load variation on a piece of network of interest (e.g. feeder) will produce changes in current and consequent changes in voltage dependent on the characteristics of the upstream network. Similarly, an upstream voltage changes like tap changes, or load variation on the wider network will produce changes in current dependent on downstream characteristics.

Load changes which cause a voltage change give an estimate of the wider network (source) impedance. Similarly, load changes which are caused by a voltage step

[20] File 'Outram PM7000FLM Operating Procedure' via e-mail from Kieran Bailey dated 08/92/2016 (FLM docs)

give an estimate of the induction motors fault infeed downstream of the point of measurement.

In other words, upstream disturbances (or Upstream 'Events') are examined to obtain downstream information, and Downstream disturbances (downstream 'Events') for upstream, or source information. Thus the combined characteristic of cables, transformers etc. upstream of the measurement point are revealed by load changes downstream, and motor contributions and downstream generators by tap changes or other load changes upstream.

Figure 4-2 shows an example of an event recorded by the FLM and interpreted as an event caused by an upstream disturbance (voltage and current move in the same direction). In contrast, Figure 4-3 shows an event recorded by the FLM and interpreted as an event caused by a load downstream (voltage and current move in opposite directions). Both figures have been extracted from the Outram report.

When the (natural) disturbance occurs, changes in current and voltage will occur simultaneously, allowing the device to calculate the corresponding impedance. The ratio between the reactive and resistive components (X/R) provides information needed to calculate the peak current.

The FLM is designed to record many small disturbances and builds **populations of results (a form of probability density function), over specified intervals**. Intervals are typically 30 minutes. The population distribution for each interval is recorded in the FLM and the full recording of multiple intervals can be presented as a 3-D surface plot in Pronto software. This provides the opportunity to see multiple populations and to isolate and measure the precise fault level of each such population.

An extract from the FLM Operating Procedure Document can be found in Appendix F for a larger description of the bins, populations and weight factors.

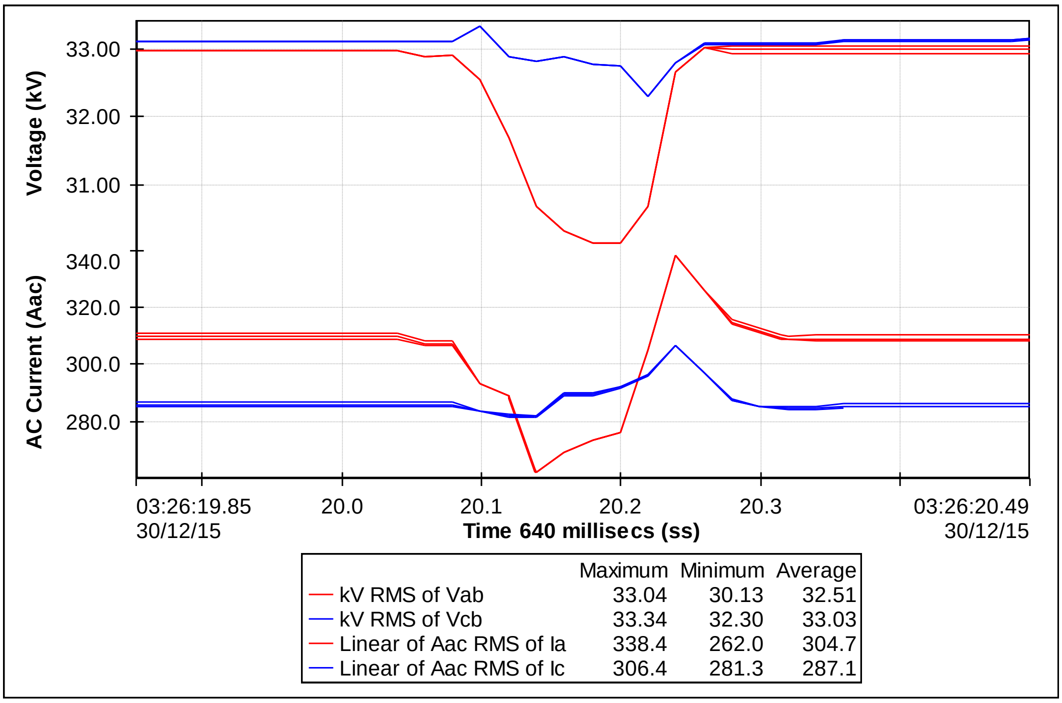


Figure 4-2 Example 1 of Event Recorded by FLM (Wigan Location)

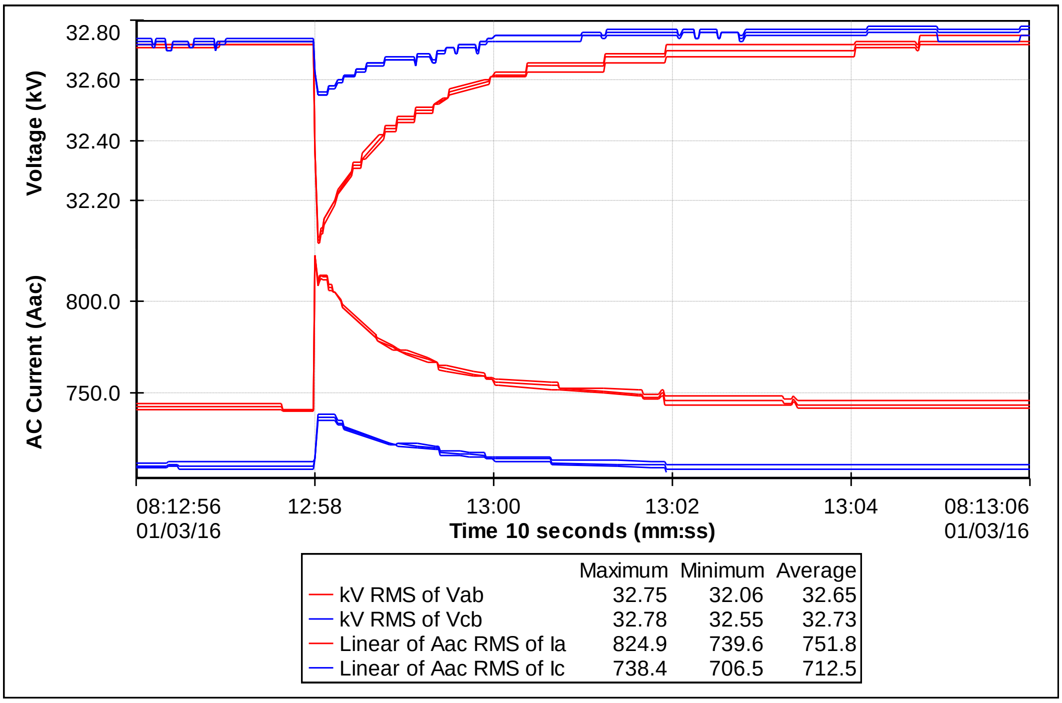


Figure 4-3 Example 2 of Event Recorded by FLM (Wigan Location)

4.1.1 Manipulation of the Data

The main Pronto manipulation tool used on the data shown in this report is the Filter/Smoothing function. If the distribution of results is irregular, or non-

Gaussian, the position of the peak may not be a good representation of the Fault Level. The Filter tool shares the "strength" of each Fault Level result with adjacent cells which effectively broadens out each result making it easier to see the aggregate strength of clusters of results. The higher the filtering, the more emphasis is out on the surrounding intervals. The degree of broadening is controlled by the filter selection, i.e. from 0 % to 10 %. According to the Outram report, the general rule is to use as little filtering as is necessary to create a bell-shaped distribution around the area of interest.

4.2 FLM Fault Level Results

The Outram report presents the results obtained from Fault Level Monitors installed at the selected ENWL trial sites, together with the Outram interpretation of the results.

The Denton West recording period is shorter than the other locations because the device was initially installed at Hindley Green Primary and later moved to Denton West.

Table 4-2 shows the recommended fault level results from the Outram report. The report provides more detailed results for different filtering values of the distributions. These recommended results (Table 4-2 and the graphs below) have been extracted and used in the report as the representative ones. These values will be compared with the results from fault level modelling in IPSA in the subsequent sections of the report.

Table 4-2 FLM Fault Level Results (kA)

Location	10 ms Peak Upstream	10 ms Peak Downstream	90 ms RMS upstream	Combined 10 ms Peak
Broadheath (100134)	29.56	3.217	10.16	(32.78)
Denton West (100111)	34.84	3.47	14.08	(38.31)
Irlam Primary (100615)	29.4	4.27	11.63	(33.67)
Wigan (200421)*	16.83	1.60	7.51	(18.43)

* Results for Wigan have been adjusted to suit a Secondary CT ratio of 2000:1. (The original data was recorded with CT ratio entry of 1600:1, i.e. all currents were initially reported at 80% of correct value.)

It should be noted that the combined peak values listed in the previous table is not generated by the FLM but the result of an arithmetic summation in the Outram report. The Outram report states that this value may be slightly overstated as the arithmetic sum assumes that the upstream and downstream results are recorded at the same time and that the phase of the downstream contribution is exactly in phase with the upstream contribution, both of which may not be the case.

In reality, the combined peak values could be as low as 32.50 kA for Broadheath, 38.01 kA for Denton West, 33.32 kA for Irlam and 18.29 kA for Wigan respectively. These values were calculated by applying the Law of Cosines to two vectors whose magnitudes are the values in the table above and with a angle difference of 25 deg. It would be unrealistic to assume a phase angle difference of more than 30 deg between the two equivalent circuits, i.e. upstream and downstream of measurement point. For example, if the X/R ratios of the two circuits are extreme values like 2 (63.44 deg) and 100 (89.43 deg) respectively, this corresponds to an angle difference of about 26 deg.

4.2.1 Broadheath Location

Figure 4-4 to Figure 4-6 show the fault level results at Broadheath estimated by the FLM in graphical format, as described by the Outram report for the entire period of measurements. The graphs represent the two dimensional distribution plot (2D) and the three dimensional surface plot (3D) shown by the Pronto software. These graphs are built up from arrays of data stored at specific intervals during the recording period. The graphs show results over a period of time as a Probability Density Function (PDF) or a series of PDFs.

The fault level current (kA) is shown on the horizontal axis, while the strength of result (weight or value) is on the vertical axis. The vertical axis basically represents the accumulated incidence x size of disturbance. The weight refers to how much notice should be taken of each disturbance when estimating the fault level and it is linked to the size and the quality of the disturbance.

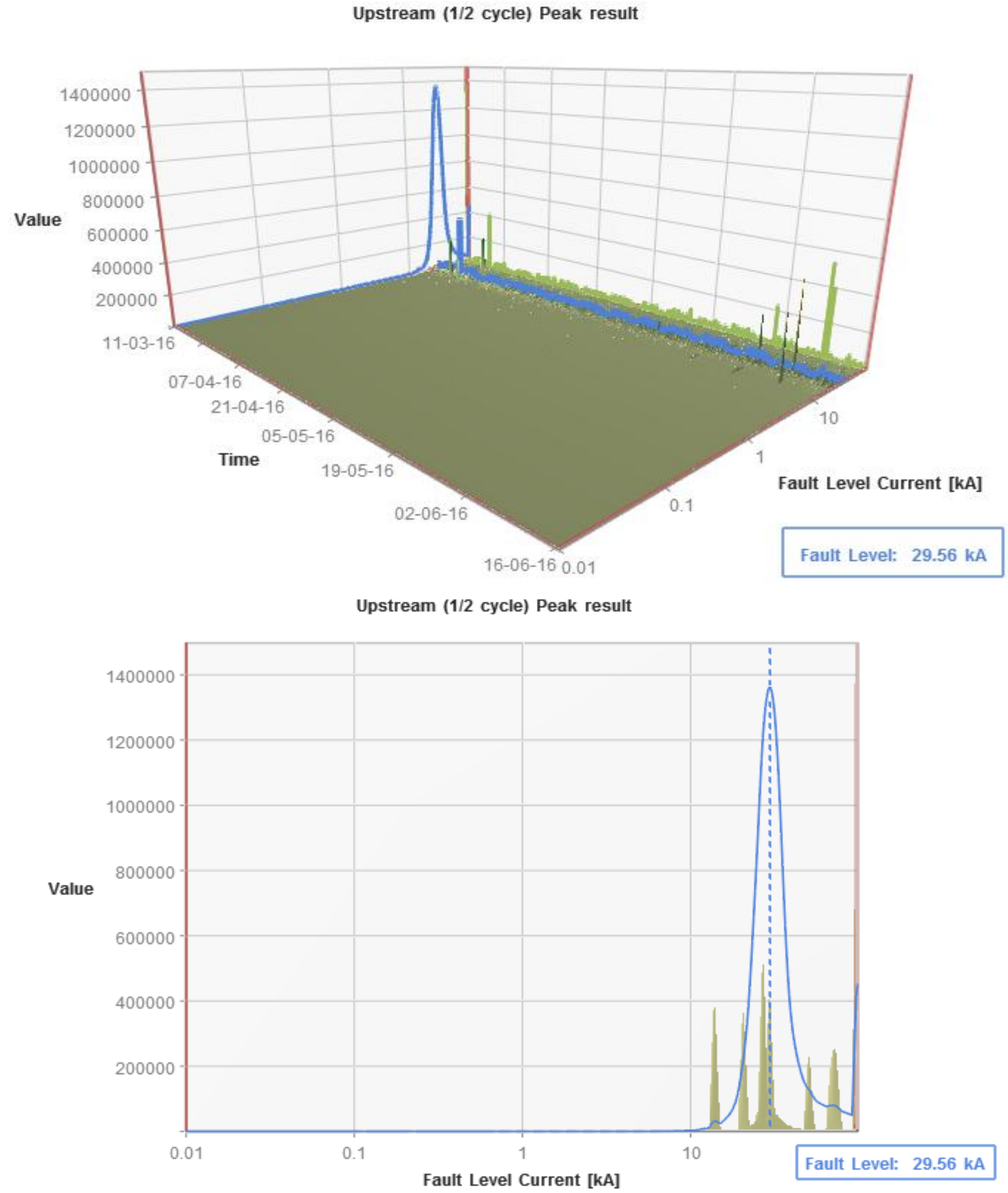


Figure 4-4 Upstream (1/2 cycle) Peak Fault Level Results, 3D and 2D Distribution shown with 2 % filtering – Broadheath Location

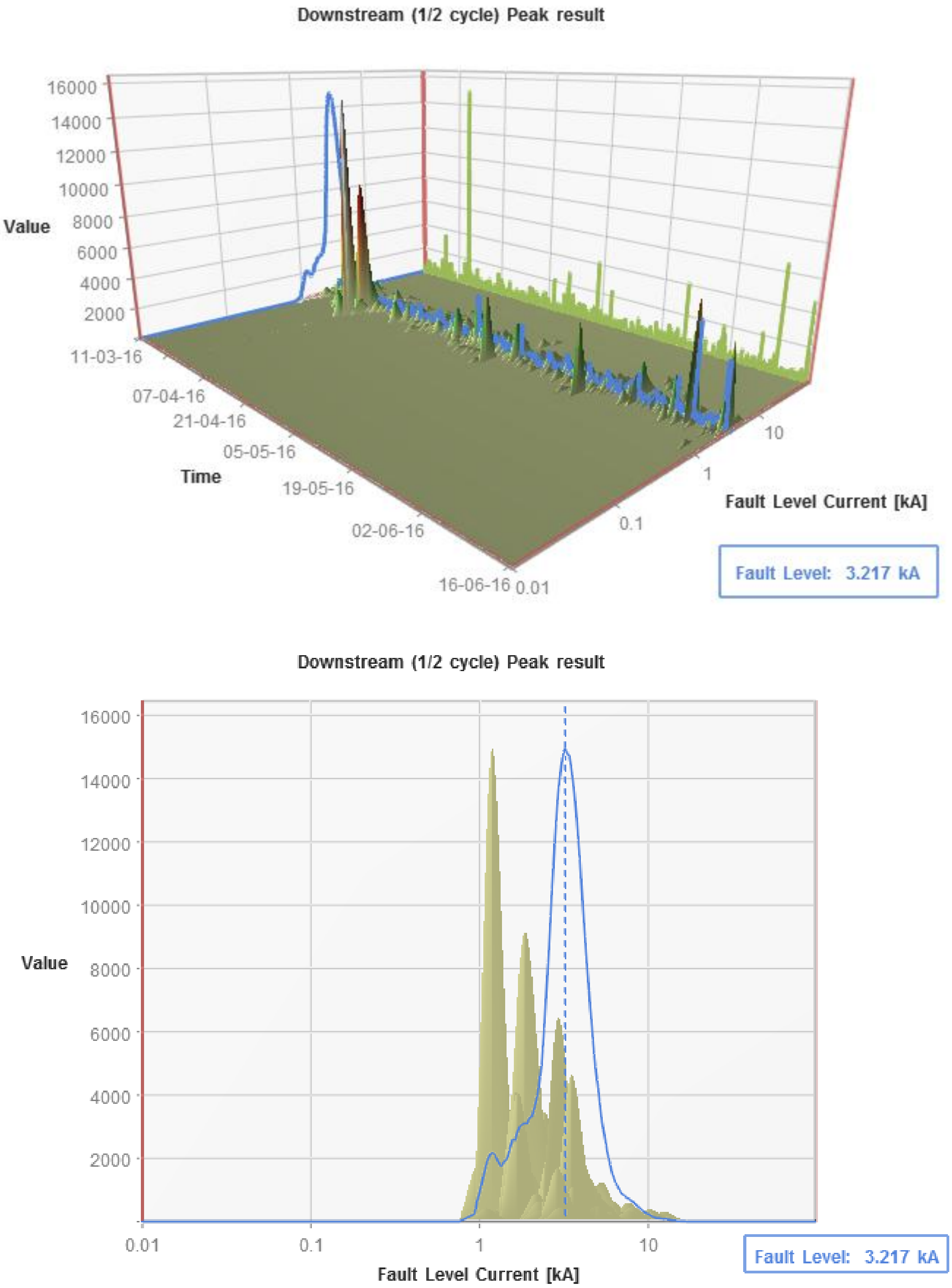


Figure 4-5 Downstream (1/2 cycle) Peak Fault Level Results, 2D Distribution shown with 7 % filtering- Broadheath Location

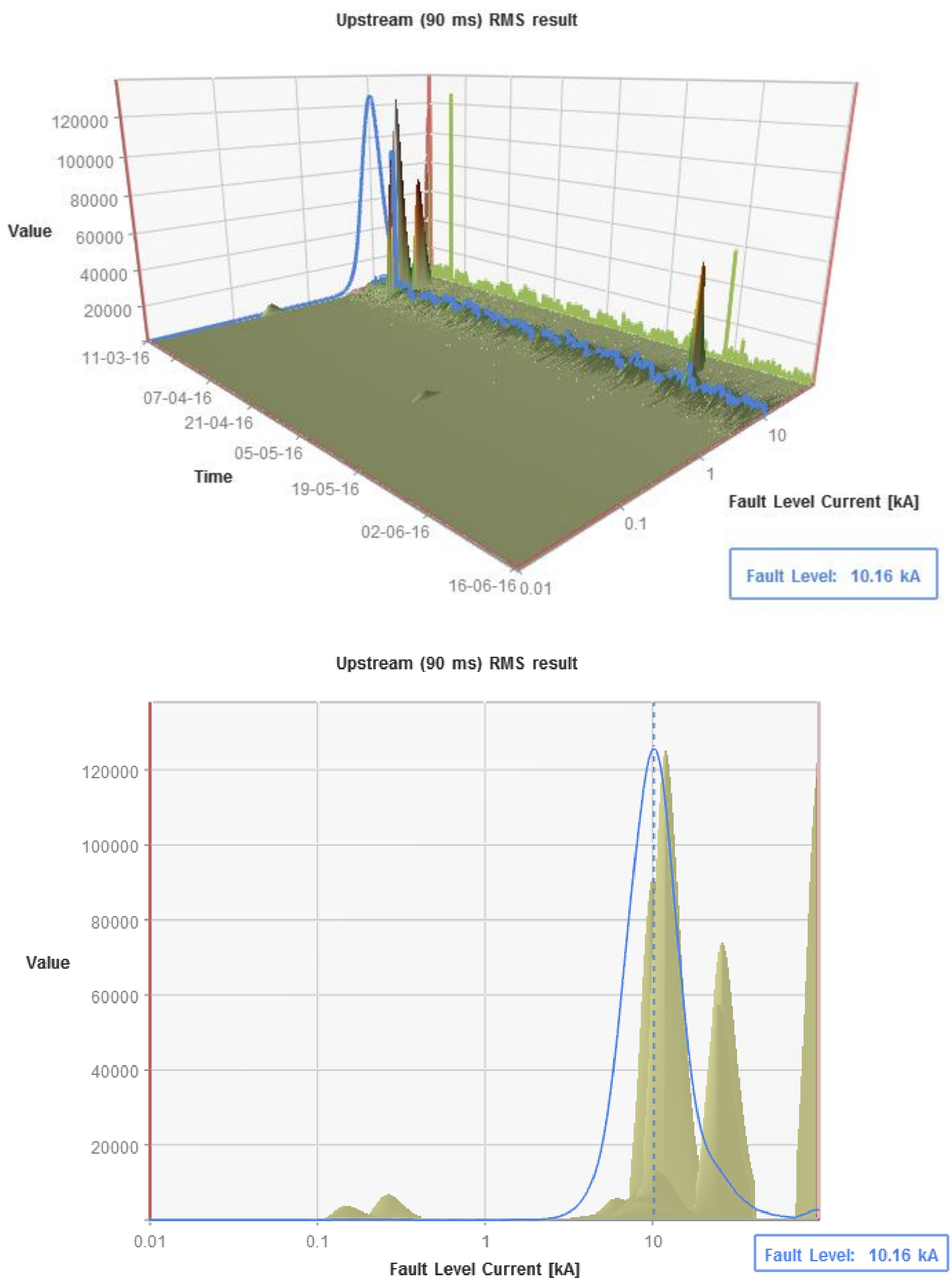
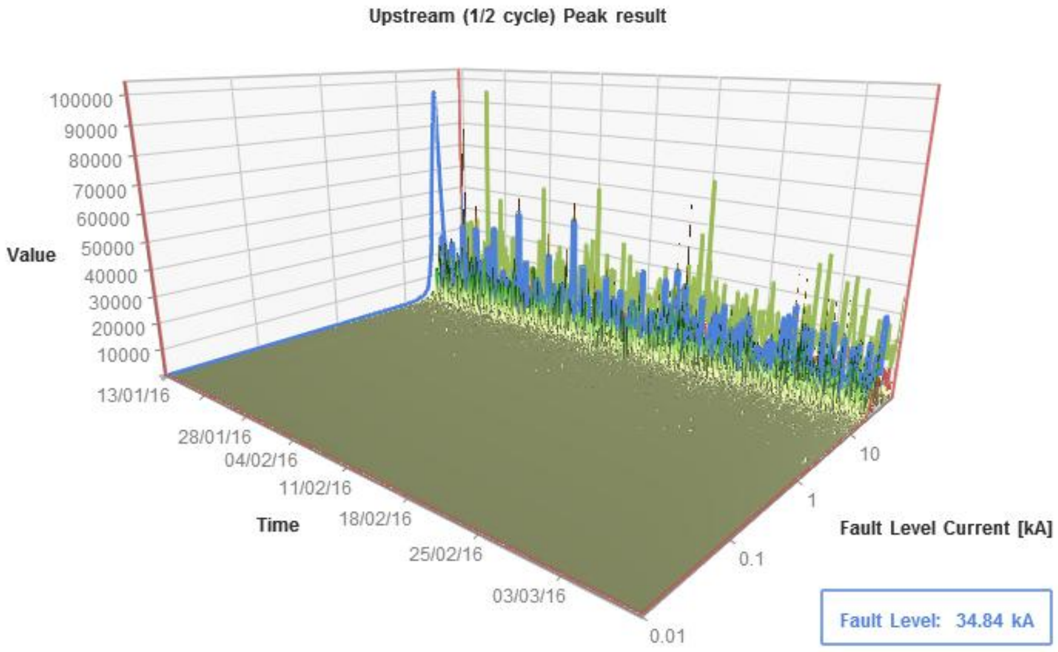


Figure 4-6 Upstream (90 ms) RMS Fault Level Results, 3D and 2D Distribution shown with 10 % filtering – Denton West Location

4.2.2 Denton West Location

Similar to previous graphs, Figure 4-7 to Figure 4-9 show fault level results at Denton West estimated by the FLM in graphical format, as described by the Outram report for the entire period of measurements.



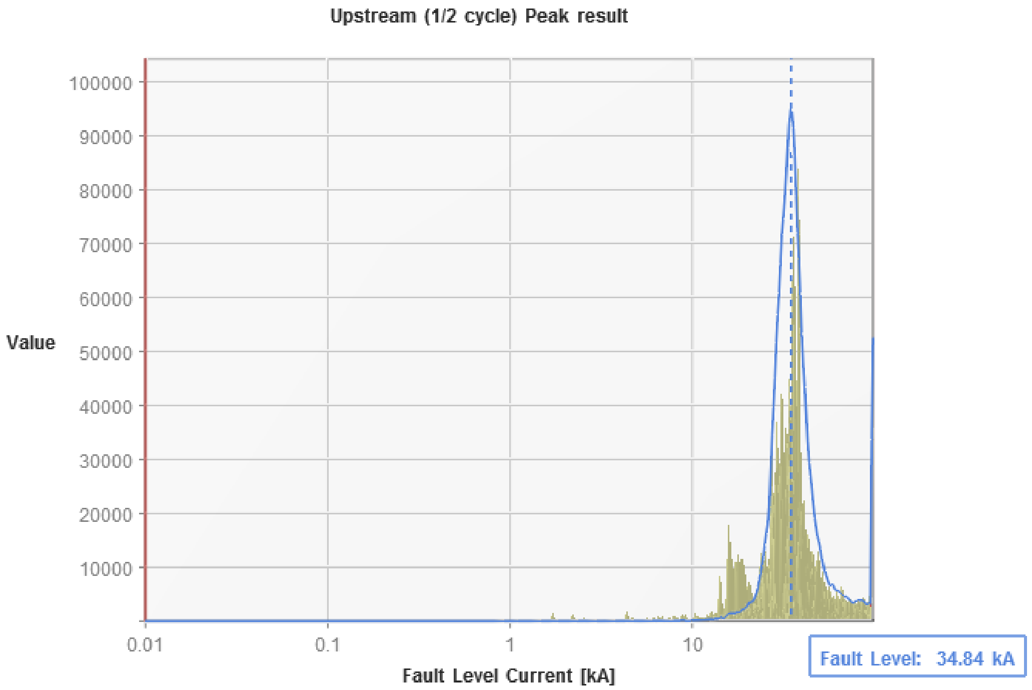


Figure 4-7 Upstream (1/2 cycle) Peak Fault Level Results, 3D and 2D Distribution shown with 1 % filtering – Denton West Location

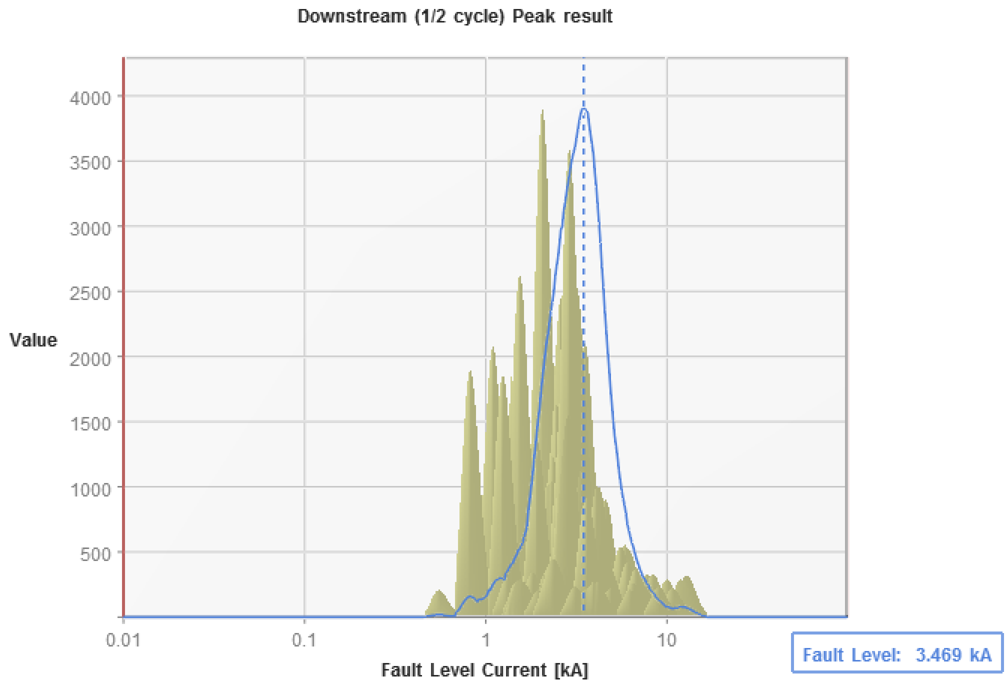
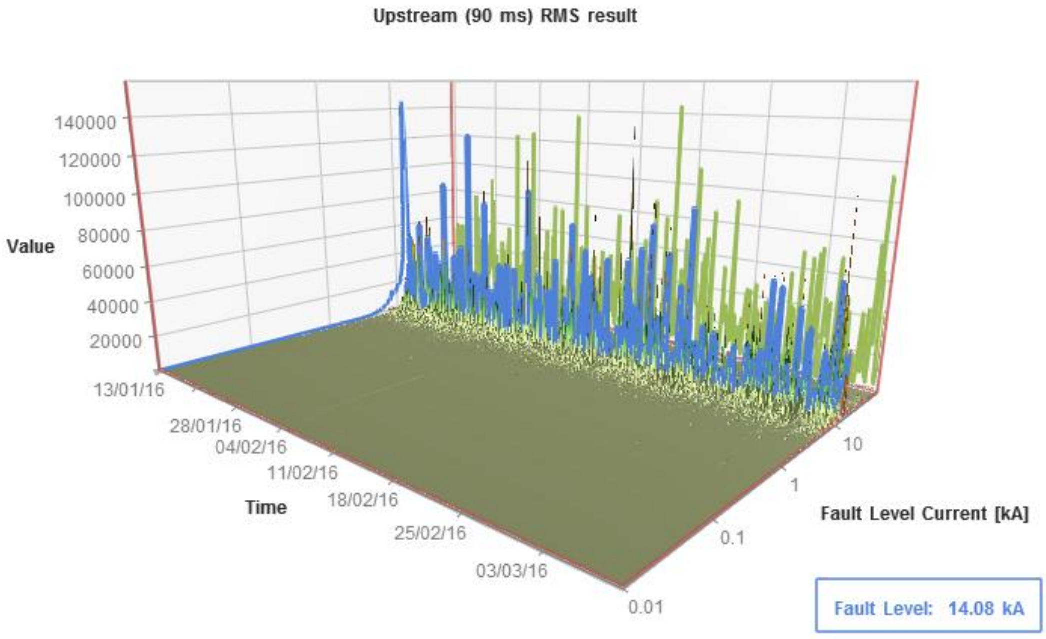


Figure 4-8 Downstream (1/2 cycle) Peak Fault Level Results, 2D Distribution shown with 6 % filtering- Denton West Location



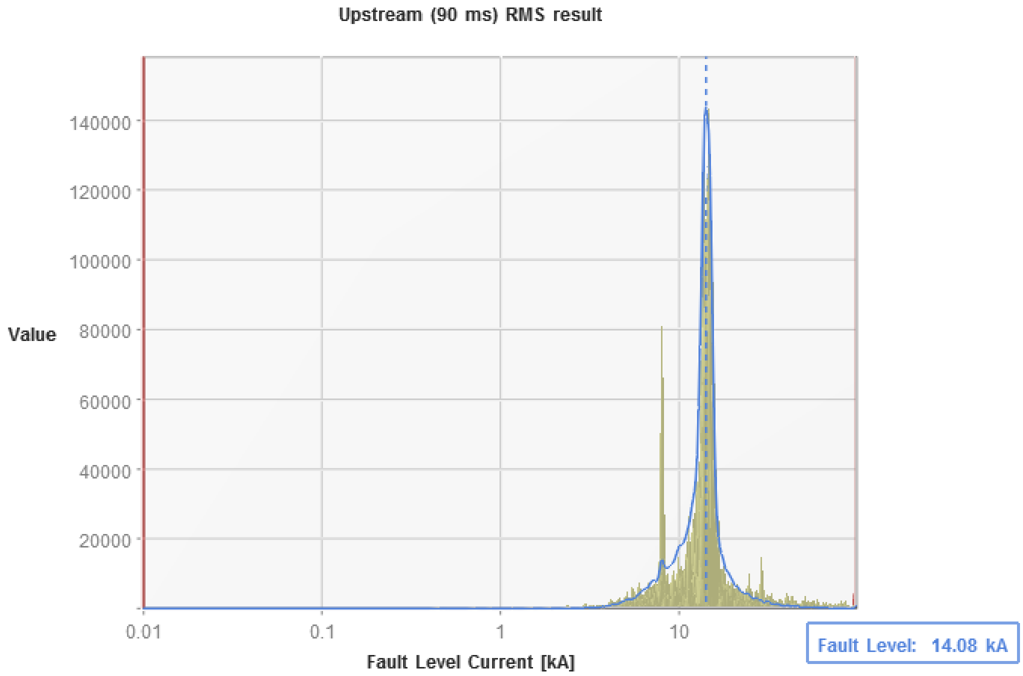


Figure 4-9 Upstream (90 ms) RMS Fault Level Results, 3D and 2D Distribution shown with 1 % filtering - Denton West Location

4.2.3 Irlam Location

Similar to previous graphs, Figure 4-10 to Figure 4-12 show fault level results at Irlam estimated by the FLM in graphical format, as described by the Outram report for the entire period of measurements.

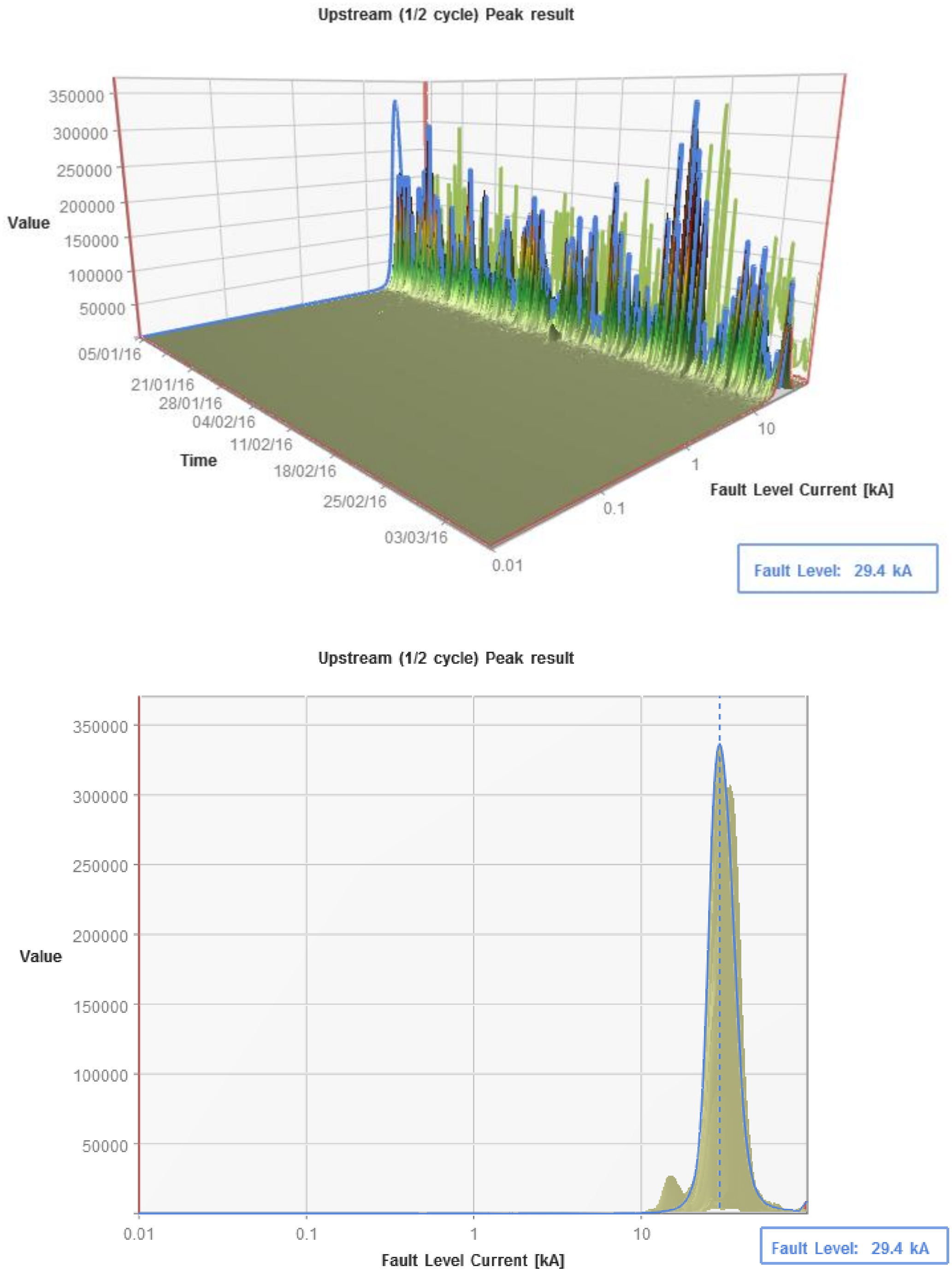


Figure 4-10 Upstream (1/2 cycle) Peak Fault Level Results, 3D and 2D Distribution shown with 3 % filtering – Irlam Location

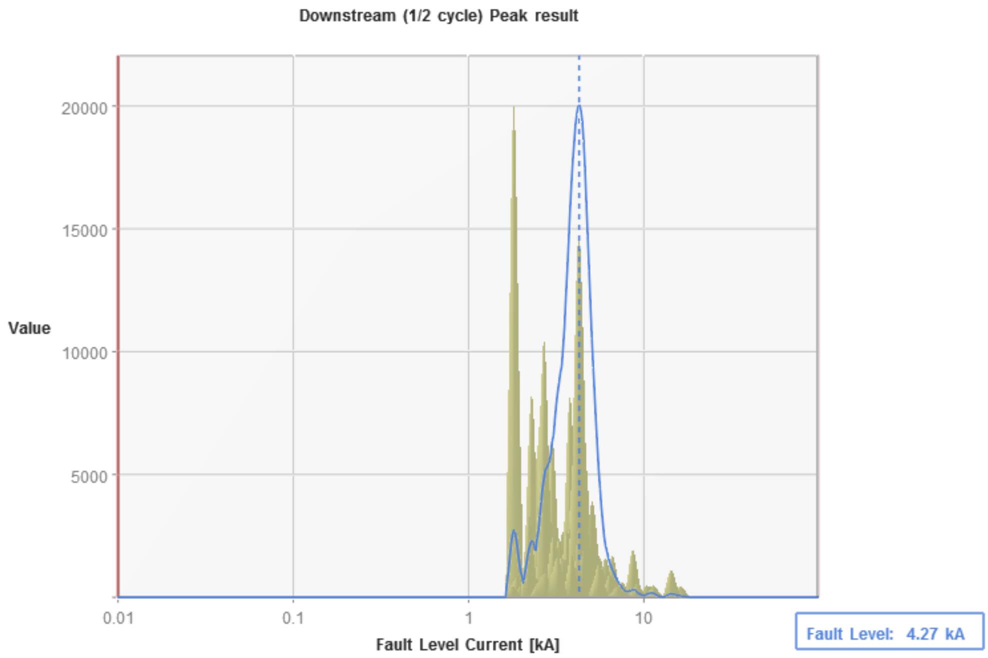
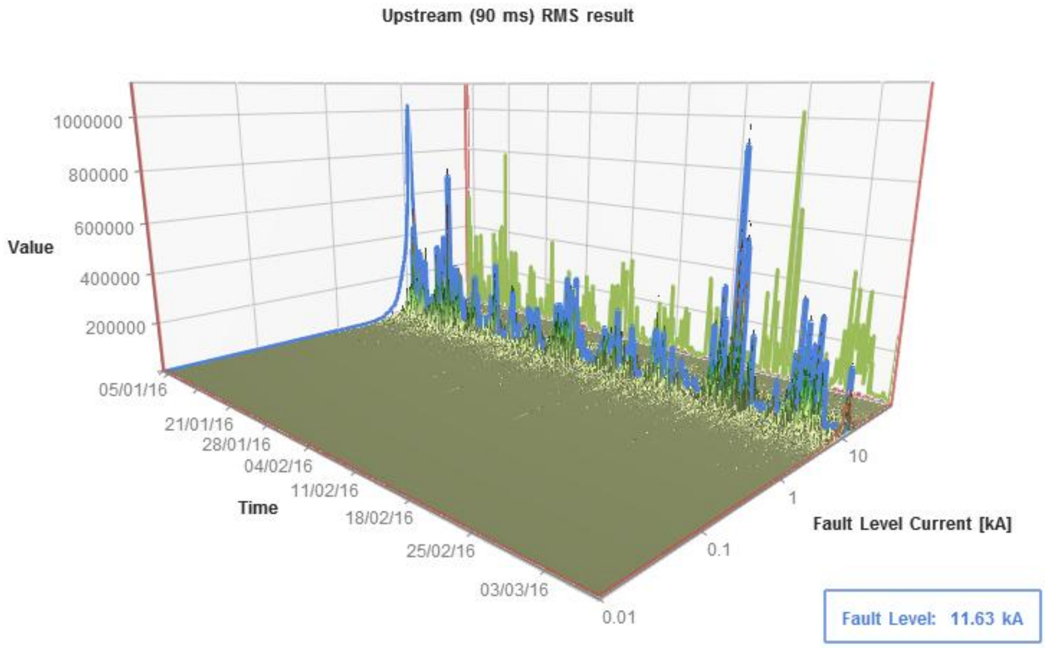


Figure 4-11 Downstream (1/2 cycle) Peak Fault Level Results, 2D Distribution shown with 3 % filtering – Irlam Location



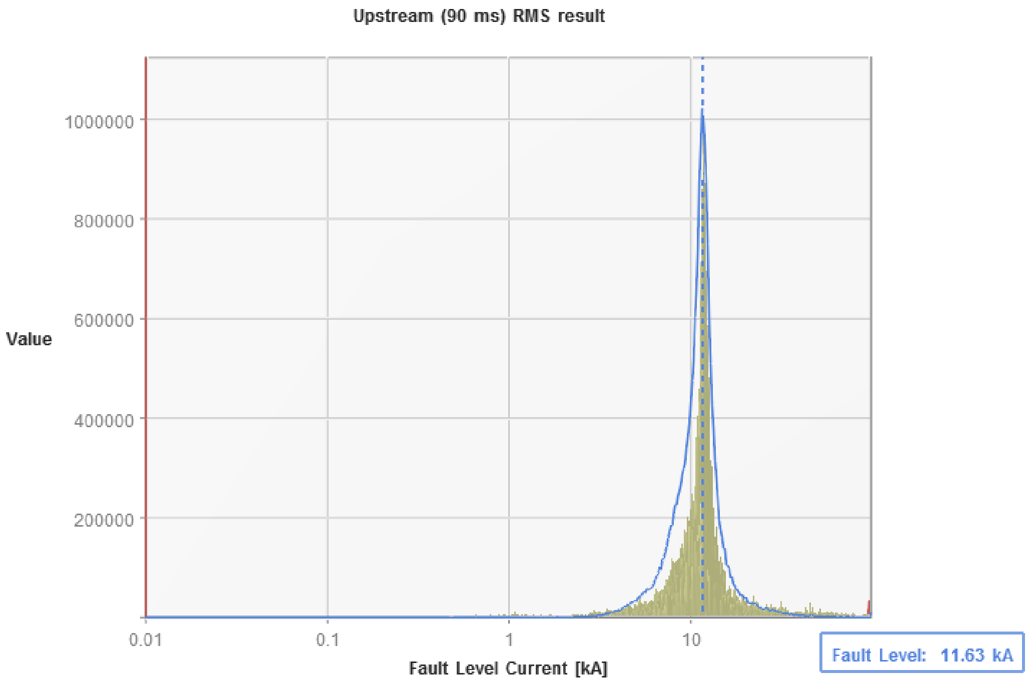


Figure 4-12 Upstream (90 ms) RMS Fault Level Results, 3D and 2D Distribution shown with no filtering – Irlam Location

4.2.4 Wigan Location

Figure 4-13 to Figure 4-15 show fault level results at Wigan estimated by the FLM in graphical format, as described by the Outram report for the entire period of measurements.

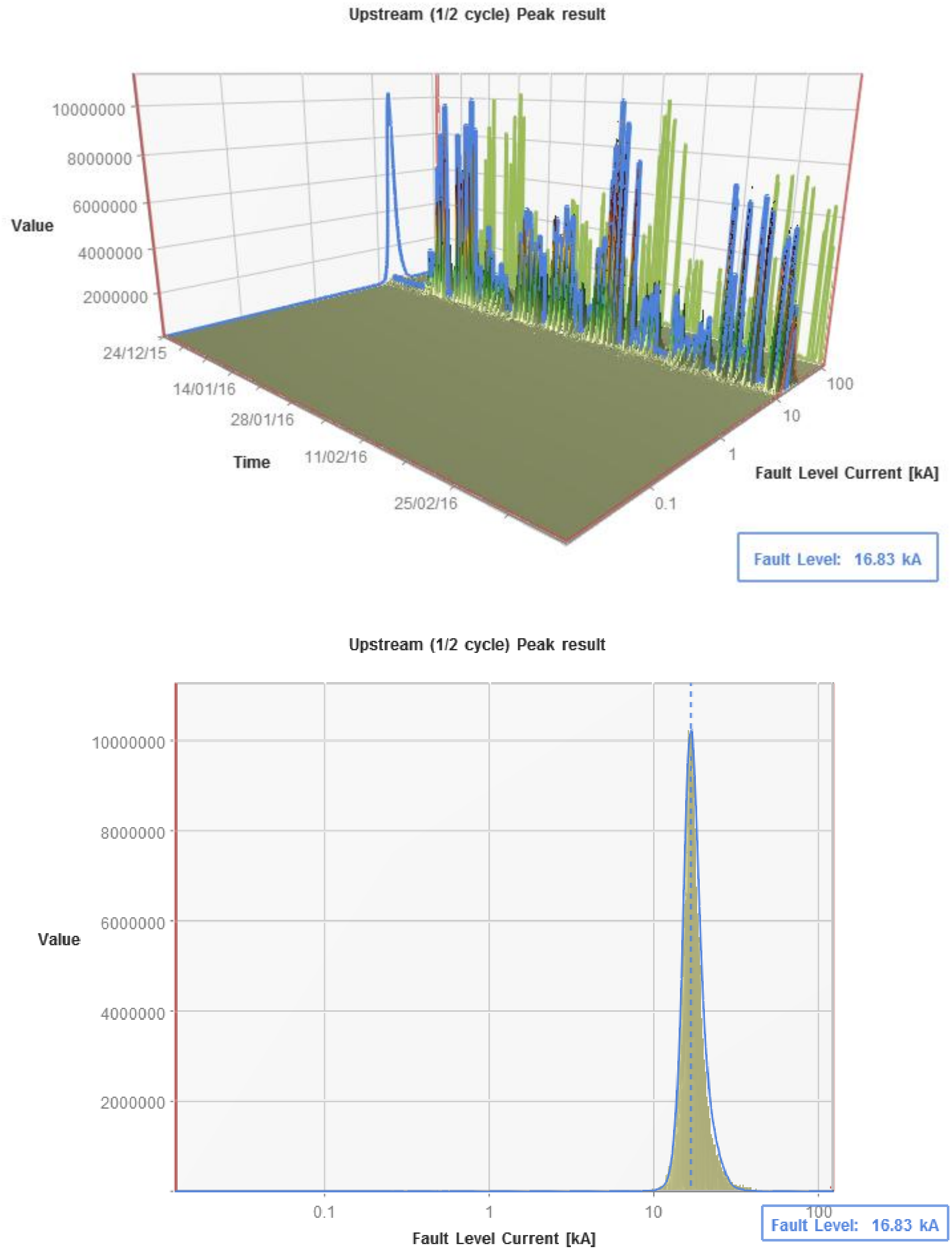


Figure 4-13 Upstream (1/2 cycle) Peak Fault Level Results, 3D and 2D Distribution shown with no filtering – Wigan Location

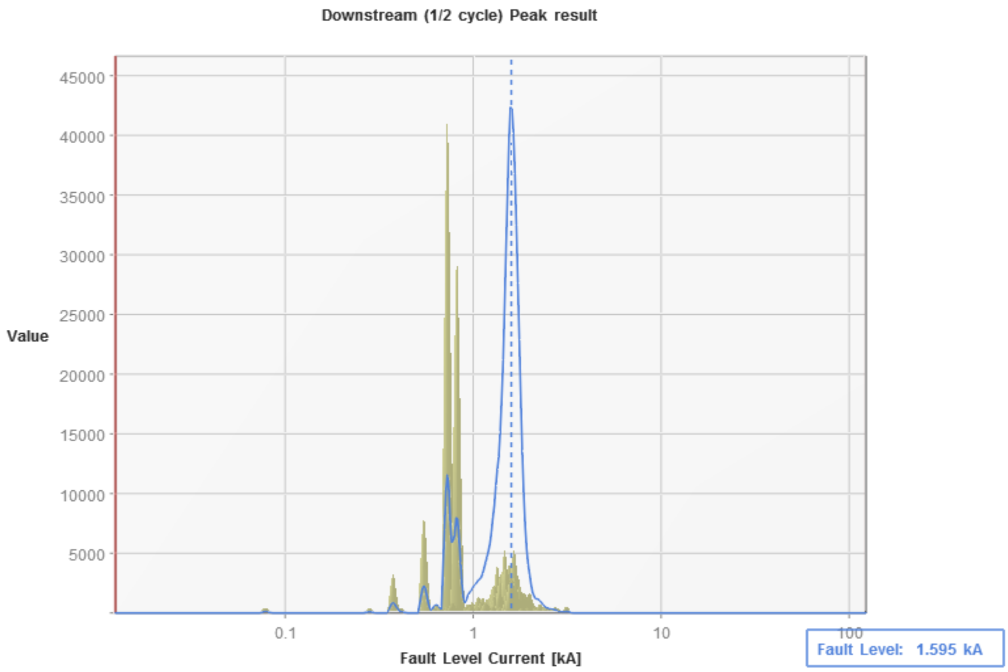
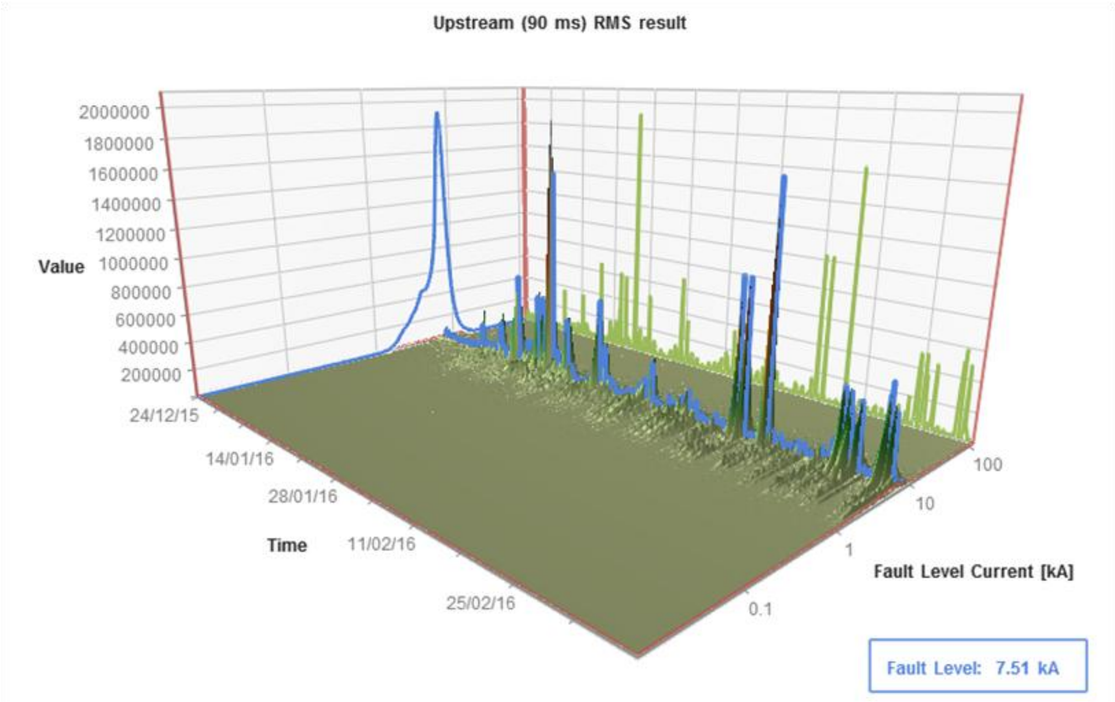


Figure 4-14 Downstream (1/2 cycle) Peak Fault Level Results, 2D Distribution shown with 3 % filtering – Wigan Location



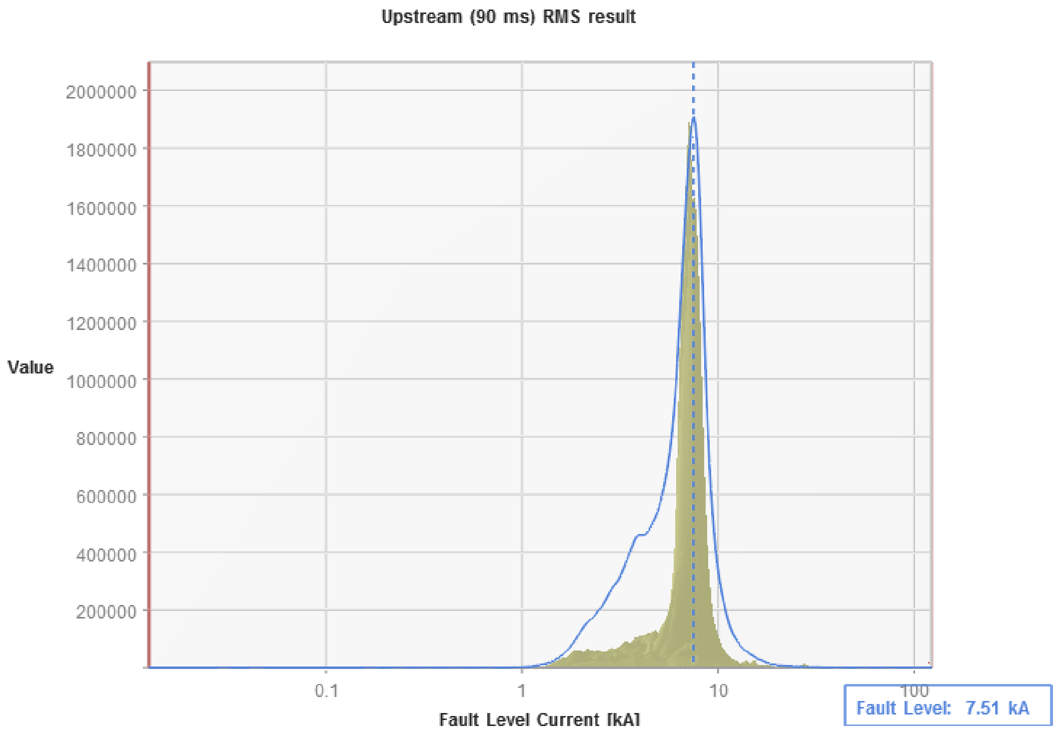


Figure 4-15 Upstream (90 ms) RMS Fault Level Results, 3D and 2D Distribution shown with no filtering - Wigan Location

4.3 FLM Voltage and Current Measurements against ENWL Data

For the purpose of validating the IPSA network model, it is essential that the IPSA model should be representative of the actual network for the period of measurements. As the FLM fault level results are estimated based on current and voltage changes, it is important that the current and voltage values recorded by the FLM and the measurements recorded by ENWL are consistent with one another. This section shows the results of the comparison of these parameters.

TNEI have received, upon request, Feeder Load Analysis (FLA) results for the period 11/03/2016 to 16/06/2016 for Broadheath location and for the period 18/01/2016 to 24/01/2016 for Denton West and Irlam locations[21]. These include half hourly current recordings on each feeder connected to the Primary substation and on the Primary transformers. Active and reactive half hourly recordings on the Primary transformers have also been received.

Similarly, for Wigan location, half hourly current recordings and voltage measurements on the 33 kV side of the transformers in Wigan Grid[22] have been

[21] File 'FLA data Broadheath 1103 to 1606.xlsx' via e-mail from Kieran Bailey dated 27th June 2016 (RE FL Reprot.msg), 'FLA data Denton West 18012016' and 'FLA data Irlam 18012016' via e-mail from Kieran Bailey dated 23rd February 2016

[22] Files 'Wigan Data.xlsx' via e-mail from Kieran Bailey dated 5th May 2016 (RE Supplementary note to ENW re Wigan etc.msg)

provided by ENWL for the entire period of measurement (24/12/2015 to 09/03/2016).

When comparing the two sources of measurements, the following have to be considered:

- the FLM device recorded every 5 minutes for Broadheath, Irlam and Denton West and every 10 minutes for Wigan (includes maximum, minimum and average values), while the ENWL data is half hourly measurement (average)
- the FLM device recorded two phases ('Ia' and 'Ic') while the ENWL data refers to one phase measurements
- the FLA data measurement period is shorter for Irlam and Denton West (as requested) while for Broadheath and Wigan locations, the ENWL measurements period matches the FLM ones

In the following tables and graphs, the maximum, minimum and average values of the FLM current and voltage were calculated based on the 10 minutes averages extracted from Pronto software. The maximum, minimum and average values of the ENWL current were calculated based on the summated current measurements of the feeders for Broadheath case, and based on summated current measurements on the T1/GT1 and T2/GT2 transformers for the other three locations.

For Wigan, the maximum, minimum and average values of the ENWL voltages are applied to both GT1 and GT2 transformers measurements.

Table 4-3 to Table 4-10 and Figure 4-16 to Figure 4-23 show a comparison of current and voltage measurements between ENWL data and FLM recordings.

The FLM versus ENWL comparison of current and voltage measurements show a general similarity between in all four locations. The FLM current recordings are used to represent the load profile in the IPSA network model for fault level studies.

The FLM current measurements results suggest that the load demand consumption on the two measured phases in Denton West and Wigan is slightly unbalanced (phases are not equally loaded). This would not affect the predicted fault currents, as advised by Outram. This aspect is easily noticed in the corresponding graphs from Section 4.4.2.

The average voltage in the four locations is close to 1 p.u., consistent with the voltage set point of the transformers used in the IPSA Master Network Model.

Table 4-3 Summary of Current Values - Broadheath

Broadheath Current (A)		Maximum	Minimum	Average
ENWL	One phase	1247.5	0.0	760.8
FLM	Phase Ia	1234.0	362.0	747.1
	Phase Ic	1207.0	348.0	731.0

Table 4-4 Summary of Voltage Values - Broadheath

Broadheath Voltage		Maximum	Minimum	Average
FLM	V1 (kV)	11.19	10.81	11.02
	V3 (kV)	11.28	10.89	11.10
	V1 (p.u.)	1.02	0.98	1.00
	V3 (p.u.)	1.03	0.99	1.01

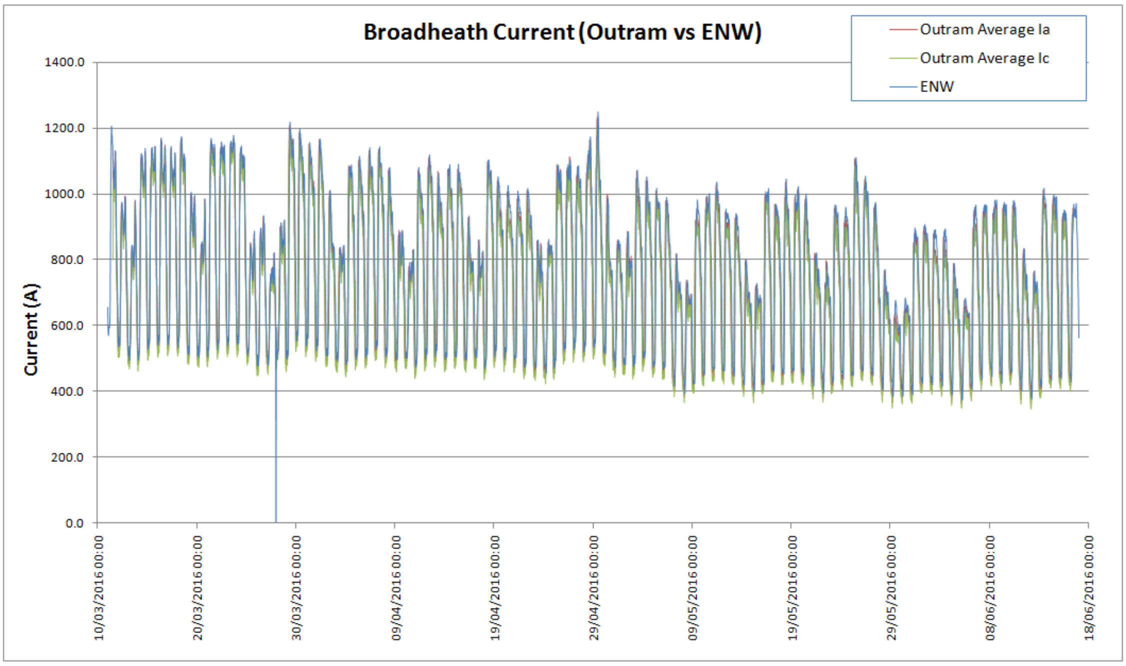


Figure 4-16 Current Profile - Broadheath

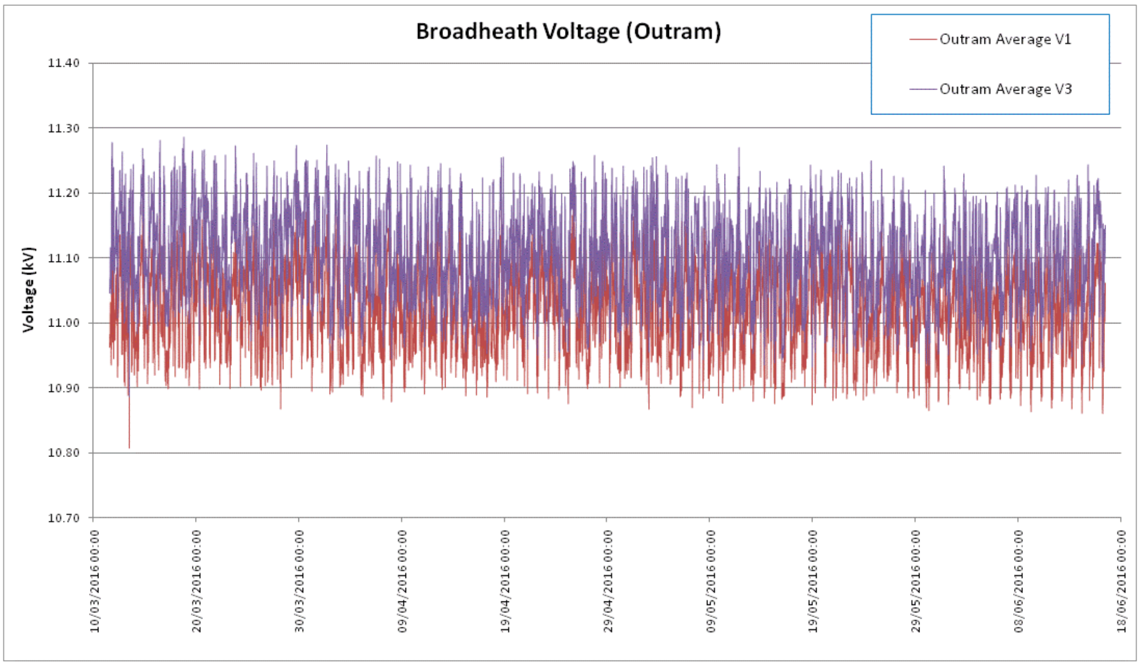


Figure 4-17 Voltage Profile - Broadheath (only FLM)

Table 4-5 Summary of Current Values - Denton West

Denton West Current (A)		Maximum	Minimum	Average
ENWL	One phase	1265.5	499.5	874.4
FLM	Phase Ia	1286.0	478.0	847.1
	Phase Ic	1227.0	457.0	808.5

Table 4-6 Summary of Voltage Values - Denton West

Denton West Voltage		Maximum	Minimum	Average
FLM	V1 (kV)	6.69	6.42	6.54
	V3 (kV)	6.69	6.44	6.55
	V1 (p.u.)	1.01	0.97	0.99
	V3 (p.u.)	1.01	0.98	0.99

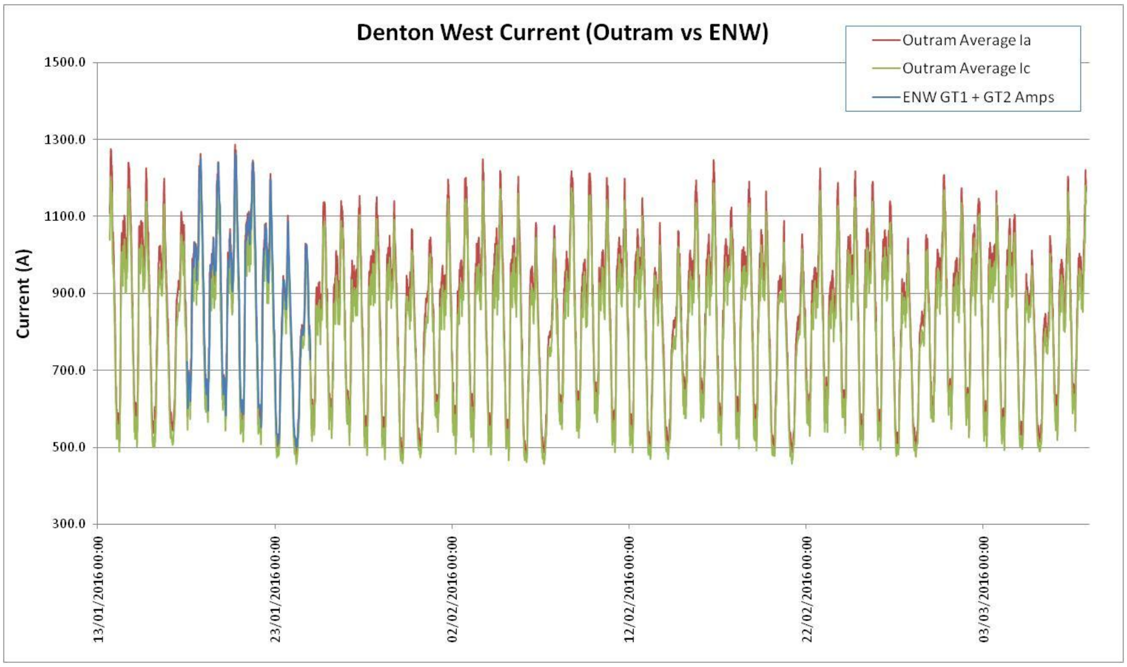


Figure 4-18 Current Profile - Denton West

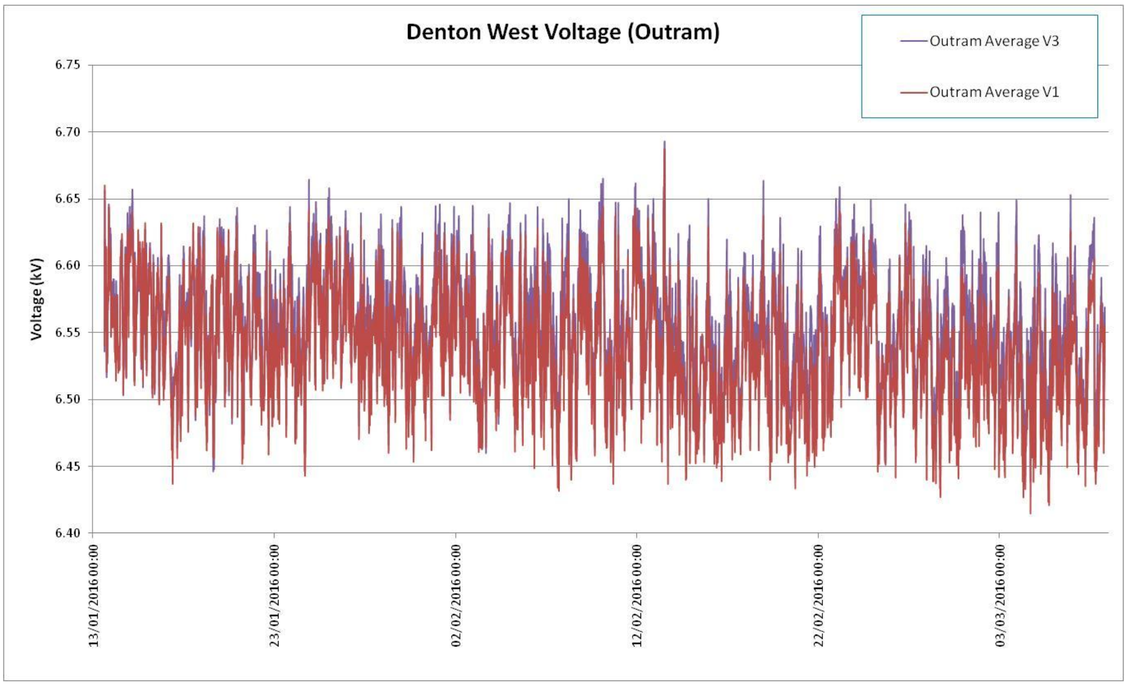


Figure 4-19 Voltage Profile - Denton West (only FLM)

Table 4-7 Summary of Current Values - Irlam

Irlam Current (A)		Maximum	Minimum	Average
ENWL	One phase	1470.9	610.0	1025.6
FLM	Phase Ia	1480.0	597.0	995.8
	Phase Ic	1470.0	587.0	989.1

Table 4-8 Summary of Voltage Values - Irlam

Irlam Voltage		Maximum	Minimum	Average
FLM	V1 (kV)	6.72	6.49	6.61
	V3 (kV)	6.74	6.48	6.62
	V1 (p.u.)	1.02	0.98	1.00
	V3 (p.u.)	1.02	0.98	1.00

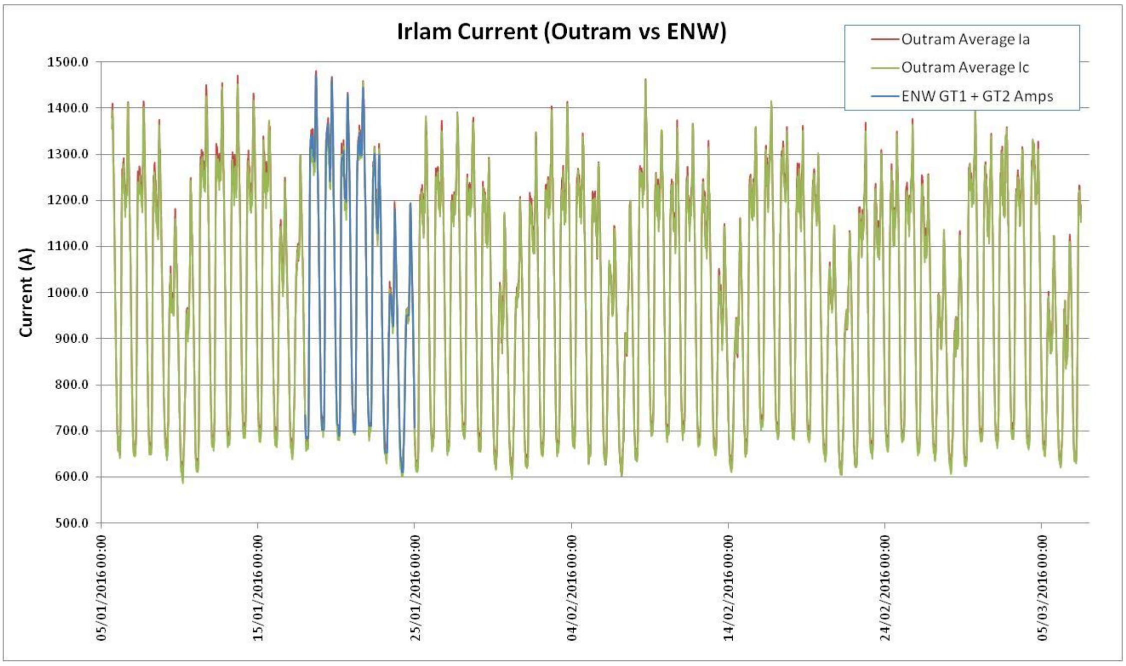


Figure 4-20 Current Profile - Irlam

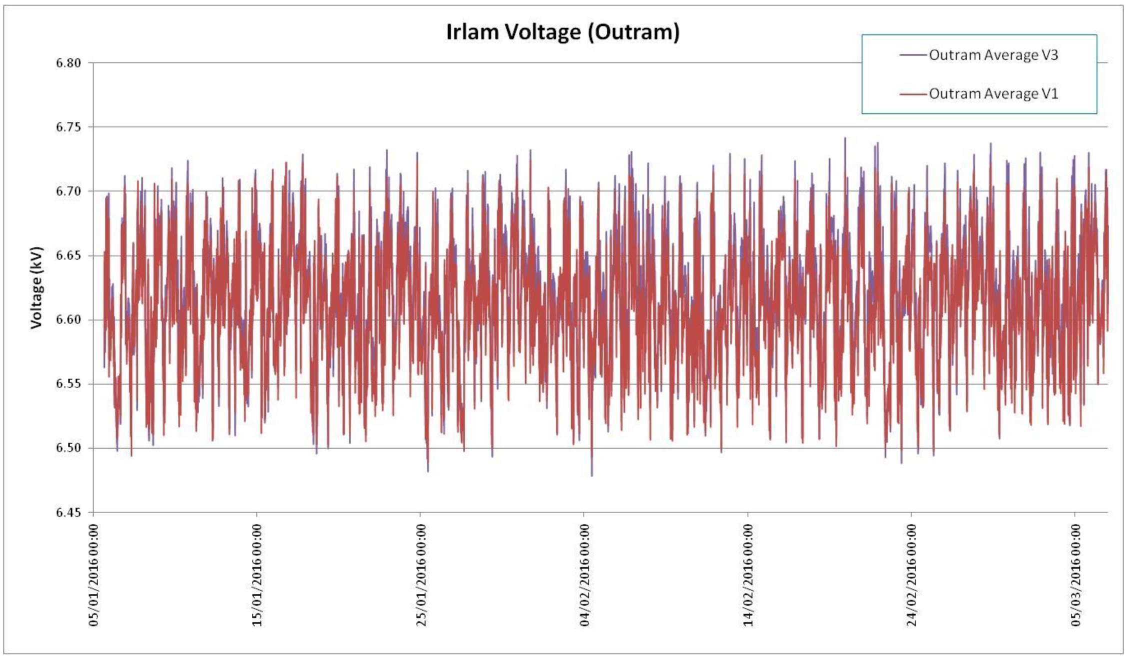


Figure 4-21 Voltage Profile - Irlam (only FLM)

Table 4-9 Summary of Current Values - Wigan

Wigan Current (A)		Maximum	Minimum	Average
ENWL	One phase	818.8	292.7	525.7
FLM	Phase Ia	823.6	283.4	515.4
	Phase Ic	778.5	258.0	480.5

Table 4-10 Summary of Voltage Values - Wigan

Wigan Voltage		Maximum	Minimum	Average
ENWL	One Phase (GT1, GT2) (kV)	33.58	0.03	31.77
	One Phase (GT1, GT2) (p.u.)	1.02	0.00	0.96
FLM	V1 (kV)	33.51	32.42	32.95
	V3 (kV)	33.47	32.47	32.97
	V1 (p.u.)	1.02	0.98	1.00
	V3 (p.u.)	1.01	0.98	1.00

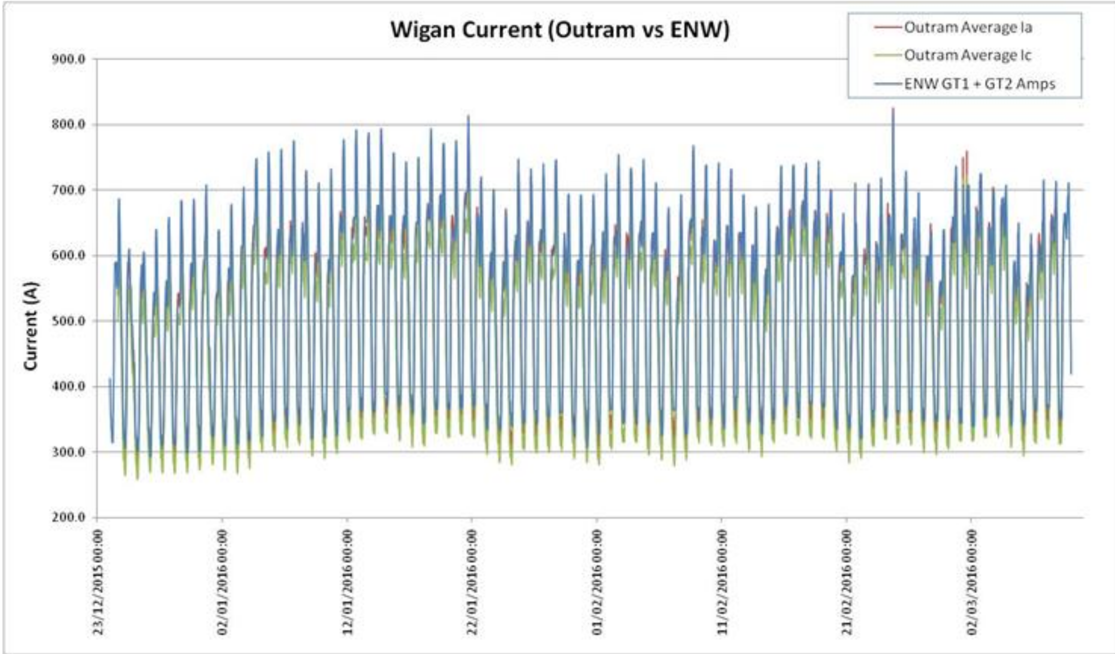


Figure 4-22 Current Profile - Wigan

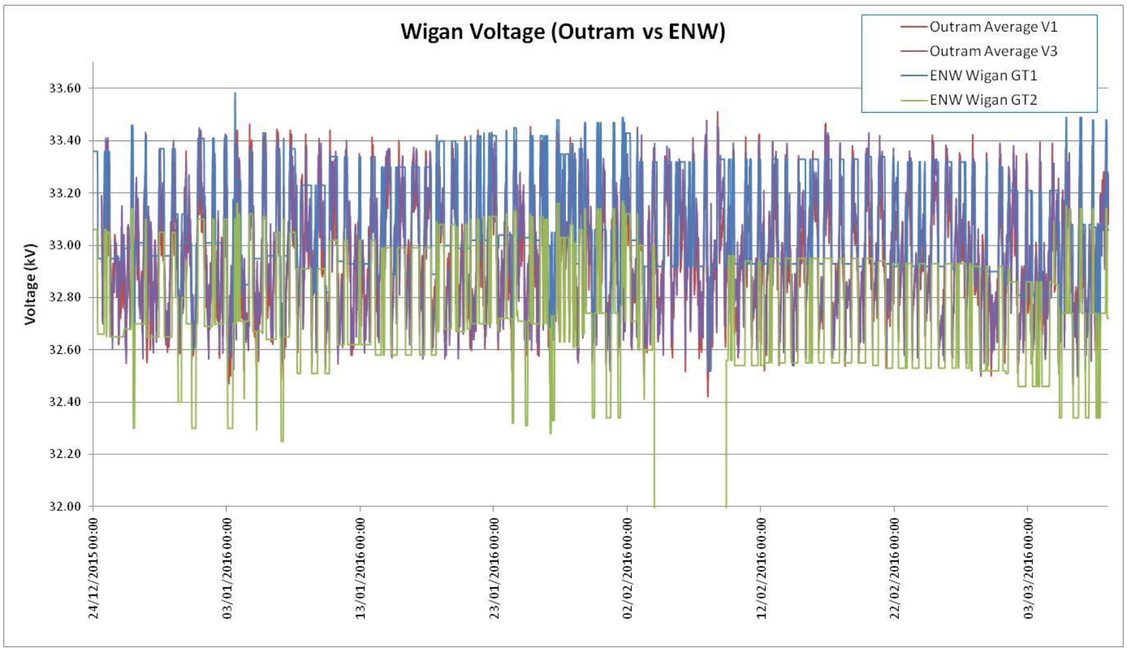


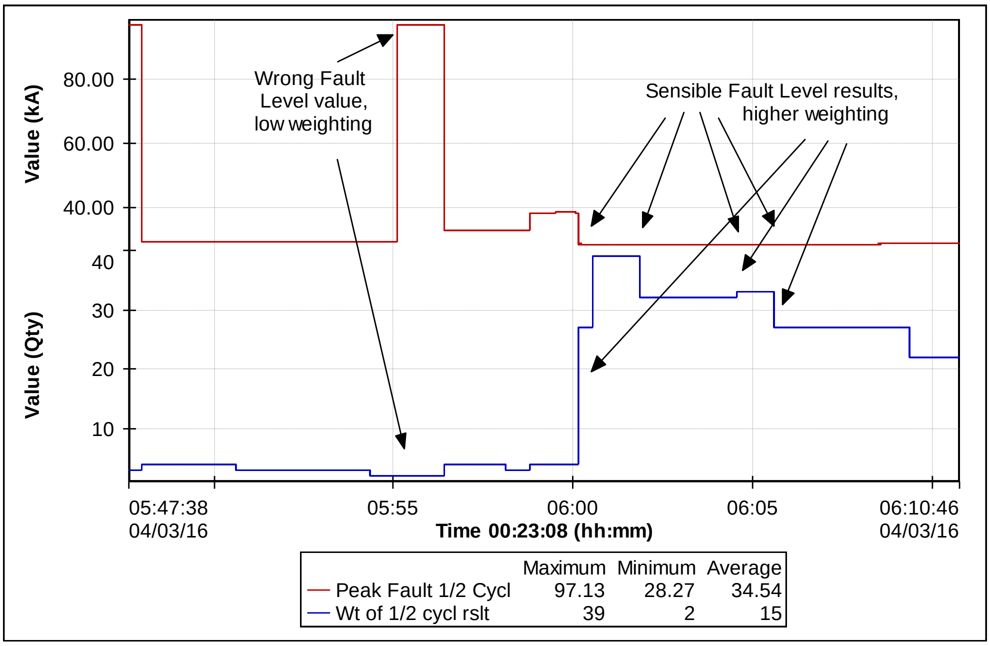
Figure 4-23 Voltage Profile - Wigan Location

4.4 Correlation of Fault Level Results with Load

According to the Outram report, the fault level is recorded against time, like the voltage and the current flow, thus it may be graphed against time in the same way as the other parameters. This type of fault level data presentation provides useful information as it can show the correlation between certain events in the grid at specific moments in time and the corresponding estimated fault levels together with their weight.

Outram reports states that this type of fault level presentation can be misleading and should be treated with caution. The Outram report also states that the presentation of Fault Level results and weighting data against time in the standard Pronto graphing system may not be recognisable and will generally never produce the same average results as might be expected from the Fault Level 2D and 3D graphic presentations. This is because of the irregular arrival times of evaluated disturbances. The averages calculated from the standard graphing system take into account the time between consecutive results, and not the quality of the results/events, i.e. the weight. The weight refers to how much notice should be taken of each disturbance when estimating the fault level and it is linked to the size and the quality of the disturbance.

Figure 4-24 shows an example of fault recording and corresponding weight values, as extracted from the Outram report, for Denton West location.



'Graph 15. Beware using the Standard Pronto graphing. Relationship between quality of Fault Level result and weighting'.

Figure 4-24 Example of Fault Level Results Fault Recording and Corresponding Weight Values

4.4.1 Reconciliation of Downstream Fault Level Contribution with Load

Outram has provided a supplementary note to show the reconciliation of downstream peak fault level contribution with the load in Denton West and Irlam substations[23]. Two graphs have been extracted from the Outram report and presented below, in Figure 4-25 for Irlam and Figure 4-26 for Denton West respectively, as examples.

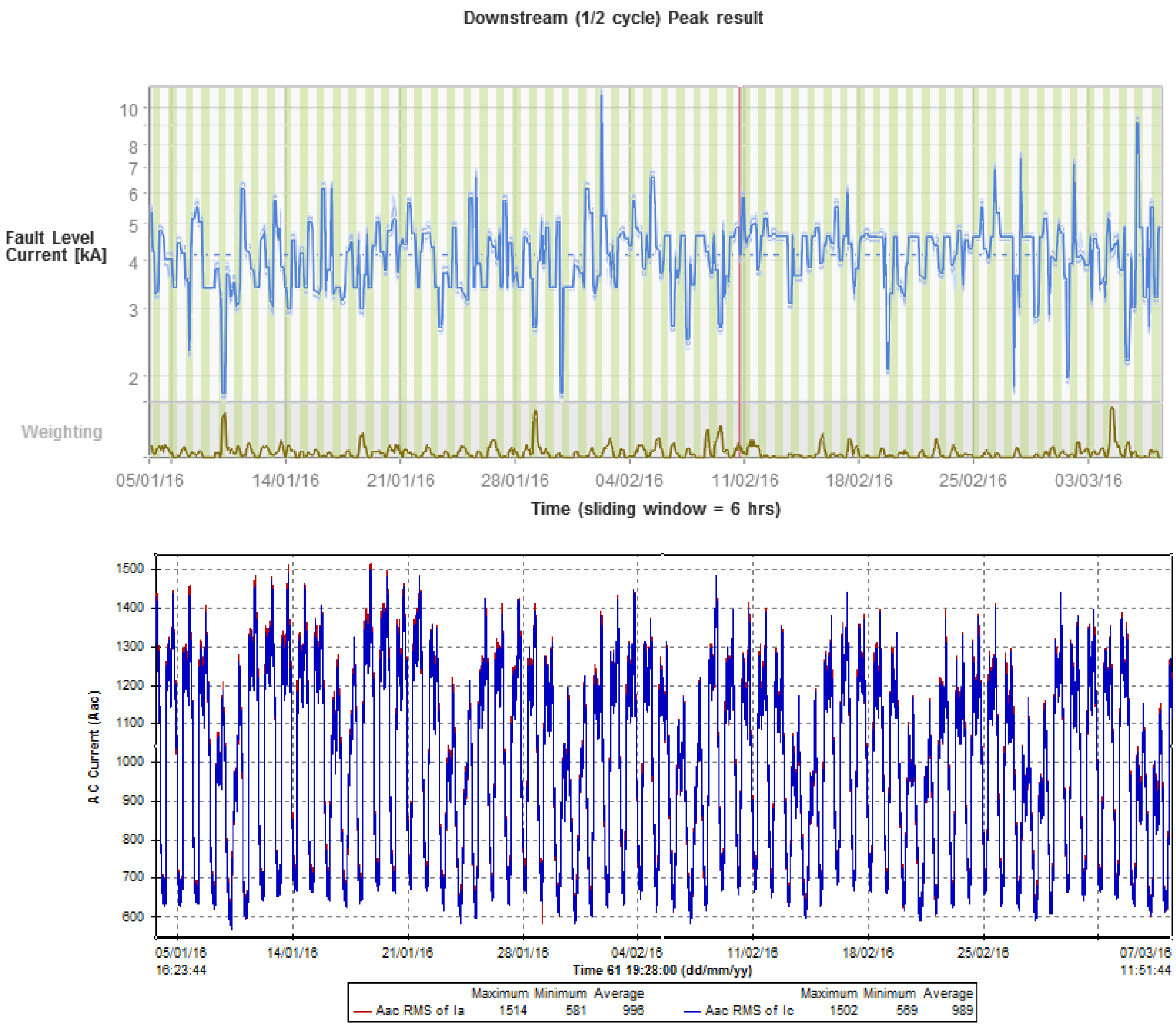


Figure 4-25 First graph: Downstream ½ cycle Fault level contribution with 6 hour sliding window, 2 % filtering. Second graph: Currents observed indicating load. Irlam Location

[23] Files 'Supplementary note on RESPOND Project Fault Level results for Wigan D2.docx' via e-mail from Kieran Bailey dated 5th May 2016 (RE Supplementary note to ENW re Wigan etc.msg)

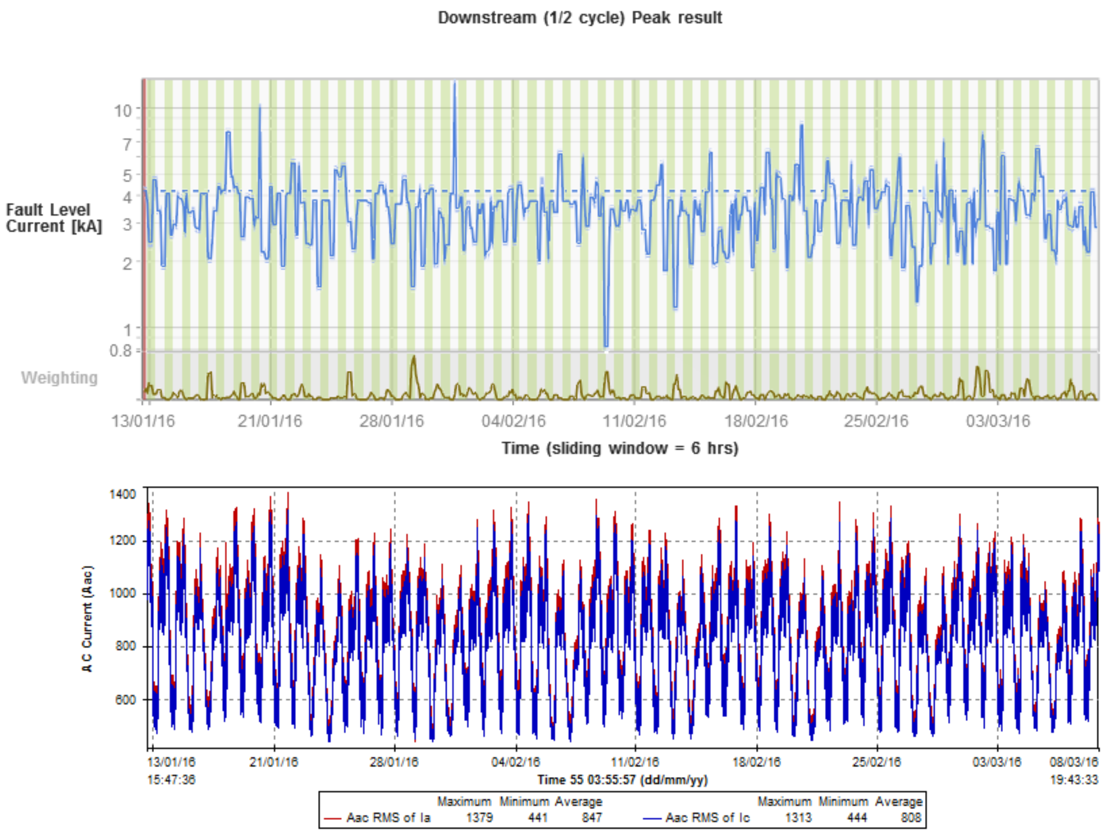


Figure 4-26 First graph: Downstream ½ cycle Fault level contribution with 6 hour sliding window, 2% filtering. Second graph: Currents observed indicating load. Denton West Location

4.4.2 Correlation of Recommended Peak Downstream Contribution with Load

The recommended or most probable peak downstream contribution for the entire period of measurements is 3.22 kA in Broadheath, 3.47 kA in Denton West, 4.27 kA in Irlam and 1.6 kV in Wigan Location (Table 4-2), as per Outram report.

The presentation of Fault Level results and weighting data against time in the standard Pronto graphing system suggests that it is possible to identify for which 30 minutes time intervals the most probable fault level listed above has been 'seen' and identify a possible correlation with the consumption during those time intervals, i.e. the corresponding load values.

For the recommended peak downstream contribution values of each location, the corresponding load (10 minutes average, two phases) and weight have been extracted for the entire measuring period, on 30 minutes intervals, from Pronto software and listed in Figure 4-27 and Figure 4-34 below.

For each location, the first figure represents the load on each phase and the weight of the peak value, against time. In the second graph, the load data is sorted in descending order in order to highlight the entire load range.

The graphs show that the range of load in the network when the particular peak contribution has been ‘seen’ is similar to the load range of the entire period of measurement. It can be noticed that the event with the highest weight corresponds to an average load value of:

- 919 A (average of the two phases) for Broadheath
- 1015 A (average of the two phases) for Denton West
- 1313 A (average of the two phases) for Irlam
- 400 A (average of the two phases) for Wigan

No particular correlation is observed between the load and the time intervals where the fault level is seen. It should be emphasised that the peak downstream contribution is calculated by the device when an upstream disturbance is seen.

As these load values are situated between the maximum and modal load values to be modelled in the IPSA network for the fault level studies in Section 5, it has been considered that studying an additional load case does not bring additional value to the conclusions of this report.

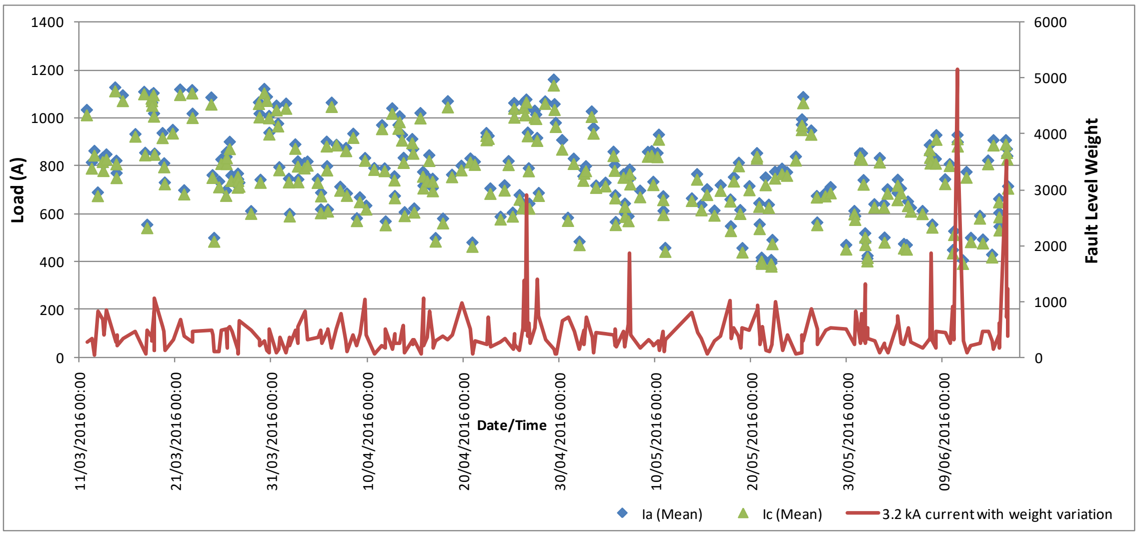


Figure 4-27 Correlation of the Peak Downstream Fault Level (3.22 kA) with Load against Time - Broadheath

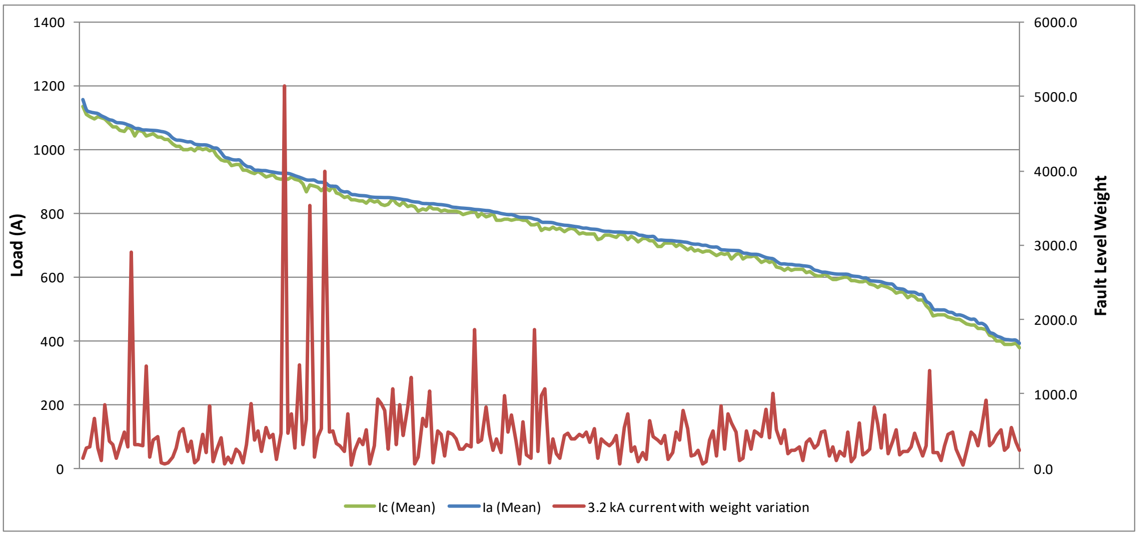


Figure 4-28 Correlation of the Peak Downstream Fault Level (3.22 kA) with Load in Descending Order - Broadheath

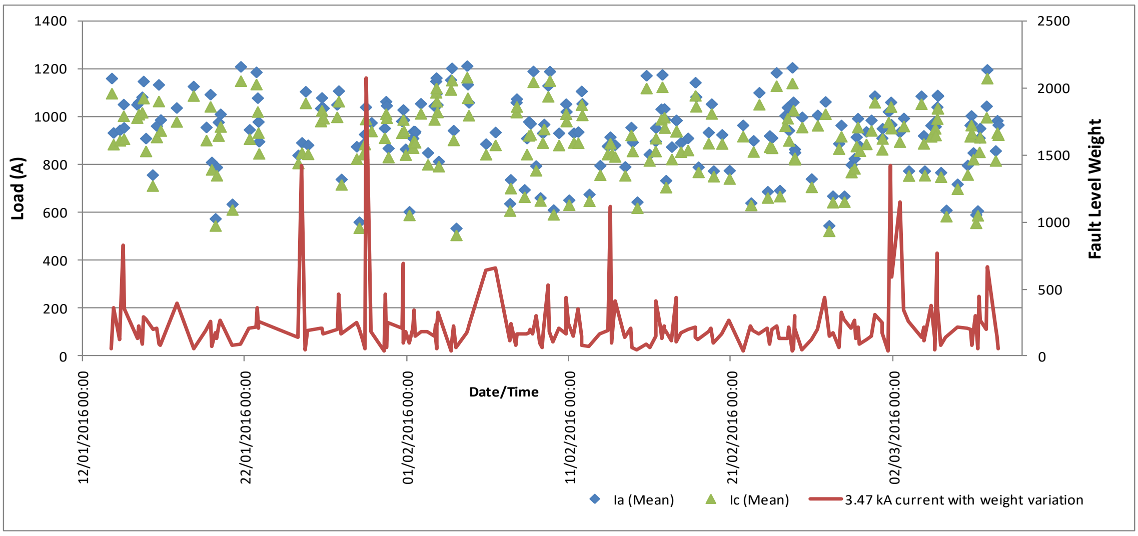


Figure 4-29 Correlation of the Peak Downstream Fault Level (3.47 kA) with Load against Time - Denton West

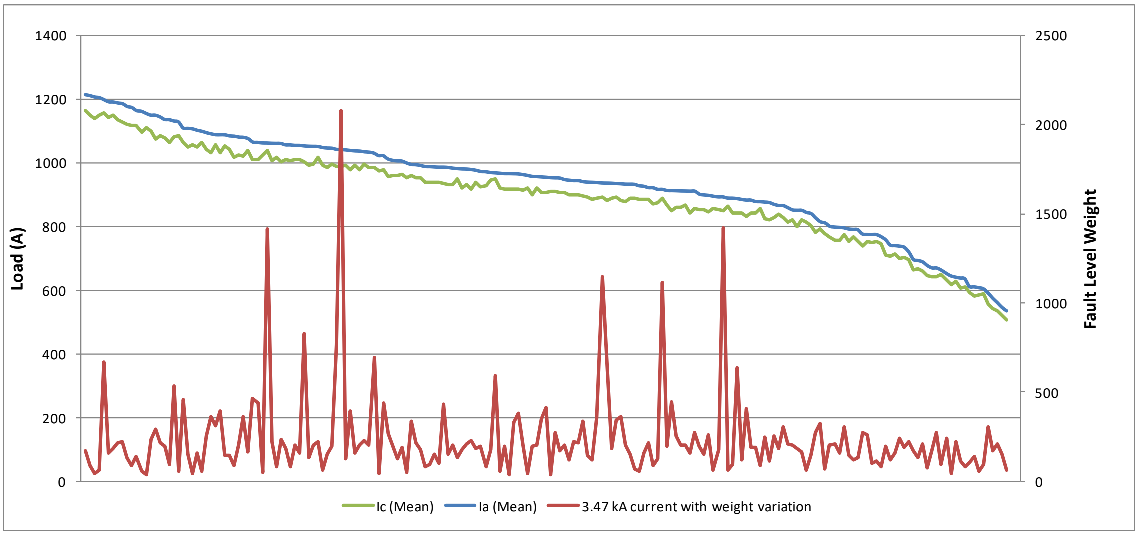


Figure 4-30 Correlation of the Peak Downstream Fault Level (3.47 kA) with Load in Descending Order - Denton West

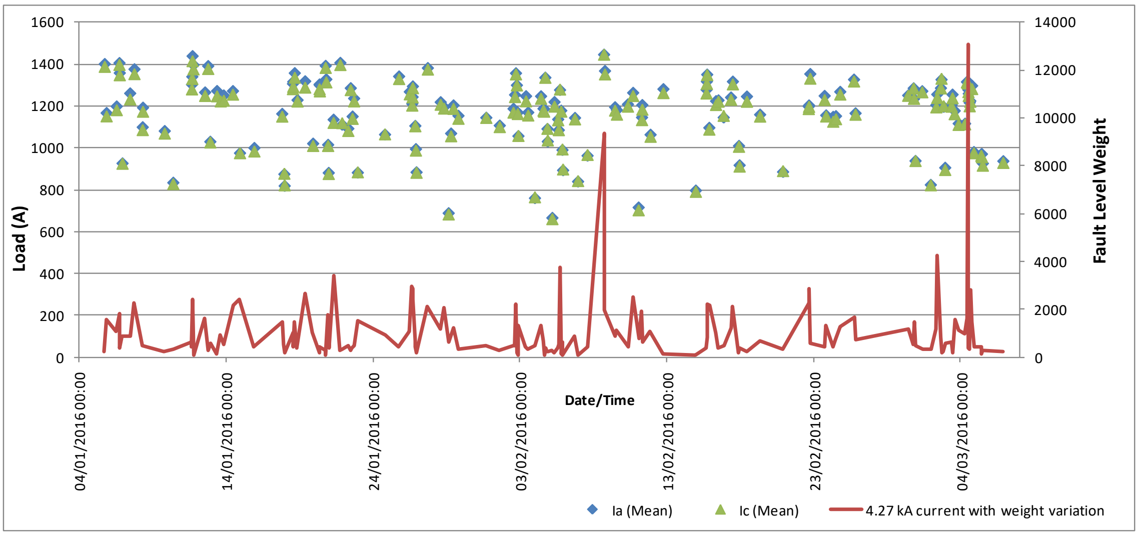


Figure 4-31 Correlation of the Peak Downstream Fault Level (4.27 kA) with Load against Time - Irlam

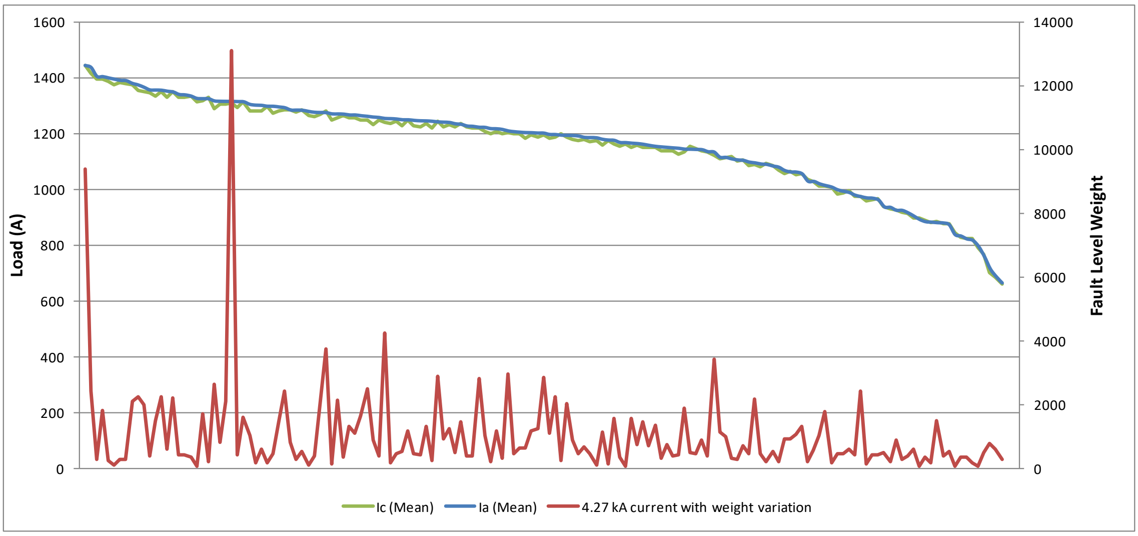


Figure 4-32 Correlation of the Peak Downstream Fault Level (4.27 kA) with Load in Descending Order - Irlam

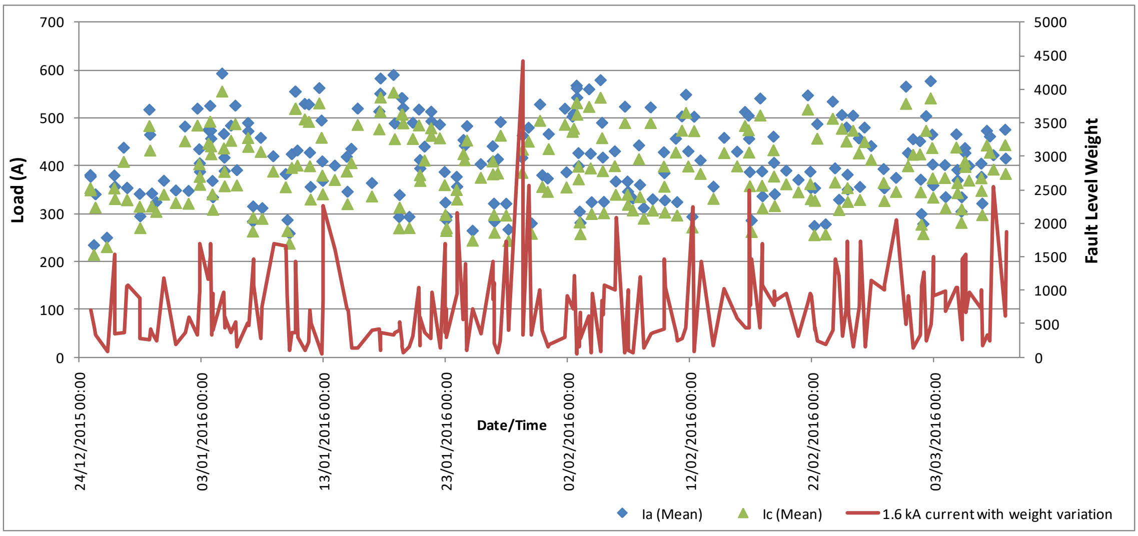


Figure 4-33 Correlation of the Peak Downstream Fault Level (1.6 kA) with Load against Time - Wigan

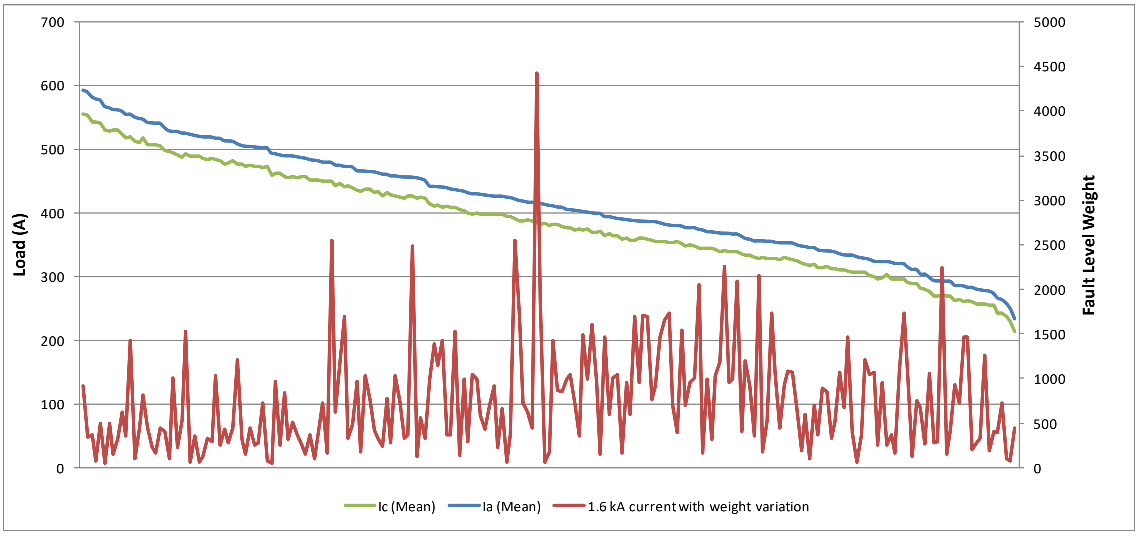


Figure 4-34 Correlation of the Peak Downstream Fault Level (1.6 kA) with Load in Descending Order - Wigan

4.5 Sources of Uncertainty in Fault Level Measurements

The quality of the data presented to the Fault level Monitor's algorithms depends on the magnitude (size) and type of the disturbances (the larger and the more abrupt the disturbance or voltage step, the better). Thus the accuracy is influenced by a low disturbance level (lack of disturbances). According to the PM7000FLM operating procedure, the FLM is capable of successfully detecting the voltage steps down to about 0.15 %.

The downstream contributions depend heavily on what motors or other downstream energy sources were present and in operation at the time of the upstream disturbances upon which the downstream assessments depend.

The FLM does not record any RMS break contribution from downstream of the measurement point, an aspect that needs to be considered when comparing with simulated values.

Based on the FLM operating procedure provided by Outram, it is understood that results may be influenced by systematic errors due to incorrect assumptions, wrong CT settings, faulty sensors, cables etc.

Errors in fault level estimation will result from errors in the measurement of voltage and current; measurement errors will be influenced by:

- The type and accuracy class of switchboard CT connected to the circuit where the FLM is measuring current
- The type and accuracy of switchboard VT connected to the circuit where the FLM is measuring current.

These switchboard CTs and VTs can introduce errors in both the measurement of magnitude and the measurement of angle. It should be noted that the FLM utilises magnitude measurements in the calculation of RMS fault level. The calculation of peak fault level utilises both the measurement of magnitude and angle (for X/R ratio calculation) and therefore contains two possible errors. It is stated in Outram literature that at high X/R ratios, 1 degree error in phase angle measurement can cause peak fault level to be wrongly calculated by 2.5 %.

It should also be noted that switchboard transformers will be of the standard iron core type and as such significant measurement error will occur when waveforms become heavily distorted such as during transformer inrush. The measurement of asymmetrical current via a standard iron core CT may also produce large errors. These errors can be reduced in the FLM by the use of a compensation mechanism based on a user definable 'CT DC decay setting'. The reduction in error will be dependent on the accuracy of the 'CT DC decay setting' chosen for a particular CT arrangement.

The FLM current transducers also have an associated measurement error. This error is influenced by the physical location of the FLM current transformer in relation to the conductor of the measured circuit. The smallest error will result from a conductor that is centrally and orthogonally placed within the FLM current transducer. In practice the position of the conductor within the FLM current transducer is influenced by physical restrictions around these circuits.

The results are also influenced by the low disturbance level or lack of disturbance and downstream motors not being present during the trial period.

The Pronto software allows for interpretation of results for different filtering values of the distributions. The Outram recommended fault level values (Table 4-2) have been extracted to be used in the studies as the representative ones. These values are defined as 'recommended' in the graphs and tables below.

However, a comparison of the FLM results across the full range of the filtering interval (between 0 and 10 %) is presented in this section for information, as it can provide an indication of the fault level variation due to data manipulation (i.e. smoothing/filtering). If the recorded data is irregular, this could generate misinterpretations of results during data manipulation via the filtering tool and confirms that the results should be interpreted by specialists.

In all cases apart from Broadheath, it can be noticed that the differences (%) due to smoothing/filtering in RMS values are much smaller than the peak differences. This is expected because the RMS contributions are generally denser populations.

4.5.1 Broadheath Location

Table 4-11 and Figure 4-35 show the recommended and the extreme values of the fault level results extracted from Pronto and the corresponding filter values.

Relatively modest disturbance energy is seen in Broadheath measurements. A difference of 17.0 % is seen between the maximum value and the recommended one, in the case of the RMS break. There is some room for interpretation for the RMS break result compared to other locations studied. This seems to be mainly due to an event with very high weighting but isolated. By increasing the filter value, this event loses its importance in the overall distribution against the events around the recommended fault level value, which have smaller weight but are numerous.

Table 4-11 Fault Level Results Variation for Different Filter Values - Broadheath Location

Broadheath Location		10 ms Peak Upstream	10 ms Peak Downstream	90 ms RMS Upstream
Maximum	**Fault Level Value**	30.05	3.35	11.89
	Gaussian Filter (%)	10	9.8	0
	Difference (%)	1.7%	4.0%	17.0%
Minimum	**Fault Level Value**	29.48	2.99	10.04
	Gaussian Filter (%)	2.3	0	0.6
	Difference (%)	-0.3%	-7.1%	-1.2%
Recommended	**Fault Level Value**	29.56	3.22	10.16
	Gaussian Filter (%)	2	7	10
	Difference (%)			

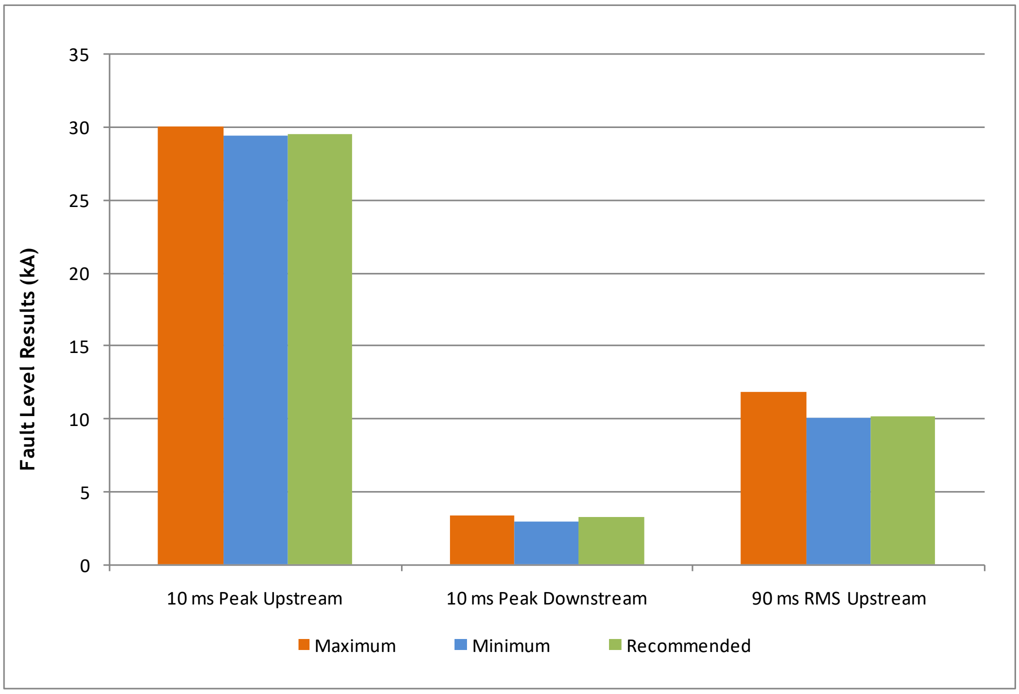


Figure 4-35 Extreme and Recommended Fault Level Results - Broadheath

4.5.2 Denton West Location

Table 4-12 and Figure 4-36 show the recommended and the extreme values of the fault level results extracted from Pronto and the corresponding filter values.

A difference of 16.6 % is seen between the minimum value and the recommended one, in the case of the peak downstream results. This is most likely due to a few events with high weighting, but isolated.

Table 4-12 Fault Level Results Variation for Different Filter Values - Denton West Location

Denton West Location		10 ms Peak Upstream	10 ms Peak Downstream	90 ms RMS Upstream
Maximum	Fault Level Value	35.12	3.63	14.22
	Gaussian Filter (%)	10	3.1	2.5
	Difference (%)	0.8%	4.7%	1.0%
Minimum	Fault Level Value	34.53	2.89	13.94
	Gaussian Filter (%)	4.5	0.9	0
	Difference (%)	-0.9%	-16.6%	-1.0%
Recommended	Fault Level Value	34.84	3.47	14.08
	Gaussian Filter (%)	1	6	1
	Difference (%)			

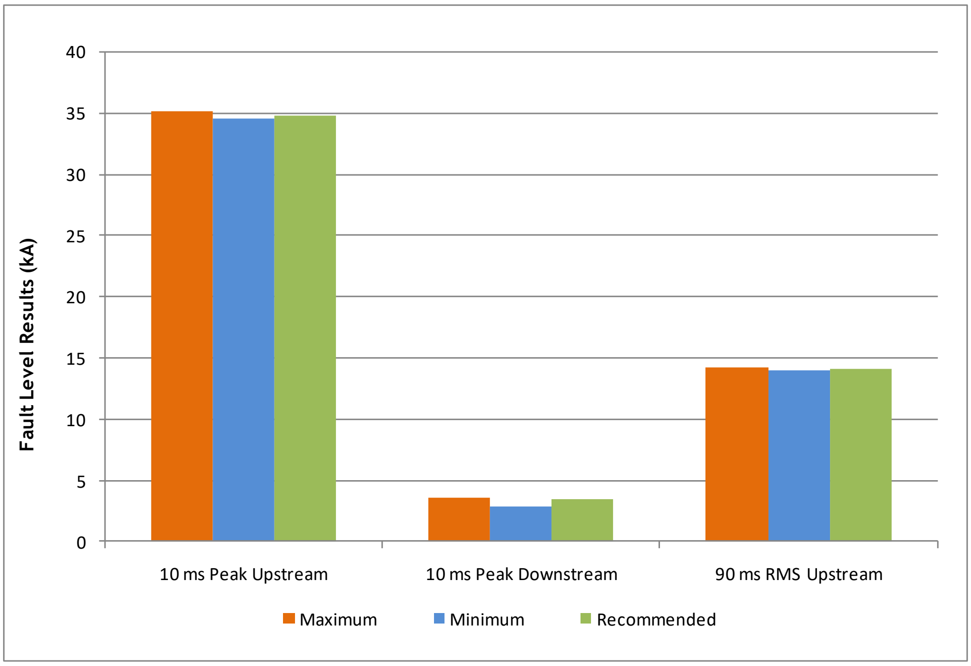


Figure 4-36 Extreme and Recommended Fault Level Results - Denton West

4.5.3 Irlam Location

Table 4-13 and Figure 4-37 show the recommended and the extreme values of the fault level results extracted from Pronto and the corresponding filter values.

In the Irlam case, there is little room for manipulation of the results in the Pronto software via the filtering tool, smoothing/filtering variations being small (maximum 4.4 %).

Table 4-13 Fault Level Results Variation for Different Filter Values - Irlam

Irlam Location		10 ms Peak Upstream	10 ms Peak Downstream	90 ms RMS Upstream
Maximum	Fault Level Value	30.70	4.32	11.67
	Gaussian Filter (%)	10	2.3	2.2
	Difference (%)	4.4%	1.1%	0.3%
Minimum	Fault Level Value	28.64	4.14	11.51
	Gaussian Filter (%)	0	0	10
	Difference (%)	-2.6%	-3.0%	-1.0%
Recommended	Fault Level Value	29.40	4.27	11.63
	Gaussian Filter (%)	3	3	0
	Difference (%)			

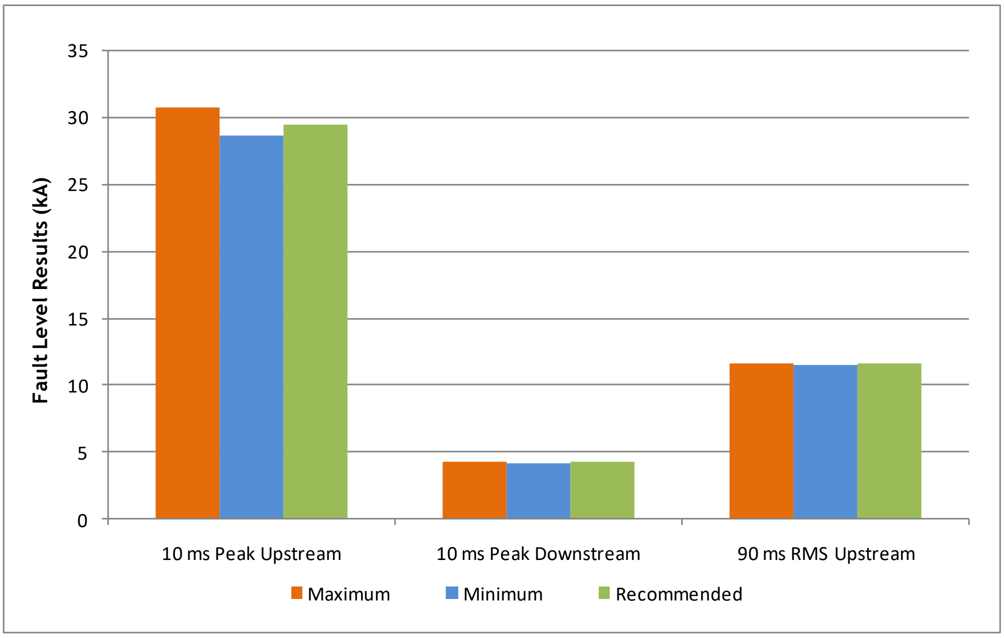


Figure 4-37 Extreme and Recommended Fault Level Results - Irlam

4.5.4 Wigan Location

Table 4-14 and Figure 4-38 show the recommended and the extreme values of the fault level results extracted from Pronto and the corresponding filter values.

In the Wigan case, a difference of 54.4 % is seen between the minimum value and the recommended one of the peak downstream fault level. This is most likely due to a high weighting but isolated event. By increasing the filter value, this event loses its importance in the overall distribution against the events around the recommended fault level value, which have smaller weight but are numerous.

Table 4-14 Fault Level Results Variation for Different Filter Values - Wigan Location

Wigan Location		10 ms Peak Upstream	10 ms Peak Downstream	90 ms RMS Upstream
Maximum	Fault Level Value	17.41	1.62	7.57
	Gaussian Filter (%)	10	0.5	1
	Difference (%)	3.4%	1.0%	0.8%
Minimum	Fault Level Value	16.83	0.73	7.33
	Gaussian Filter (%)	0	0	10
	Difference (%)	0.0%	-54.4%	-2.4%
Recommended	Fault Level Value	16.83	1.60	7.51
	Gaussian Filter (%)	0	2	2
	Difference (%)			

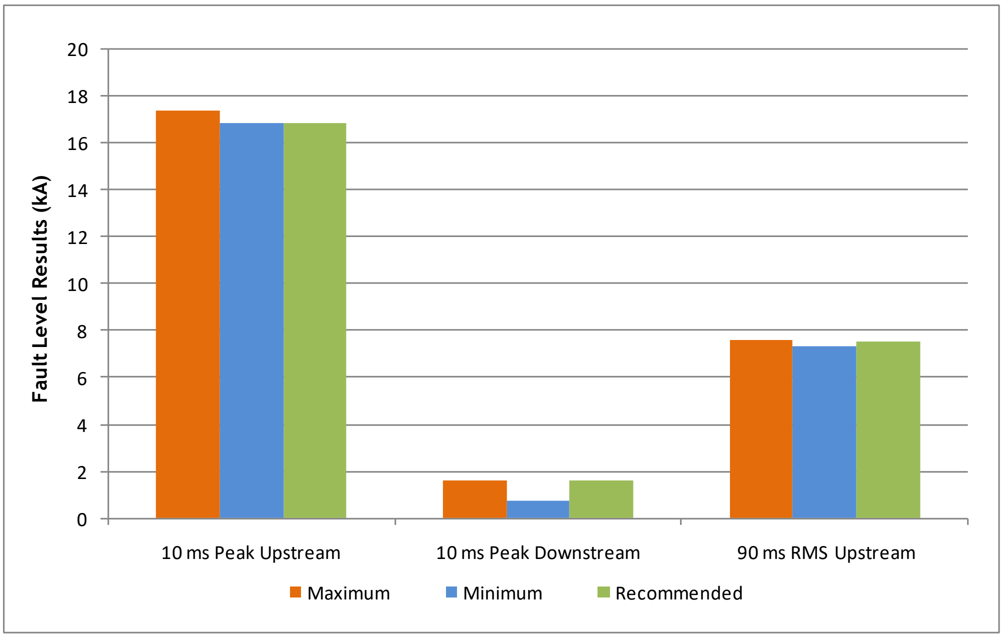


Figure 4-38 Extreme and Recommended Fault Level Results - Wigan

5 Stage 2: Comparison of Results

5.1 Final IPSA Network Model 132/33/11(6.6) kV

The ENWL IPSA Master Network 132/33 kV model has been combined with the 11 kV and 6.6 kV IPSA2 models of the selected Primary locations: Broadheath, Denton West and Irlam. Details about the network models have been presented in the Section 2.1 and 2.2 respectively. For Wigan fault studies, the intact ENWL IPSA Master Network 132/33 kV model has been used.

5.2 Study Model and Methodology

For the purpose of validating the IPSA network model, it is essential that this model is representative of the network and operational scenario for the period of measurements, and that accurate information is used for the network components, network topology, load profile, motors and distributed generation operation status and their fault contribution.

A description of the loads, distributed generation, G74 modelling and of the methodology is presented below.

5.2.1 Distributed Generation Modelling

ENWL have provided information about HV distributed generation (DG) larger than 200 kW in the selected locations, at TNEI request. The distributed generators have been modelled as described in Section 2.2.3.

It has been assumed that the distributed generators were in operation during the period of measurements, and at rated output.

A fixed unity power factor has been used for the DG units. Due to small size and capacity of the DG units, it is not expected that they will have a significant impact on the fault level at the Primaries, in each location. For future locations with larger DG capacities, additional sensitivity cases may be studied, e.g. variation of the fault level with the DG power factor within typical range.

5.2.2 Load/Demand Modelling

The variation of the consumption affects the network voltage profile and general load fault infeed in the network model. These two have opposite effects on fault levels. Increasing consumption may result in lower fault current, due to reduced voltage profile. However, the general load fault infeed increases if demand increases, as per ER G74 recommendations.

TNEI have received, upon request, Feeder Load Analysis (FLA) results for the period 18/01/2016 to 24/01/2016 for the Irlam and Denton West Primary locations and for the entire period of FLM recordings in Broadheath case. For each of the three locations, half hourly current recordings on each feeder[24] connected to the Primary substations and on the Primary transformers were received.

In addition, active (MW) and reactive power (MVAr) at half hourly measurement intervals for the same period of time have been received[25], on the secondary side of the Primary transformers.

The list of feeders for each selected location has been presented in Appendix C.

Similarly, for Wigan location, Voltage, Amps and MW/MVAr measurements on the 33 kV side of the transformers in Wigan Grid[26] have been provided by ENWL for the entire period of the FLM recordings.

For the purpose of comparing the IPSA and FLM fault level results, maximum, modal and minimum load scenarios have been implemented in the IPSA model. The comparison of current and voltage measurements with ENWL data was undertaken in Section 4.3 and this showed a general similarity for each location.

Maximum load scenario has been considered, as it is the industry practice to use (winter) maximum load network models for fault level studies. As the Outram recommended fault level is based on a probabilistic distribution, the modal value of the load has also been considered for the IPSA network model. Minimum load scenario has been added to the study as a sensitivity analysis.

All load values are based on the FLM 10 minutes average current values for two phases extracted via Pronto software. For each location, the maximum value represents the maximum values among the two phases. Similarly, the minimum value represents the minimum values among the two phases. The modal load has been calculated with a 10 A resolution (each 10 minutes average value was rounded to the nearest 10 A) and phase 'Ia' recordings have been chosen to be representative values.

Table 5-1 lists the load values for the scenarios used in the studies, for each location.

[24] File 'FLA data Broadheath 1103 to 1606.xlsx' via e-mail from Kieran Bailey dated 27th June 2016 (RE FL Reprot.msg), 'FLA data Denton West 18012016' and 'FLA data Irlam 18012016' via e-mail from Kieran Bailey dated 23rd February 2016

[25] Files 'Broadh_DenW_Irlam_MW_WC18012016' and 'Broadh_DenW_Irlam_MVAR_WC18012016' via e-mail from Kieran Bailey dated 10th March 2016 (RE TNEI - IPSA+ Model) and 'FLA data Broadheath 1103 to 1606.xlsx' via e-mail from Kieran Bailey dated 27th June 2016 (RE FL Reprot.msg)

[26] Files 'Wigan Data.xlsx' via e-mail from Kieran Bailey dated 5th May 2016 (RE Supplementary note to ENW re Wigan etc.msg)

Table 5-1 Load Range used in the IPSA Network Model

Location	Unit	Maximum Load	Modal Load	Minimum Load	Modal/ Maximum (%)
Broadheath 11 kV	A	1234	510	348	41.3
	MVA	23.51	9.72	6.63	
Denton West 6.6 kV	A	1286	960	457	74.7
	MVA	14.70	10.97	5.22	
Irlam 6.6 kV	A	1480	700	587	47.3
	MVA	16.92	8.00	6.71	
Wigan 33 kV	A	824	350	258	42.5
	MVA	47.08	20.01	14.75	

In order to preserve the load distribution of the HV feeders for Broadheath, Irlam and Denton West locations and the power factor measured by ENWL at the secondary side of the Primary transformers, the load values from Table 5-1 have been searched in the FLA data and the matching values (or as close as possible) have been identified. Once the maximum, modal and minimum load and corresponding point in time have been identified, the 'PQ type' loads on each feeder have been scaled so that the current flow from the Primary bus to each feeder matches the selected data. This was done via an automatic iterative process. The scaling of feeder loads was based on their rating provided via the DINIS file, i.e. each load in the final model is a percentage of the initial rating.

In a similar manner, for Wigan location, the load values from Table 5-1 have been searched in the ENWL data and the matching values (or as close as possible) have been identified. Once the maximum, modal and minimum load and corresponding point in time have been identified, the 'PQ type' loads at the Gidlow Primary 6.6 kV, Green Street T12 & T13 6.6 kV and Worsley Mesnes 6.6 kV have been scaled based on the their initial values from the IPSA Master Network Model.

Generally, the power factor of the HV loads can be estimated based on their type:

- 0.96-0.97 for industrial loads
- 0.985-0.999 for domestic loads

Information was not provided in order to differentiate the loads, thus the half hourly MW and MVAr recordings have been used to estimate the overall power factor in Broadheath, Denton West and Irlam, for the studied load scenarios. The same power factor has been distributed to all the loads on the feeders. Similarly, for Wigan, hourly MW and MVAr recordings have been used to calculate the power factor at the Wigan 33 kV bus.

A summary of the loads (A) on each feeder for the three load scenarios and the overall power factor at the Primary bus are listed in Appendix G. This appendix also shows the overall load (A) and power factor at the Wigan 33 kV.

5.2.3 General Load Fault In-Feed (G74 Models)

A detailed fault level analysis needs to consider the accurate modelling of the motors in the network model. Where information is not available, Engineering Recommendation G74 provides instructions on how to estimate the fault level contribution of downstream motors by means of equivalent motors connected to the Primary substations. This has been discussed in Section 3 of the report.

Part of the general load consists of asynchronous machines which contribute to the fault level (both Peak Make and, potentially, RMS Break). In the case of the ENWL model, the G74 model contribution decays to zero, prior to the 90 ms break time.

According to ER G74, the initial symmetrical fault contribution from the general load connected to the low voltage network is around 1 MVA for every 1 MVA of load when aggregated at 33 kV. In the ENWL computer model, the fault contribution from a general load is usually modelled with an equivalent motor at the 11 kV or 6.6 kV points where the aggregate load is connected. This model assumes a 1 MVA initial symmetrical fault contribution per 1 MVA of load using an X/R ratio of 2.76.

Due to its magnetising branch component and depending on the grid strength, the presence/absence of the G74 model affects the pre-fault voltage conditions, but in a negligible way.

We used the G74 models contained in the network database, as advised by ENWL, by adapting the equivalent motor parameters to match the change in loads considered. After the loads are updated with the maximum, modal and minimum load values, the existing G74 models connected to the 11 kV and 6.6 kV buses in the selected locations are updated accordingly, based on the total load MVA value of the buses.

It should be noted that ER G74 methodology was developed in 1992 and since then the load mix and appliances used in commercial and industrial environments may have changed. The sensitivity of fault level to general load contribution is studied by re-running the fault level studies with a variation of the G74 model that produces 2 MVA of initial symmetrical fault contribution per 1 MVA load.

5.2.4 Network Topology and Operation

Any change in the network configuration or asset operation in the selected locations during the period of fault level measurements can affect the fault level results. These changes may include outage of circuits and transformers, replacement of equipment in the network, connection of new circuit for the connection of new generators etc.

ENWL has advised to consider the normal network configuration as received via the IPSA Network Model and no circuit configuration change for the period of measurements. A sensitivity analysis has been undertaken by disconnecting one transformer in each location. Depending on the conclusions of this report, additional information may be provided to TNEI if any change in topology is suspected to have been undertaken during the period of measurements.

Transformer tapping is automated in the primary system to maintain the voltage profile on the 11 kV and 6.6 kV networks within the acceptable limits. Fault level results are related to the pre-fault voltage conditions. The position of the tap at the selected substations can alter the voltage profile of the network and consequently the fault current contributions.

The voltage set point of 1 p.u. for the primary and grid transformers in the selected locations have been maintained in the studies, in accordance with the IPSA Network Model. This is generally consistent with the average voltage recorded by the FLM, as shown in Section 4.4 (Table 4-4, Table 4-6, Table 4-8 and Table 4-10 respectively).

In order to show the variation of the fault level results with the change of tap/voltage set point, the tap position of the 33/11 kV, 33/6.6 kV and 132/33 kV transformers in the selected locations is changed to reach different target voltages as close as possible to the extremes listed in the tables mentioned above.

5.3 Comparison of Results

The fault level study has been performed based on the final IPSA Network Model to which the updates described in Section 5.2 have been applied.

When implementing ER G74, the pre-fault voltage conditions on the network should be first calculated to determine the pre-fault internal voltage of motors and power plants. Therefore, the option ‘Apply Flat Start Voltages before a fault’ has been unchecked in the IPSA2 software. All the other Advanced Settings have been maintained as in the IPSA Master Network Model received from ENWL, including the ‘DC decay’ method for the calculation of the X/R ratio.

The IPSA results have been compared against the FLM ‘recommended’ fault level results from Table 4-2, Section 4. As additional information and for the cases where larger differences between FLM and IPSA were noticed, further comparisons with the FLM ‘extreme’ values discussed in Section 4.5 have been presented.

The system normal with all the DG units and the G74 models connected to the network is considered to be the ‘base case’ scenario.

In order to understand the sensitivity of fault levels to input parameters, a series of scenarios have been studied. Peak make at 10 ms and RMS break at 90 ms fault currents were calculated in IPSA for each scenario and compared with the values extracted from the FLM device, via the Pronto software.

The FLM device does not provide results for the downstream RMS break fault contribution, aspect that is reflected in the tables from the subsequent sections.

All the differences are percentage (%) related to FLM results.

5.3.1 Broadheath Location

General Results

Table 5-2 shows the comparison of fault levels obtained from the final IPSA Network Model against the FLM results.

The voltage at the Primary bus in each load demand scenario has also been shown in order to study the impact of the pre-fault voltage on the fault level results.

The fault level results along the feeders for the maximum load are listed in Appendix H.

The total RMS break fault level results show that the differences between IPSA and FLM are relatively high, up to 9.8 %. The peak make differences are small, up to 4.3 %. It is very likely that the total peak make results are less than 32.78 kA, as this value represents the arithmetic sum of its upstream and downstream components. Figure 5-1 shows the differences in the total fault level results against FLM values, in percentage.

The upstream and downstream breakdown results are discussed separately in subsequent sections.

Table 5-2 General Fault Level Results (System Normal) – Broadheath

Broadheath 11kV Location (General Results)		Make			Break			Primary Voltage
		Upstream	Downstream	Total	Upstream	Downstream	Total	
		kA	kA	kA	kA	kA	kA	kV
FLM		29.56	3.22	32.78	10.16	-	-	-
IPSA	Maximum Load	30.40	2.16	32.55	11.14	0.01	11.16	1.00
	Modal Load	30.58	0.92	31.50	11.09	0.01	11.10	1.01
	Minimum Load	30.63	0.74	31.37	11.09	0.01	11.10	1.01
		%	%	%	%	%	%	
FLM								
IPSA	Maximum Load	-2.8%	32.8%	0.7%	-9.7%	-	-9.8%	
	Modal Load	-3.5%	71.6%	3.9%	-9.1%	-	-9.2%	
	Minimum Load	-3.6%	77.1%	4.3%	-9.1%	-	-9.2%	

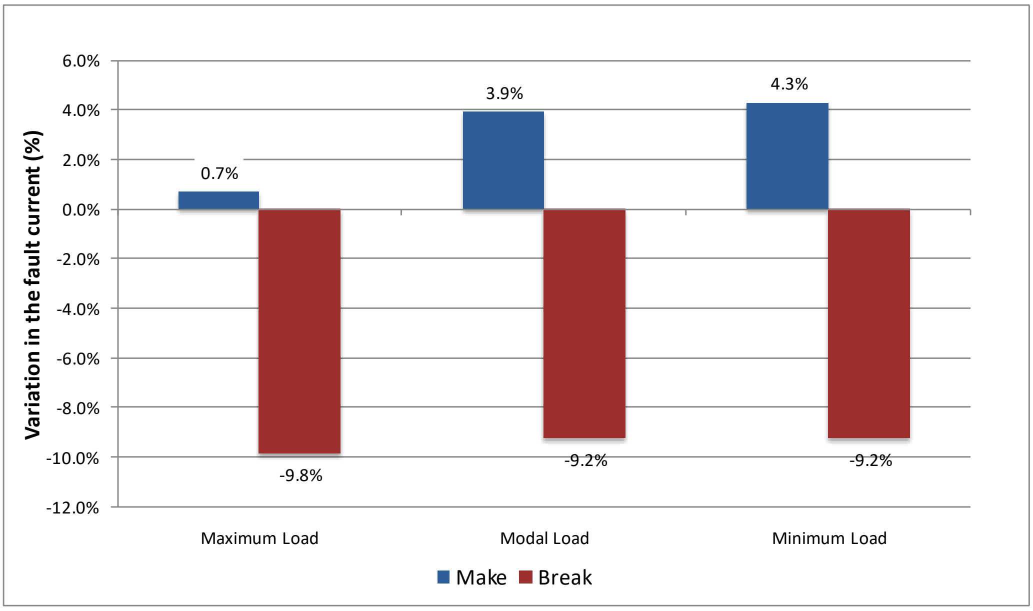


Figure 5-1 Variation of the Total Current Contribution with Load against FLM Results - Broadheath

<u>Sensitivity of Fault Currents to the Transformer Voltage Set Point/Transformer Tap Position</u>

The 33/11 kV transformers taps in Broadheath will influence the fault level results due to the change of pre-fault voltage at the 11 kV terminals. For modal case, the voltage set-point has been changed from 1.01 p.u. to 1.03 p.u. and then to 0.98 p.u. in order to replicate the voltage variation seen by FLM based on 10 minutes average values (Table 4-4).

The results show that a voltage variation from 1.03 p.u. to 0.98 p.u. reduces the fault levels as expected. For example, this reduces the peak make upstream difference between IPSA and FLM values from 4.2 % to 2.6 %. Figure 5-2 shows the sensitivity of the upstream contribution with the voltage at the Primary bus.

Table 5-3 Sensitivity of Fault Currents with Voltage (Modal Load Case) - Broadheath

Broadheath 11kV Location (General Results)	Make			Break			Primary Voltage
	Upstream	Downstream	Total	Upstream	Downstream	Total	
	kA	kA	kA	kA	kA	kA	kV
FLM	29.56	3.22	32.78	10.16	-	-	-
IPSA	30.58	0.92	31.50	11.09	0.01	11.10	1.01
	30.81	0.93	31.75	11.18	0.01	11.19	1.03
	30.32	0.91	31.23	10.98	0.01	11.00	0.98
	%	%	%	%	%	%	
FLM							
IPSA	-3.5%	71.6%	3.9%	-9.1%	-	-9.2%	
	-4.2%	71.2%	3.2%	-10.0%	-	-10.1%	
	-2.6%	71.7%	4.7%	-8.1%	-	-8.3%	

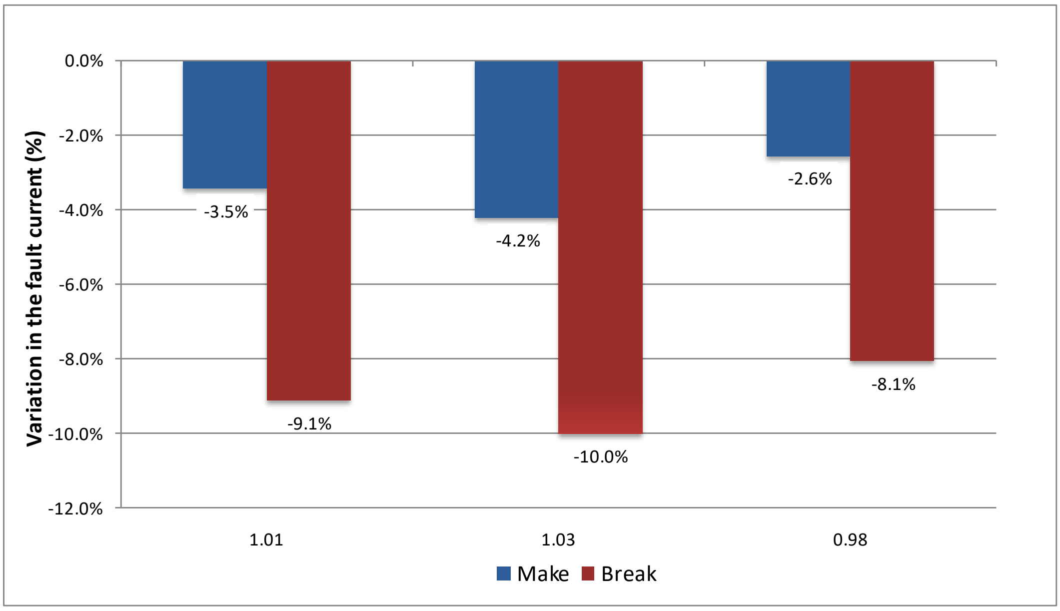


Figure 5-2 Variation of the Upstream Current Contribution with Voltage against FLM Results (Modal Load Case) - Broadheath

Upstream Contribution Discussion

Table 5-4 shows the comparison of the upstream fault level contribution from the final IPSA Network Model with the FLM results, in different network operating scenarios.

In the case of break, the differences are relatively high, up to 9.7 % for maximum load and 9.1 % for modal load scenario. However, the differences in peak make are smaller, up to 2.8 % for maximum load and 3.5 % for modal load scenario.

Compared to the FLM upstream results, IPSA network model generates higher fault level values for both break and peak. The IPSA values seem to be closer to the 'maximum extreme' FLM result presented in Table 4-11 in Section 4.5.1.

The upstream contribution is not as largely dependent on load as the downstream contribution via the G74 models.

Other G74 machines in Altrincham area do not have significant impact on the Broadheath 11 kV fault level, apart from their minor influence via pre-fault voltage profile.

The differences in break (almost 1 kA) could be explained by the possible inconsistency in 132 kV grid in Altrincham area between the IPSA Master Network and the actual operating scheme during the period of measurements, the relative modest disturbance energy seen by the FLM and larger room for interpretation of the results in Pronto software compared to the other locations.

Table 5-4 Upstream Fault Level Results - Broadheath

Broadheath 11kV Location (Upstream Contribution)			Make	Break	Make	Break	Voltage
			kA	kA	%	%	kV
FLM			29.56	10.16			-
IPSA	System Normal	Maximum Load	30.40	11.14	-2.8%	-9.7%	1.00
		Modal Load	30.58	11.09	-3.5%	-9.1%	1.01
		Minimum Load	30.63	11.09	-3.6%	-9.1%	1.01
	Altrincham 't11' transformer out	Maximum Load	23.10	8.54	21.9%	15.9%	1.00
		Modal Load	23.14	8.42	21.7%	17.1%	1.00
		Minimum Load	23.19	8.42	21.6%	17.1%	1.01
	Without other G74 machines in Altrincham area	Maximum Load	30.05	11.16	-1.7%	-9.9%	1.00
		Modal Load	30.24	11.11	-2.3%	-9.4%	1.01
		Minimum Load	30.24	11.09	-2.3%	-9.2%	1.01

Downstream Contribution Discussion

In Table 5-5 the downstream contribution is decomposed into DG units and G74 models. The results in Table 5-2 and Table 5-5 show that the variation of load in the IPSA network affects the peak make downstream fault current while the RMS break fault remains generally constant. This is expected because the ENWL G74 model current contribution decays to zero before the 90 ms break time and the RMS break fault contribution is given by the DG units in the HV area. The FLM device does not provide results for the break level.

It can be noticed that the (downstream) motor contribution in IPSA is much lower than the FLM results, the difference being 32.8 % for maximum load and 71.6 % for modal load.

Table 4-11 in Section 4.5.1 shows the variation of the downstream peak fault level results with the Gaussian filter, as extracted from the Pronto software. The maximum and minimum downstream peak values are 3.35 kA and 2.99 kA respectively, close to the recommended value of 3.22 kA. When the IPSA results are compared to the minimum value of 2.99 kA, the differences are still large (27.8 % for maximum load and 69.2 % for modal load scenario).

This poses relevant questions whether the ER G74 and ETR 120 guidelines are still valid for the network and load mix of today in the Broadheath area.

Table 5-5 Downstream Fault Level Results (System Normal) - Broadheath

Broadheath 11kV Location (Downstream Contribution)		Make			Break		Make	Break	Voltage
		kA	kA	kA	kA	kA	%	%	kV
		DG	G74	Total	DG	G74	Total	Total	-
FLM		-	-	3.22	-	-			-
IPSA	Maximum Load	0.04	2.12	2.16	0.01	0.00	32.8%	-	1.00
	Modal Load	0.02	0.89	0.92	0.01	0.00	71.6%	-	1.01
	Minimum Load	0.02	0.72	0.74	0.01	0.00	77.1%	-	1.01

Table 5-6 shows the comparison of the fault levels obtained from the final IPSA Network Model against the FLM results, when the G74 models are modified to provide 2 MVA of initial symmetrical fault contribution per 1 MVA of load.

Figure 5-3 shows the peak downstream results for the two cases (1 MVA and 2 MVA per 1 MVA of load respectively) against FLM results. The orange continuous line shows the recommended value (3.22 kA) while the dashed ones show the extreme values (3.35 kA and 2.99 kA) taken from Table 4-11 in Section 4.5.1.

The results of the default 1MVA/MVA of Load Infeed G74 model are much smaller than the FLM results irrespective of the load scenarios studied. With the variation of 2MVA/MVA of Load Infeed G74 model being applied, the resultant downstream peak currents from the IPSA model increase from 0.92 kA to 1.81 kA, giving a 43.7 % difference in the modal load scenario.

The results suggest that for this location, the G74 model variation to provide 2 MVA fault contribution per 1 MVA of load is more compatible with the FLM results than the default G74 model, for both maximum load and modal load scenarios.

Table 5-6 General Fault Level Results (System Normal) for 2MVA/MVA of Load Infeed - Broadheath

Broadheath 11kV Location		Make			Break			Primary Voltage
		Upstream	Downstream	Total	Upstream	Downstream	Total	
		kA	kA	kA	kA	kA	kA	kV
FLM		29.56	3.22	32.78	10.16	-	-	-
IPSA	Maximum Load	30.33	4.27	34.58	11.14	0.02	11.17	0.99
	Modal Load	30.55	1.81	32.35	11.09	0.02	11.10	1.00
	Minimum Load	30.61	1.45	32.05	11.09	0.01	11.10	1.01
		%	%	%	%	%	%	
FLM								
IPSA	Maximum Load	-2.6%	-32.6%	-5.5%	-9.7%	-	-9.9%	
	Modal Load	-3.4%	43.7%	1.3%	-9.1%	-	-9.3%	
	Minimum Load	-3.5%	54.9%	2.2%	-9.1%	-	-9.2%	

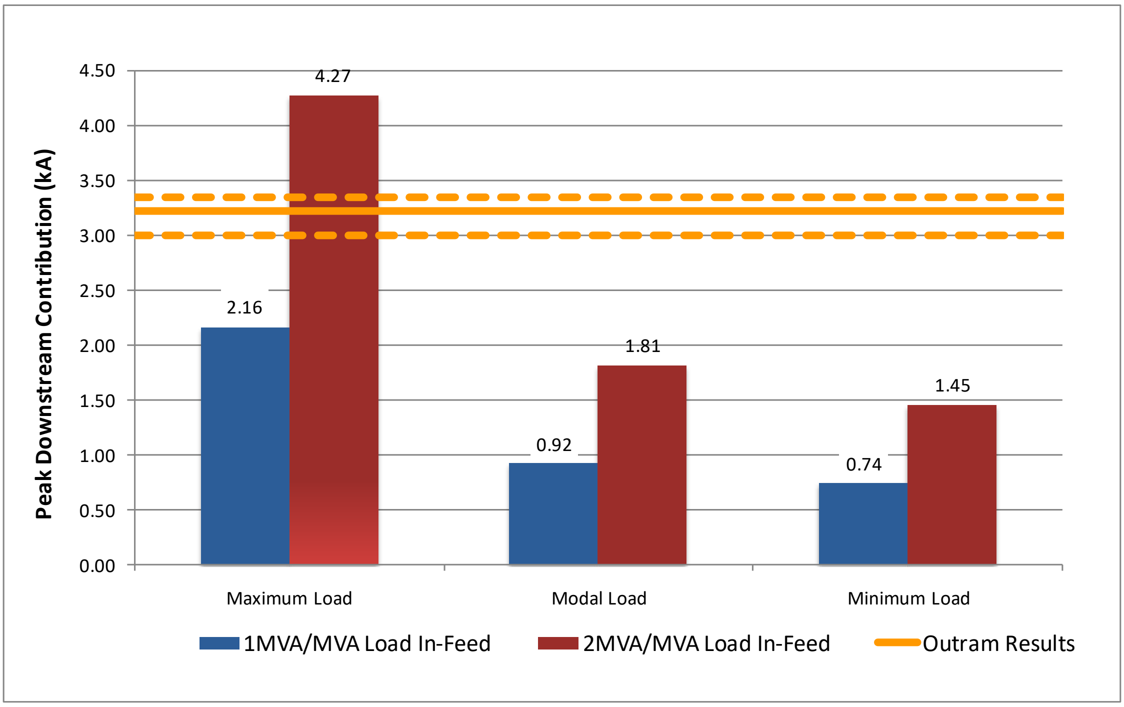


Figure 5-3 General Load Fault In-Feed Variation against FLM Results - Broadheath

5.3.2 Denton West Location

General Results

Table 5-7 shows the comparison of fault levels obtained from the final IPSA Network Model against the FLM results.

No DG units with a rated capacity higher than 200 kW are modelled in the HV network; therefore the downstream contribution in the table is composed of the G74 models only.

The voltage at the Primary bus in each load demand scenario has also been shown in order to assess the impact of pre-fault voltage on the fault level results.

The fault level results along the feeders for maximum load scenario are listed in Appendix H.

The total fault level results show that the differences between IPSA and FLM are quite small, up to 3.1 % for peak make and up to 3.8 % for break. Figure 5-4 shows the differences in the total fault level results against FLM values, in percentage. It is very likely that the total peak make FLM result is slightly less than 38.31 kA, this value representing the arithmetic sum of its upstream and downstream components.

If the fault results are decomposed into upstream and downstream contributions, the differences in peak make are obvious. In the case of break, the differences are small, up to 3.1 % for maximum load and 3.0 % for modal load scenario. The upstream and downstream results are discussed separately in subsequent sections.

Table 5-7 General Fault Level Results (System Normal) - Denton West

Denton West 6.6 kV Location (General Results)		Make			Break			Primary Voltage
		Upstream	Downstream	Total	Upstream	Downstream	Total	
		kA	kA	kA	kA	kA	kA	kV
FLM		34.84	3.47	38.31	14.08	-	-	-
IPSA	Maximum Load	37.17	2.35	39.51	13.65	0.00	13.65	0.99
	Modal Load	37.39	1.78	39.17	13.65	0.00	13.65	1.01
	Minimum Load	37.25	0.89	38.13	13.55	0.00	13.55	1.00
		%	%	%	%	%	%	
FLM								
IPSA	Maximum Load	-6.7%	32.3%	-3.1%	3.1%	-	3.1%	
	Modal Load	-7.3%	48.6%	-2.2%	3.0%	-	3.0%	
	Minimum Load	-6.9%	74.4%	0.5%	3.8%	-	3.8%	

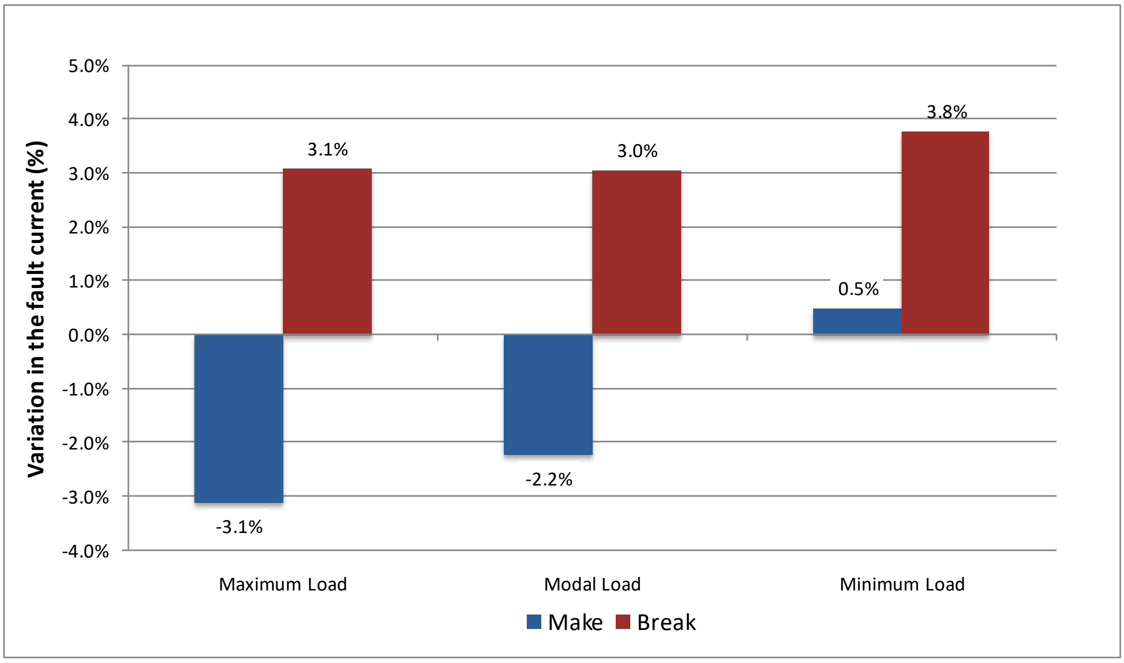


Figure 5-4 Variation of the Total Current Contribution with Load against FLM Results - Denton West

Sensitivity of Fault Currents to the Transformer Voltage Set Point/Transformer Tap Position

The 33/6.6 kV transformers in Denton West operating at different tap positions will influence the fault level results due to the change of pre-fault voltage at the 6.6 kV terminals. For modal load case, the voltage set-point for the two 33/6.6 kV transformers has been changed from 1.01 p.u. to 0.99 p.u. and then to 0.98 p.u. in order to replicate the voltage variation seen by the FLM, based on 10 minutes average values (Table 4-6).

The results show that a voltage variation from 1.01 to 0.98 p.u. reduces the fault levels as expected. For example, this reduces the peak make upstream difference between IPSA and FLM values from 7.3 % to 5.5 %.

Figure 5-5 shows the sensitivity of the upstream contribution with the voltage at the Primary bus.

Table 5-8 Sensitivity of Fault Currents with Voltage (Modal Load Case) - Denton West

Denton West 6.6kV Location	Make			Break			Voltage
	Upstream	Downstream	Total	Upstream	Downstream	Total	
	kA	kA	kA	kA	kA	kA	kV
FLM	34.84	3.47	38.31	14.08	-	-	-
IPSA	37.39	1.78	39.17	13.65	0.00	13.65	1.01
	37.07	1.76	38.82	13.55	0.00	13.55	0.99
	36.75	1.73	38.48	13.44	0.00	13.44	0.98
	%	%	%	%	%	%	
FLM							
IPSA	-7.3%	48.6%	-2.2%	3.0%	-	3.0%	
	-6.4%	49.3%	-1.3%	3.8%	-	3.8%	
	-5.5%	50.1%	-0.4%	4.5%	-	4.5%	

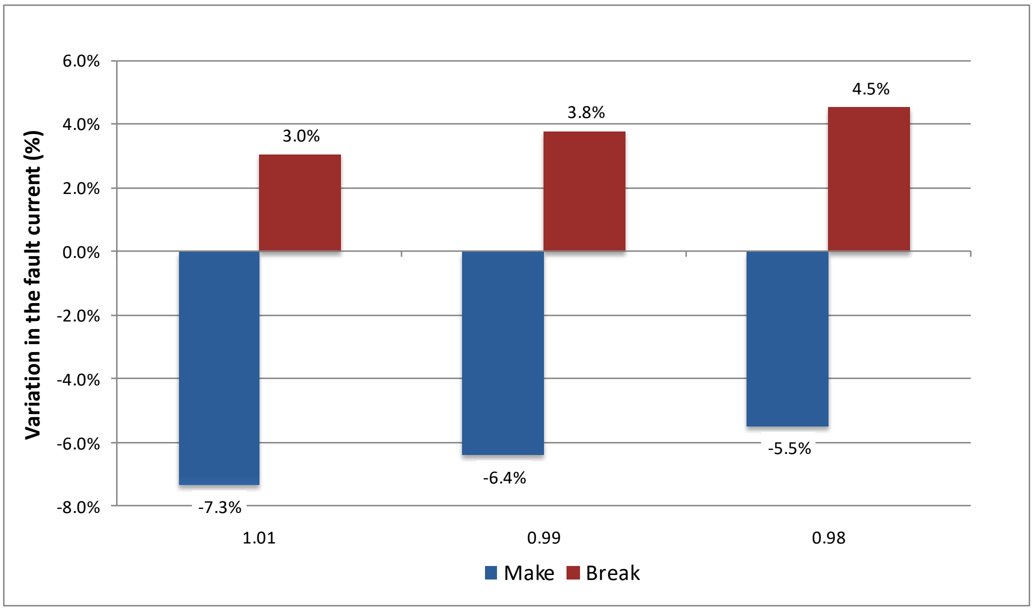


Figure 5-5 Variation of the Upstream Current Contribution with Voltage against FLM Results (Modal Load Case) - Denton West

Upstream Contribution Discussion

Table 5-9 shows the comparison of the upstream fault level contribution from the final IPSA Network Model against the FLM results, for different network operating scenarios.

In the case of break, the differences are generally small, up to 3.1 % for maximum load and 3.0 % for modal load scenario. However, the differences in peak make are generally larger, up to 6.7 % for maximum load and 7.3 % for modal load scenarios. Compared to FLM upstream fault current values, lower values in break and higher values in peak make were seen in the IPSA network model. The IPSA values seem to be closer to the 'maximum extreme' values presented in Table 4-12 in Section 4.5.2.

The upstream contribution is not as largely dependent on load as the downstream contribution via the G74 models.

Other G74 machines in Droylsden area do not have significant impact on the Denton West 6.6 kV fault level, apart from their influence via the load flow results.

Table 5-9 Upstream Fault Level Results - Denton West

Denton West 6.6kV Location (Upstream Contribution)			Make	Break	Make	Break	Voltage
			kA	kA	%	%	kV
FLM			34.84	14.08	-	-	-
IPSA	System Normal	Maximum Load	37.17	13.65	-6.7%	3.1%	0.99
		Modal Load	37.39	13.65	-7.3%	3.0%	1.01
		Minimum Load	37.25	13.55	-6.9%	3.8%	1.00
	Denton West 't11' transformer out	Maximum Load	21.26	7.92	39.0%	43.7%	1.00
		Modal Load	21.26	7.84	39.0%	44.3%	1.00
		Minimum Load	21.00	7.68	39.7%	45.5%	0.99
	Without other G74 machines in Droylsden area	Maximum Load	37.27	13.70	-7.0%	2.7%	1.01
		Modal Load	37.58	13.69	-7.9%	2.8%	1.01
		Minimum Load	37.20	13.60	-6.8%	3.4%	1.00

Downstream Contribution Discussion

The results in Table 5-7 show that the variation of load in the IPSA network affects the peak make downstream fault current while the break fault remains generally constant, in this case being zero as there are no DG in the HV area. This is expected because the ENWL G74 model current contribution decays to zero before the 90 ms break time.

This section refers only to peak make from downstream network, as FLM device does not provide results for the break level.

It can be noticed that the motor contribution in IPSA is much lower than the FLM results, the difference being 32.3 % for maximum load and 48.6 % for modal load.

Table 4-12 in Section 4.5.3 shows the variation of the downstream peak fault level results with the Gaussian filter, as extracted from the Pronto software. The maximum and minimum downstream peak values are 3.63 kA and 2.89 kA respectively. When the IPSA results are compared to the minimum value of 2.89 kA, differences are still large (18.6 % for maximum load and 38.4 % for modal load scenario).

This poses relevant questions whether the ER G74 and ETR 120 guidelines are still valid for the network and load mix today in the Denton West area.

Table 5-10 shows the comparison of the fault levels obtained from the final IPSA Network Model against the FLM results, when the G74 models are modified to provide 2 MVA fault contribution per 1 MVA of load. With the variation of the G74 model applied, the resultant downstream peak currents from the IPSA model increase from 1.78 kA to 3.56 kA for modal load scenario, giving a 2.5 % difference as compared with the FLM results.

Figure 5-6 shows the peak downstream results for the two cases (1 MVA and 2 MVA fault contribution per 1 MVA of load respectively) against FLM results. The orange continuous line shows the recommended value (3.47 kA), while the dashed ones show the extreme values (3.63 kA and 2.89 kA) taken from Table 4-12 in Section 4.5.2.

The results suggest that the G74 model variation to provide 2 MVA fault contribution per 1 MVA of load is more compatible with the FLM results than the default G74 model having 1 MVA fault contribution per 1 MVA of load for the modal load scenario. For the maximum load scenario, the FLM fault results are quite equidistant between the 2 MVA/MVA and 1 MVA/MVA IPSA results.

Table 5-10 General Fault Level Results (System Normal) for 2MVA/MVA of Load Infeed - Denton West

Denton West 6.6kV Location		Make			Break			Primary Voltage
		Upstream	Downstream	Total	Upstream	Downstream	Total	
		kA	kA	kA	kA	kA	kA	kV
FLM		34.84	3.47	38.31	14.08	-	-	-
IPSA	Maximum Load	37.34	4.75	42.08	13.75	0.00	13.75	1.00
	Modal Load	37.33	3.56	40.86	13.65	0.00	13.65	1.00
	Minimum Load	37.21	1.77	38.98	13.55	0.00	13.55	1.00
		%	%	%	%	%	%	
FLM								
IPSA	Maximum Load	-7.2%	-36.9%	-9.8%	2.3%	-	2.3%	
	Modal Load	-7.2%	-2.5%	-6.7%	3.0%	-	3.0%	
	Minimum Load	-6.8%	48.9%	-1.7%	3.8%	-	3.8%	

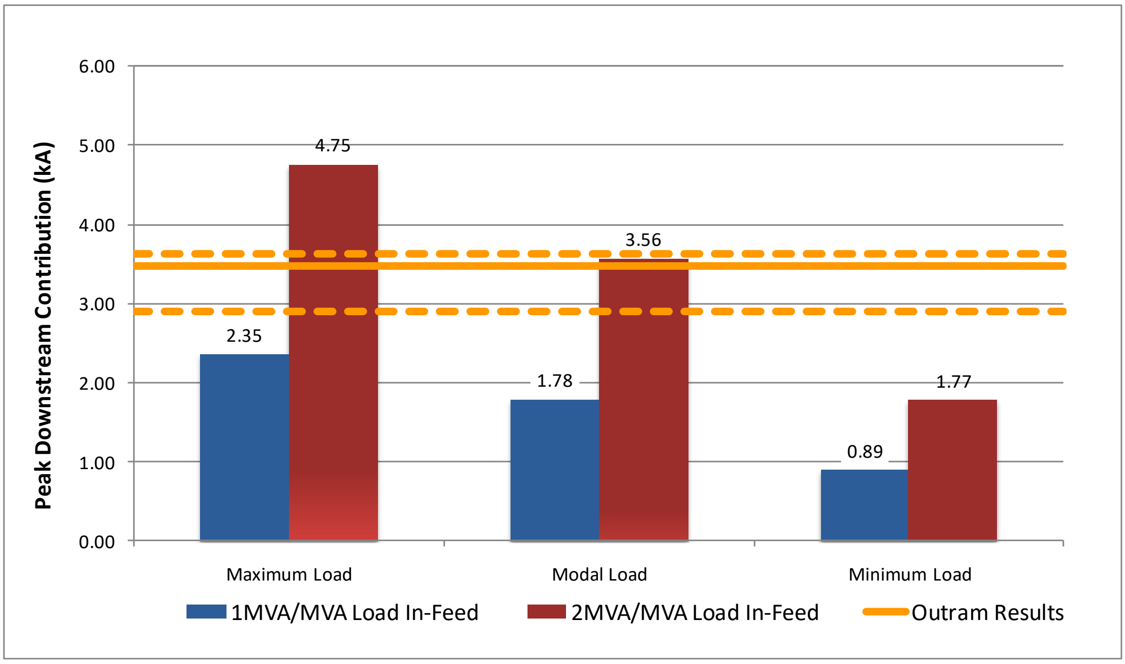


Figure 5-6 General Load Fault Infeed Variation against FLM Results - Denton West

5.3.3 Irlam Location

General Results

Table 5-11 shows the comparison of fault levels obtained from the final IPSA Network Model against the estimated the FLM results.

The voltage at the Primary bus in each load demand scenario has also been shown in order to study the impact of pre-fault voltage on the fault level results.

The fault level results along the feeders for maximum load are listed in Appendix H.

The total fault level results show that the differences between IPSA and FLM are quite small, up to 3.1 % for peak make and up to 1.9 % for break. It is very likely that the total peak make results are less than 33.67 kA, as this value represents the arithmetic sum of its upstream and downstream components. Figure 5-7 shows the differences in the total fault level results against FLM values, in percentage.

However, if the fault results are decomposed into upstream and downstream contributions, the differences in peak make are obvious. In the case of break, the differences are small, up to 1.7 % for maximum load and 1.0 % for modal load scenario, even smaller than in Denton West case. The upstream and downstream results are discussed separately in subsequent sections.

Table 5-11 General Fault Level Results (System Normal) - Irlam

Irlam 6.6kV Location (General Results)		Make			Break			Primary Voltage
		Upstream	Downstream	Total	Upstream	Downstream	Total	
		kA	kA	kA	kA	kA	kA	kV
FLM		29.40	4.27	33.67	11.63	-	-	-
IPSA	Maximum Load	32.03	2.70	34.71	11.83	0.03	11.86	0.99
	Modal Load	32.37	1.54	33.90	11.75	0.03	11.77	1.01
	Minimum Load	32.02	1.23	33.25	11.66	0.03	11.68	0.99
		%	%	%	%	%	%	
FLM								
IPSA	Maximum Load	-8.9%	36.8%	-3.1%	-1.7%	-	-1.9%	
	Modal Load	-10.1%	63.9%	-0.7%	-1.0%	-	-1.2%	
	Minimum Load	-8.9%	71.2%	1.3%	-0.3%	-	-0.5%	

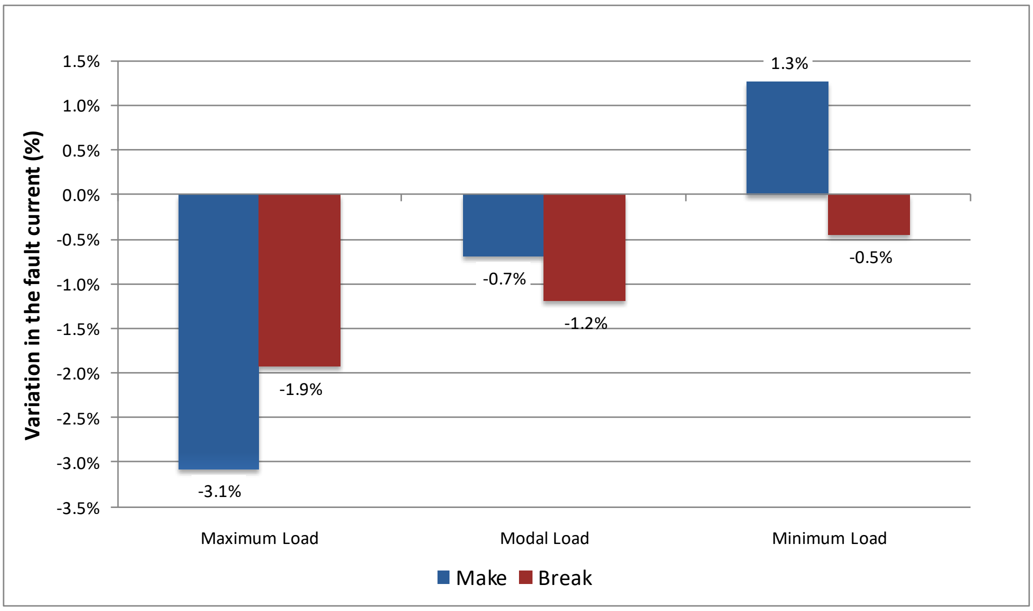


Figure 5-7 Variation of the Total Current Contribution with Load against FLM Results - Irlam

<u>Sensitivity of Fault Currents to the Transformer Voltage Set Point/Transformer Tap Position</u>

The 33/6.6 kV transformers taps in Irlam will influence the fault level results due to the change of pre-fault voltage at the 6.6 kV terminals. For modal case, the voltage set-point has been changed from 1.01 p.u. to 0.99 p.u. and then to 0.98 p.u. in order to replicate the voltage variation seen by FLM based on 10 minutes average values (Table 4-8).

The results show that a voltage variation from 1.01 p.u. to 0.98 p.u. reduces the fault levels as expected. For example, this reduces the peak make upstream difference between IPSA and FLM values from 10.1 % to 7.7 %.

Figure 5-8 shows the sensitivity of the upstream contribution with the voltage at the Primary bus.

Table 5-12 Sensitivity of Fault Currents with Voltage (Modal Load Case) - Irlam

Irlam 6.6kV Location (General Results)	Make			Break			Primary Voltage
	Upstream	Downstream	Total	Upstream	Downstream	Total	
	kA	kA	kA	kA	kA	kA	kV
FLM	29.40	4.27	33.67	11.63	-	-	-
IPSA	32.37	1.54	33.90	11.75	0.03	11.77	1.01
	31.98	1.51	33.49	11.66	0.02	11.68	0.99
	31.66	1.49	33.15	11.57	0.02	11.60	0.98
	%	%	%	%	%	%	
FLM							
IPSA	-10.1%	63.9%	-0.7%	-1.0%	-	-1.2%	
	-8.8%	64.6%	0.5%	-0.3%	-	-0.5%	
	-7.7%	65.1%	1.5%	0.5%	-	0.3%	

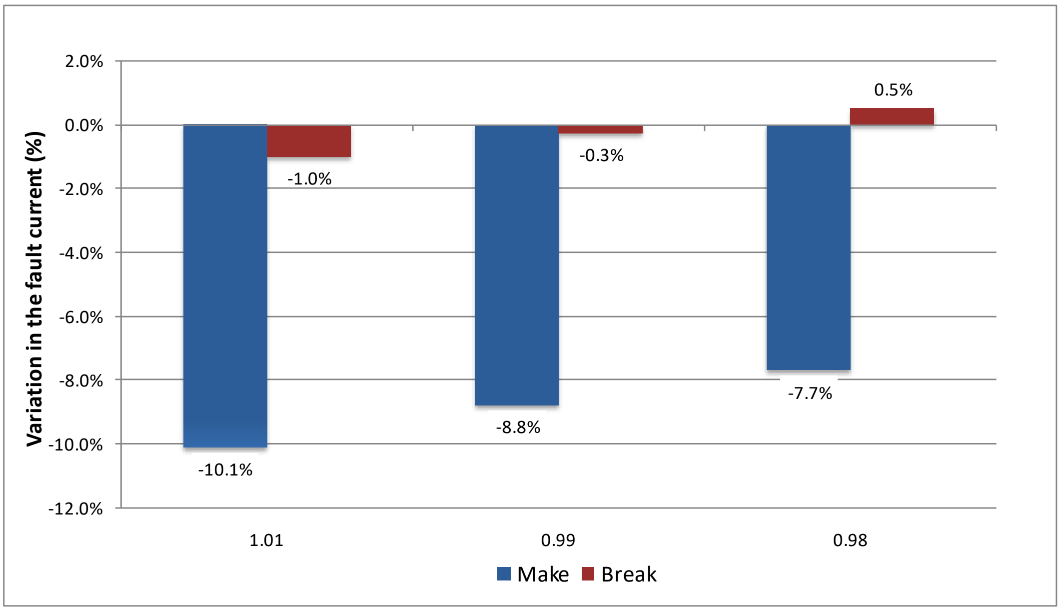


Figure 5-8 Variation of the Upstream Current Contribution with Voltage against FLM Results (Modal Load Case) - Irlam

Upstream Contribution Discussion

Table 5-13 shows the comparison of the upstream fault level contribution from the final IPSA Network Model against the FLM results, in different network operating scenarios.

In the case of break, the differences are generally small, up to 1.7 % for maximum load and 1.0 % for modal load scenario. However, the differences in peak make are generally larger, up to 8.9 % for maximum load and 10.1 % for modal load scenario.

Compared to FLM upstream values, IPSA network model generates higher fault level values for both break and peak. The IPSA values seem to be closer to the 'maximum extreme' values presented in Table 4-13 in Section 4.5.3.

The upstream contribution is not as largely dependent on load as the downstream contribution via the G74 models.

Other G74 machines in Carrington area do not have significant impact on the Irlam 6.6 kV fault level, apart from their influence via the load flow results.

Table 5-13 Upstream Fault Level Results - Irlam

Irlam 6.6kV Location (Upstream Contribution)			Make	Break	Make	Break	Voltage
			kA	kA	%	%	kV
FLM			29.40	11.63	-	-	-
IPSA	System Normal	Maximum Load	32.03	11.83	-8.9%	-1.7%	0.99
		Modal Load	32.37	11.75	-10.1%	-1.0%	1.01
		Minimum Load	32.02	11.66	-8.9%	-0.3%	0.99
	Irlam 't11' transformer out	Maximum Load	18.13	6.83	38.3%	41.3%	0.99
		Modal Load	18.10	6.63	38.4%	43.0%	1.00
		Minimum Load	17.87	6.56	39.2%	43.6%	0.99
	Without other G74 machines in Carrington area	Maximum Load	32.03	11.85	-8.9%	-1.9%	0.99
		Modal Load	32.20	11.76	-9.5%	-1.2%	1.01
		Minimum Load	31.99	11.68	-8.8%	-0.4%	1.00

<u>Downstream Contribution Discussion</u>

In Table 5-14 the downstream contribution is decomposed into DG units and G74 models. The results in Table 5-11 and Table 5-14 show that the variation of load in the IPSA network affects the peak make downstream fault current while the RMS break fault remains generally constant. This is expected because the ENWL G74 model current contribution decays to zero before the 90 ms break time and the RMS break fault contribution is given by the DG units in the HV area. The FLM device does not provide results for the break level.

It can be noticed that the motor contribution in IPSA is much lower than the FLM results, the difference being 63.9 % for maximum load and 36.8 % for modal load.

Table 4-13 in Section 4.5.3 shows the variation of the downstream peak fault level results with the Gaussian filter, as extracted from the Pronto software. The maximum and minimum downstream peak values are 4.32 kA and 4.14 kA respectively, close to the recommended value of 4.27 kA. Even if the IPSA results are compared to the minimum value of 4.14 kA, differences are still large (34.7 % for maximum load and 62.8 % for modal load scenario).

This poses relevant questions whether the ER G74 and ETR 120 guidelines are still valid for the network and load mix of today in the Irlam area.

Table 5-14 Downstream Fault Level Results (System Normal) - Irlam

Irlam 6.6 kV Location (Downstream Contribution)		Make			Break		Make	Break	Voltage
		kA	kA	kA	kA	kA	%	%	kV
		DG	G74	Total	DG	G74	Total	Total	-
FLM		-	-	4.27	-	-	-	-	-
IPSA	Maximum Load	0.06	2.64	2.70	0.03	0.00	36.8%	-	0.99
	Modal Load	0.06	1.49	1.54	0.03	0.00	63.9%	-	1.01
	Minimum Load	0.05	1.18	1.23	0.03	0.00	71.2%	-	0.99

Table 5-15 shows the comparison of the fault levels obtained from the final IPSA Network Model against the FLM results, when the G74 models are modified to provide 2 MVA fault contribution per 1 MVA of load.

Figure 5-9 shows the peak downstream results for the two cases (1 MVA and 2 MVA per 1 MVA of load respectively) against FLM results. The orange continuous line shows the recommended FLM value (4.27 kA), while the dashed ones show the extreme values (4.32 kA and 4.14 kA) taken from Table 4-13 in Section 4.5.3.

The results of the default 1MVA/MVA of Load Infeed G74 model are much smaller than the FLM results irrespective of the load scenarios studied. With the variation of 2MVA/MVA of Load Infeed G74 model being applied, the resultant downstream peak currents from the IPSA model increase from 1.54 kA to 3.00 kA, giving a 29.8 % difference in the modal load scenario.

The results suggest that for this location, the G74 model variation to provide 2 MVA fault contribution per 1 MVA of load is more compatible with the FLM results than the default G74 model, for both maximum load and modal load scenarios.

Table 5-15 General Fault Level Results (System Normal) for 2MVA/MVA of Load Infeed - Irlam

Irlam 6.6kV Location		Make			Break			Primary Voltage
		Upstream	Downstream	Total	Upstream	Downstream	Total	
		kA	kA	kA	kA	kA	kA	kV
FLM		29.40	4.27	33.67	11.63	-	-	-
IPSA	Maximum Load	32.15	5.37	37.51	11.92	0.02	11.94	1.00
	Modal Load	32.31	3.00	35.32	11.75	0.01	11.77	1.00
	Minimum Load	31.98	2.40	34.37	11.66	0.03	11.68	0.99
		%	%	%	%	%	%	
FLM								
IPSA	Maximum Load	-9.3%	-25.8%	-11.4%	-2.5%	-	-2.7%	
	Modal Load	-9.9%	29.8%	-4.9%	-1.0%	-	-1.2%	
	Minimum Load	-8.8%	43.8%	-2.1%	-0.3%	-	-0.4%	

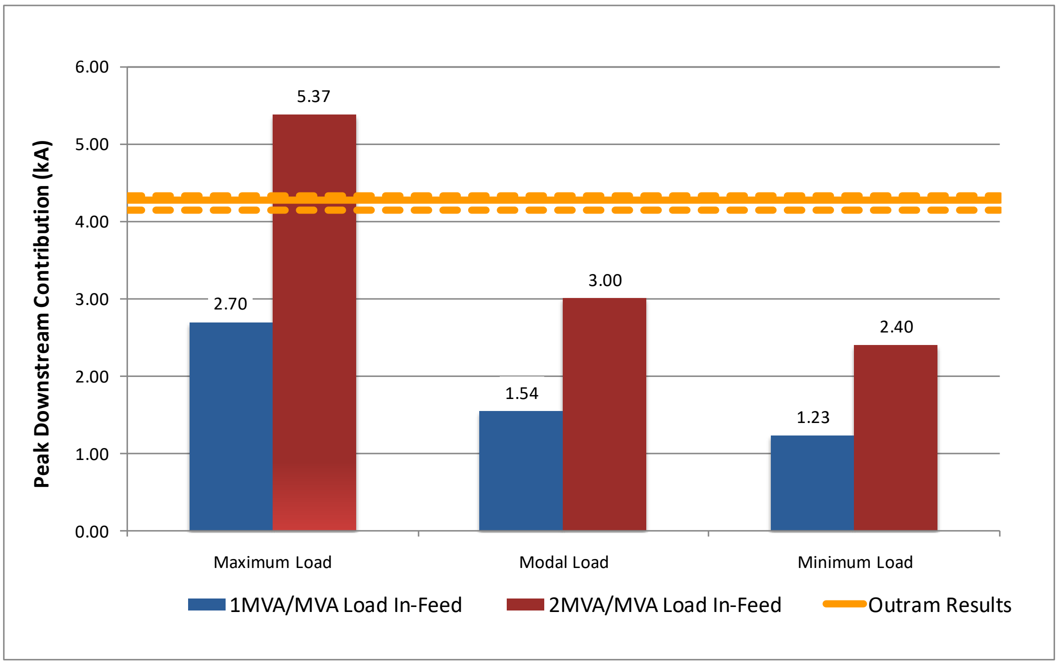


Figure 5-9 General Load Fault In-Feed Variation against FLM Results - Irlam

5.3.4 Wigan Location

General Results

Table 5-16 shows the comparison of fault levels obtained from the final IPSA Network Model against the FLM results.

No DG units with a rated capacity more than 200 kW are modelled in the HV network; therefore the downstream contribution in the table is composed of the G74 models only.

The voltage at the Wigan 33 kV bus has also been shown in each load demand scenario in order to study pre-fault voltage impact on the fault level results.

The comparison between fault level results of IPSA and FLM shows large differences, up to 30.8 % for peak make and up to 10.1 % for break. It is very likely that the total peak make results are even lower than 18.43 kA, as this value represents the arithmetic sum of the upstream and downstream components.

Figure 5-10 shows the differences in the total fault level results against FLM values, in percentage.

The upstream and downstream results are discussed separately in subsequent sections.

Table 5-16 General Fault Level Results (System Normal) - Wigan

Wigan 33kV Location (General Results)		Make			Break			Primary Voltage
		Upstream	Downstream	Total	Upstream	Downstream	Total	
		kA	kA	kA	kA	kA	kA	kV
FLM		16.83	1.60	18.43	7.51	-	-	-
IPSA	Maximum Load	22.72	1.42	24.11	8.27	0.00	8.27	1.01
	Modal Load	22.54	0.69	23.23	8.16	0.00	8.16	1.00
	Minimum Load	22.57	0.59	23.15	8.27	0.00	8.27	1.00
		%	%	%	%	%	%	
FLM								
IPSA	Maximum Load	-35.0%	11.2%	-30.8%	-10.2%	-	-10.1%	
	Modal Load	-33.9%	56.8%	-26.0%	-8.6%	-	-8.6%	
	Minimum Load	-34.1%	63.4%	-25.6%	-10.2%	-	-10.1%	

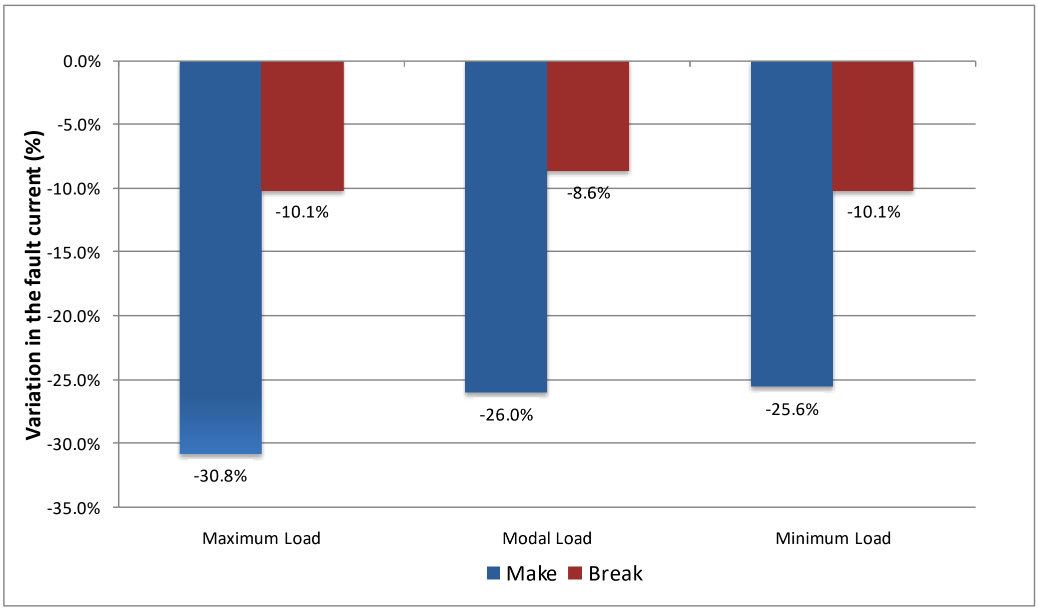


Figure 5-10 Variation of the Total Current Contribution with Load against FLM Results - Wigan

<u>Sensitivity of Fault Currents to the Transformer Voltage Set Point/Transformer Tap Position</u>

The tap positions of the 132/33 kV transformers in Wigan will influence the fault level results due to the change of pre-fault voltage at the 33 kV terminals. For modal case, the voltage set-point has been changed from 1.00 p.u. to 1.01 p.u. and then to 0.98 p.u. in order to replicate the voltage variation seen by FLM based on 10 minutes average values (Table 4-10).

The results show that a voltage variation from 1.00 p.u to 0.98 p.u reduces the fault levels as expected. For example, the peak make upstream fault levels decrease from 22.54 kA to 22.37 kA, making difference reduction between IPSA and FLM values from 35.0 % to 32.9 % in the modal load scenario.

Figure 5-11 shows the sensitivity of the upstream contribution with the voltage at Wigan 33 kV bus.

Table 5-17 Sensitivity of Fault Currents with Voltage (Modal Load Case) - Wigan

Wigan 33kV Location	Make			Break			Voltage
	Upstream	Downstream	Total	Upstream	Downstream	Total	
	kA	kA	kA	kA	kA	kA	kV
FLM	16.83	1.60	18.43	7.51	-	-	-
IPSA	22.54	0.69	23.23	8.16	0.00	8.16	1.00
	22.37	0.69	23.07	8.10	0.00	8.10	0.98
	22.73	0.69	23.41	8.21	0.00	8.21	1.01
	%	%	%	%	%	%	
FLM							
IPSA	-33.9%	56.8%	-26.0%	-8.6%	-	-8.6%	
	-32.9%	56.7%	-25.2%	-7.9%	-	-7.9%	
	-35.0%	56.6%	-27.0%	-9.3%	-	-9.4%	

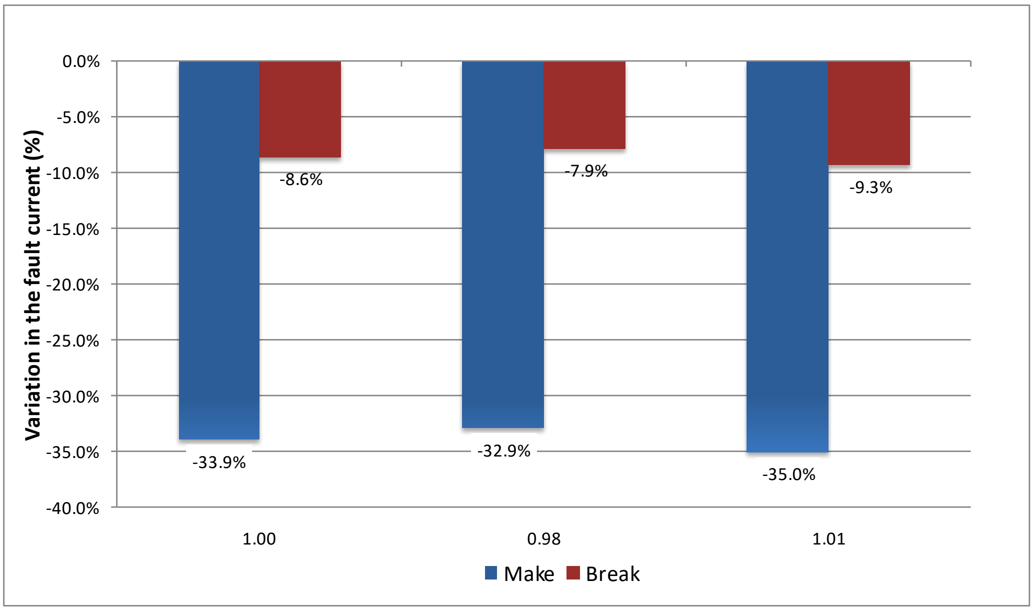


Figure 5-11 Variation of the Upstream Current Contribution with Voltage against FLM Results (Modal Load Case) - Wigan

<u>Upstream Contribution Discussion</u>

Table 5-18 shows the comparison of the upstream fault level contribution from the final IPSA Network Model against the FLM results, for different network operating scenarios. Results show large differences in both break and peak upstream values.

In the case of break, the differences are 10.2 % for maximum load and 8.6 % for modal load scenario. The differences in peak make are even larger, up to 35.0 % for maximum load and 33.9 % for modal load scenario. These differences are much larger compared to the Denton West and Irlam locations, where the maximum differences are 3.1 % for break and 10.1 % for peak make.

Wigan Grid is supplied by Washway Farm GSP and Kirkby GSP via two 132/33 kV 90 MVA OFAF transformers. Recent changes in the 132 kV area upstream Wigan have been made to the IPSA Master Network, in particular the connection of the Kirkby new transformer which is expected to have increased the fault level in the area. The operating scheme in the area modelled in the IPSA Master Network may not be consistent with the actual NGET operating diagram, a matter outside ENWL decision. This may explain the large difference in the upstream fault level between IPSA network and FLM.

Compared to FLM upstream values, IPSA network model generates higher fault level values for both break and peak.

The IPSA values seem to be closer to the 'maximum extreme' values presented in Table 4-14 in Section 4.5.4.

The upstream contribution is not as largely dependent on load as the downstream contribution via the G74 models.

Table 5-18 Upstream Fault Level Results - Wigan

Wigan 33kV Location (Upstream Contribution)			Make	Break	Make	Break	Voltage
			kA	kA	%	%	kV
FLM			16.83	7.51	-	-	-
IPSA	System Normal	Maximum Load	22.72	8.27	-35.0%	-10.2%	1.01
		Modal Load	22.54	8.16	-33.9%	-8.6%	1.00
		Minimum Load	22.57	8.27	-34.1%	-10.2%	1.00
	Wigan 'gt1' transformer out	Maximum Load	10.82	4.04	35.7%	46.2%	1.00
		Modal Load	10.80	3.92	35.8%	47.8%	1.00
		Minimum Load	10.73	3.89	36.2%	48.2%	0.99

Downstream Contribution Discussion

The results in Table 5-16 show that the variation of load in the IPSA network affects the peak make downstream fault current while the break fault remains generally constant, in this case being zero as there are no DG in the HV area. This is expected because the ENWL G74 model current contribution decays to zero before the 90 ms break time.

This section refers only to peak downstream, as FLM device does not provide results for the break level.

It can be noticed that the motor contribution in IPSA is much lower than the FLM results, the difference being 11.2 % for maximum load and 56.8 % for modal load.

Table 4-14 in Section 4.5.4 shows the variation of the downstream peak fault level results with the Gaussian filter, as extracted from the Pronto software. The maximum and minimum downstream peak values are 1.62 kA and 0.73 kA respectively. If the IPSA results are compared to the minimum value of 0.73 kA, differences are 94.5 % for maximum load and 5.5 % for modal load scenario.

This poses relevant questions whether the ER G74 and ETR 120 guidelines are still valid for the network and load mix of today in the Wigan Grid area.

Table 5-19 shows the comparison of the fault levels obtained from the final IPSA Network Model against the FLM results, when the G74 models are modified to provide 2 MVA fault contribution per 1 MVA of load.

Figure 5-12 shows the peak downstream results for the two cases (1 MVA and 2 MVA per 1 MVA of load respectively) against FLM results. The orange continuous line shows the recommended FLM value (1.60 kA), while the dashed ones show the extreme values (1.62 kA and 0.73 kA) taken from Table 4-14 in Section 4.5.4.

The results of the default 1MVA/MVA of Load Infeed G74 model are much smaller than the FLM results irrespective of the load scenarios studied. With the variation of 2MVA/MVA of Load Infeed G74 model being applied, the resultant downstream peak currents from the IPSA model increase from 0.69 kA to 1.36 kA, giving a 14.9 % difference in the modal load scenario.

The results suggest that for this location, the G74 model variation to provide 2 MVA fault contribution per 1 MVA of load is more compatible with the FLM results than the default G74 model for modal load scenario. For maximum load scenario, the default G74 model (1 MVA/MVA) is more compatible with the FLM results than the 2 MVA/MVA G74 model.

Table 5-19 General Fault Level Results (System Normal) for 2MVA/MVA of Load Infeed - Wigan

Wigan 33kV Location		Make			Break			Primary Voltage
		Upstream	Downstream	Total	Upstream	Downstream	Total	
		kA	kA	kA	kA	kA	kA	kV
FLM		16.83	1.60	18.43	7.51	-	-	-
IPSA	Maximum Load	22.66	2.67	25.29	8.27	0.00	8.27	1.01
	Modal Load	22.52	1.36	23.87	8.16	0.00	8.16	0.99
	Minimum Load	22.55	1.14	23.68	8.16	0.00	8.16	1.00
		%	%	%	%	%	%	
FLM								
IPSA	Maximum Load	-34.7%	-66.8%	-37.2%	-10.1%	-	-10.2%	
	Modal Load	-33.8%	14.9%	-29.5%	-8.6%	-	-8.6%	
	Minimum Load	-34.0%	28.6%	-28.5%	-8.6%	-	-8.6%	

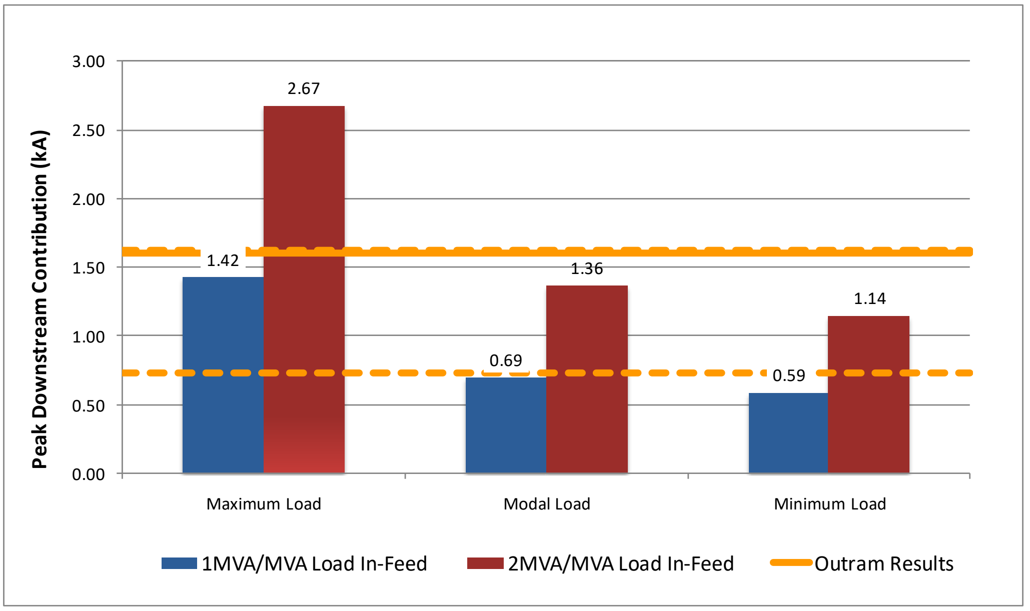


Figure 5-12 General Load Fault Infeed Variation against FLM Results - Wigan

5.3.5 Further Considerations Regarding the Upstream Contribution

For Denton West, Irlam and Wigan, the differences in upstream peak make are higher than the 90 ms RMS break values, with the IPSA peak values being generally above the FLM results. A more detailed analysis is undertaken for these three locations to further understand the differences in the asymmetrical peak fault values.

The FLM also provides, as an additional feature, the 10 ms RMS values. These values have been extracted from the Pronto software by selecting the same filter value as recommended for the 10 ms peak make.

Starting from the 10 ms peak make and 10 ms RMS values extracted from the Pronto software, the DC component and X/R ratio have been calculated based on the following formulas below and are presented in Table 5-20:

$$I_{peak} = \sqrt{2} \times I_{rms} \times (1 + e^{-\pi \times R/X})$$

$$I_{dc} = I_{peak} - \sqrt{2} \times I_{rms},$$

Nominal voltage was used in the calculation.

The IPSA fault level components have been extracted from the IPSA fault level results (maximum load scenario selected) and are presented in Table 5-20. The X/R values calculated by IPSA are generally similar to the one calculated from the FLM measurements.

Table 5-20 Upstream Contribution Fault Components at 10 ms

FLM Results									
Location	**Voltage**	**10ms peak**	**10ms RMS**	**DC component**	**% DC component**	**X/R**	**Z**	**R**	**X**
	kV	**kA**	**kA**	**kA**	**%**	**-**	**p.u.**	**p.u.**	**p.u.**
Broadheath	11	29.56	11.03	13.96	89.5	28.3	0.476	0.017	0.476
Denton West	6.6	34.84	13.98	15.07	76.2	11.6	0.626	0.054	0.623
Irlam	6.6	29.4	11.84	12.66	75.6	11.2	0.739	0.066	0.736
IPSA Results									
Broadheath	11	30.47	11.24	14.59	91.8	23.8	0.511	0.021	0.510
Denton West	6.6	37.26	13.76	17.80	91.5	15.5	0.694	0.045	0.693
Irlam	6.6	32.19	11.90	15.36	91.3	17.3	0.806	0.047	0.805

Note 1: All impedances are presented in p.u. on 100 MVA base.

Note 2: Minor differences between the IPSA 10 ms peak results in the table and throughout the report can be explained by the exclusion of the G74 models that slightly influence the pre-fault voltage profile.

The IPSA fault calculation process works on admittance and voltage matrices, from which it calculates the fault MVA and current. When the program has calculated the DC fault current (or fault MVA), it works out the X/R ratio.

The current IPSA version (2.6) has two methods of calculating the DC X/R ratio:

- Method a. Driving point impedance

The driving point impedance method calculates the DC resistance and reactance at time zero. It assumes that neither value will change with time.

- Method b. DC decay

The DC decay method assumes that the DC fault current decays according to the formula:

$$I_{dc} = I_{dco} e^{(-2\pi \times f \times t \times (R/X))}$$

IPSA calculates the DC current at time zero and time t using matrix calculations. It also calculates the DC reactance at time zero. It then assumes that the DC reactance does not change and then the above equation can be used to derive the DC resistance at time t > 0:

$$R = -X_o \log(I_{dc} / I_{dco}) / (2\pi \times f \times t)$$

The DC decay method works well when the network contains large synchronous machines and “realistic” smaller machine models. It can run into issues when equivalent machines are added to the network to represent fault infeeds, since the impedances of those machines are calculated to match given fault currents at one or two specified times. Depending upon the formula used to calculate those impedances, there are combinations of fault current and time which will produce machine parameters that are not “real”, one extreme example being synchronous machines with negative transient reactance. The DC decay method may not be the most appropriate in such cases. Applying the DC decay method for the three locations generates much higher X/R values compared to the FLM device.

The DC X/R and impedance values listed in Table 5-20 are however calculated with a new method. This method also considers that the Thevenin DC impedance can change with time, but instead of assuming an exponential decay according to the formula above, it calculates the DC resistance and reactance directly from the impedance matrix at time t > 0. The new method therefore provides a snapshot of the DC resistance and reactance at a given moment in time and is considered to be more appropriate for comparisons with the FLM device. This alternative method will be included in a new version of IPSA after the validation process on a variety of test networks has been completed.

It is important to note that this new method does not affect the actual fault currents themselves; apart from the X and R values the same results will be obtained as with the DC decay method.

5.4 Peak Downstream Detailed Analysis

5.4.1 Methodology

The scope of this analysis is to provide a general understanding on the validity of the ENWL G74 model for the locations studied and to confirm the conclusions of the previous section with respect to the peak downstream component. It is not intended to provide results for the most probable fault level for the entire period of measurements.

While this additional analysis is mainly focused on Primary locations directly supplying the HV feeders, the results of Wigan 33 kV study have also been included.

The Pronto software allows for the recorded data to be lumped into different intervals. The process of smoothing/lumping involves sliding a fixed sized window over data and taking the average of the values in the window at each point.

For each location, the entire period of measurement has been divided into 6 hours intervals and multiple IPSA fault level studies were simulated for each location, via an in-house script, as detailed below. The results were compared against the corresponding FLM results and then plotted against time. The methodology is summarised in the flowchart from Figure 5-13.

For each location, the peak downstream fault level results were lumped into 6 hours intervals and exported from the Pronto software into a spreadsheet format. This spreadsheet format is the matrix version of the 3D graphs produced by Pronto. The filtering values used in Pronto are consistent with the ones recommended in the Outram report (Table 5-21). The overall most probable fault levels shown by Pronto after lumping the fault level data into 6 hours intervals match the ones recommended in the Outram report, i.e. where no lumping has been applied (Table 5-21).

The spreadsheet format to which the lumped fault level data has been exported allows the user to easily manipulate the data and identify the relevant information. For each 6 hours time interval, the fault level with the maximum weight has been selected as representative for that specific 6 hours time interval, i.e. the most probable fault level during that interval. The time intervals with zero weight (i.e. no events) have been excluded from the analysis. This reduced the number of the studied operating points to 217 for Broadheath, 176 for Denton West, 176 for Irlam and 232 for Wigan.

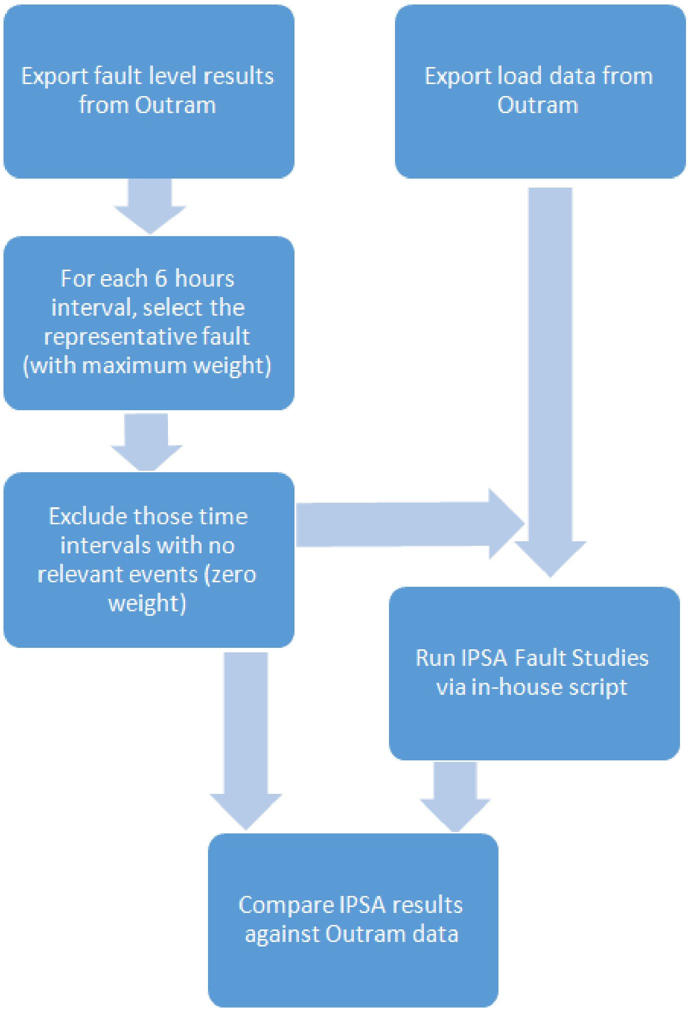


Figure 5-13 Flow chart Illustrating the Methodology used for Peak Downstream Detailed Analysis

Table 5-21 Peak Downstream Results and Corresponding Gaussian Filters

Location	Fault Level	Gaussian Filter (%)
Broadheath Primary	3.22	7
Denton West Primary	3.47	6
Irlam Primary	4.27	3
Wigan BSP	1.6	2

As shown in Section 4.4, the presentation of Fault Level results (and weighting data) against time in the standard Pronto graphing system may not be recognisable and will generally never produce the same average results as might be expected from the Fault Level 2D and 3D graphic presentations. This explains extreme values of FLM results seen in the following graphs that do not seem to be relevant in the

2D and 3D graphic presentations, e.g. they have low weight values. The weight refers to how much notice should be taken of each disturbance when estimating the fault level and it is linked to the size and the quality of the disturbance.

In order to compare the IPSA and FLM fault level results, the FLM current representing the load and power factor measurements have been lumped into 6 hours intervals and exported from the Pronto software, in a similar manner as presented above for the FLM fault results. Maximum RMS break values of phase 'Ia' together with corresponding power factor have been modelled into IPSA for fault level studies by updating the loads and the ENWL G74 models at the studied locations.

The current (load) and the power factor values corresponding to those time intervals with zero weight of the predicted fault levels have been excluded from the ISPA fault level analysis.

For the purpose of this analysis, the EHV IPSA Master Network Model has been used, without considering the HV feeders in Primary locations. For simplification, due to their low capacity, the 250 kW DG unit in Irlam HV area and the 210 kW DG unit in Broadheath area have been ignored as their presence is not expected to change the conclusions of this additional analysis.

The sensitivity of fault level to general load contribution is studied by re-running the fault level studies with a variation of the G74 model that produces 2 MVA of initial symmetrical fault contribution per 1 MVA load.

Appendix I present additional results in graph format, for each location.

For each location, the IPSA fault level results seem to provide similar fault level results for small variations of load; this is explained by the fact that the ENWL G74 model is limited to 1 MVA increments in the IPSA Network Model, as explained in Section 3.

5.4.2 Broadheath Location

As presented above, the maximum RMS values of phase 'Ia' have been extracted from FLM as representative for the load profile simulated in the IPSA software. Figure 5-14 showing the voltage and current profiles for the full recorded period highlights a spike in the current of phase 'Ia' on 19/03/2016. This current value and the corresponding point in time have been excluded from the analysis as it does not represent a consumption simulated to calculate the G74 model contribution.

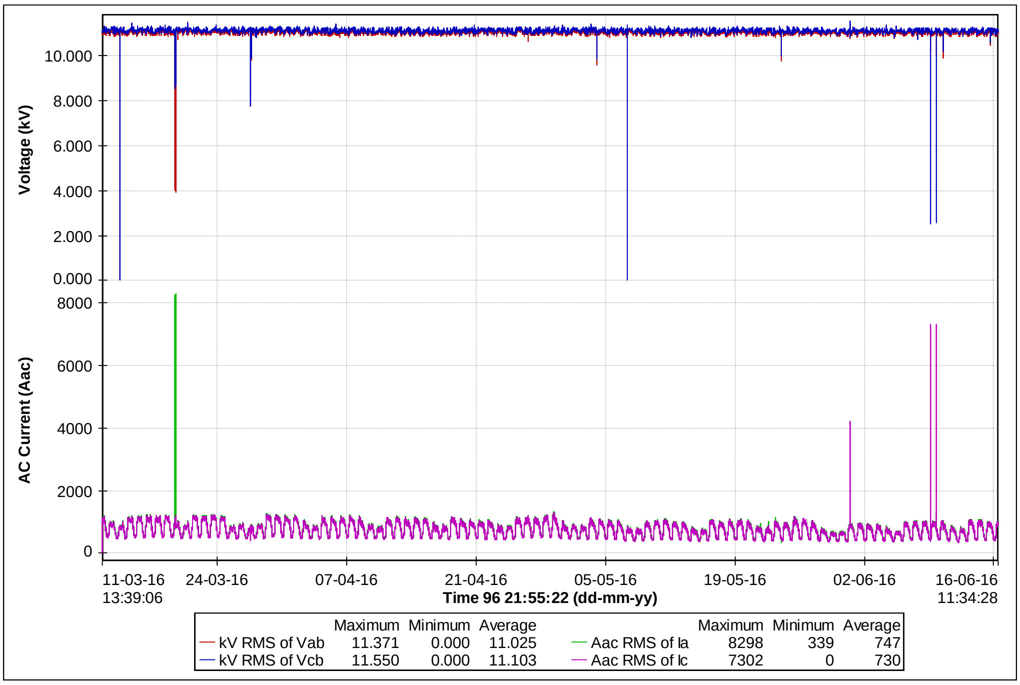


Figure 5-14 Voltage and Current Profiles - Broadheath

Figure 5-15 shows the G74 model peak downstream results for the two cases (1 MVA and then 2 MVA of initial symmetrical fault contribution per 1 MVA of load) against FLM results. The results suggest that for this location, the G74 model variation to provide 2 MVA fault contribution per 1 MVA of load is generally more compatible with the FLM results than the default G74 model.

Figure 5-15 shows number of IPSA fault level values for several bins of % difference against FLM results. The 1 MVA G74 Model has the largest number of results within 40 % to 75 % difference from the FLM results, while for the 2 MVA G74 model, the 5 % to 20 % difference interval is the one with the largest number of results.

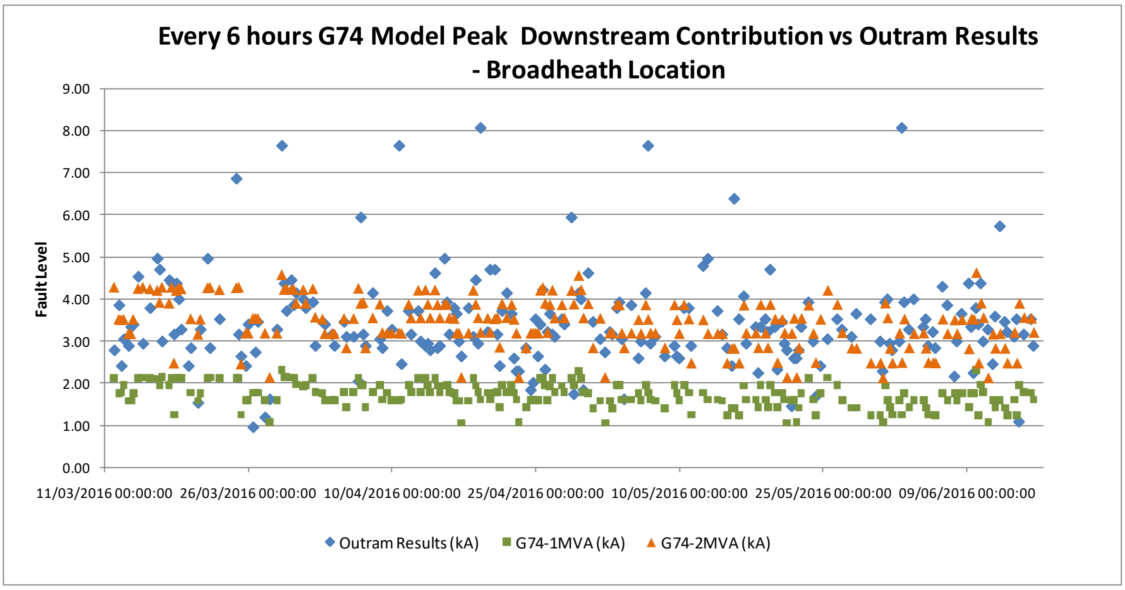


Figure 5-15 Every 6 hours G74 Model Peak Downstream Contribution vs FLM Results - Broadheath Location

Table 5-22 Number of IPSA Fault Level Values for Several Bins of % Difference against FLM Results - Broadheath Location

% Difference Bin	Number of values (G74-1MVA)	Number of values (G74-2MVA)
0% to 1%	1	8
1% to 2%	0	6
2% to 5%	3	27
5% to 10%	1	38
10% to 20%	4	55
20% to 25%	4	20
25% to 30%	7	12
30% to 35%	14	10
35% to 40%	19	12
40% to 50%	63	7
50% to 75%	93	12
75% to 100%	7	2
100% to 150%	0	4
150% to 270%	0	3

5.4.3 Denton West Location

Figure 5-16 shows the G74 model peak downstream results for the two cases (1 MVA and 2 MVA per 1 MVA of load respectively) against FLM results. The results suggest that for this location, the FLM fault results are generally equidistant between the results of the 2 MVA/MVA and 1 MVA/MVA IPSA G74 models.

Table 5-23 shows the number of IPSA fault level values for several bins of % difference against FLM results. The 1 MVA G74 Model has the largest number of results within 40 % to 75 % difference from the FLM results, while for the 2 MVA G74 model, the 5 % to 20 % difference interval is the one with the largest number of results. It can be noticed that a relatively large number of fault values generated by the 2 MVA/MVA G74 model in IPSA are more than double the FLM values. This is due to some low fault level values in Pronto and this is consistent with the conclusions in Section 4.5.2.

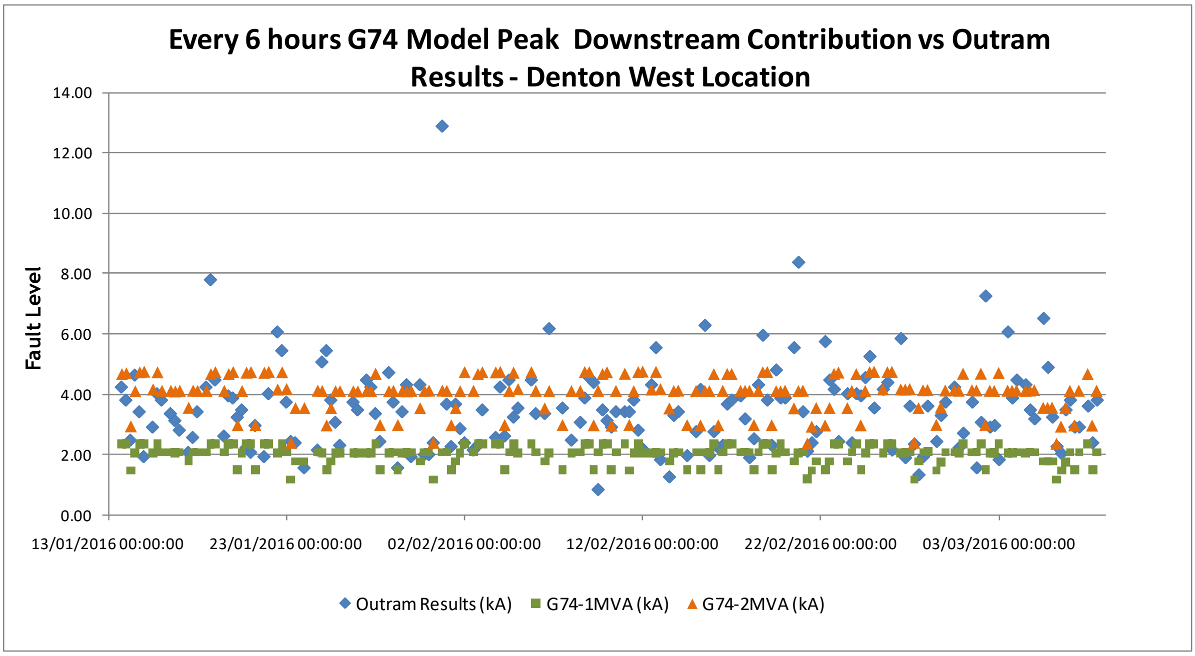


Figure 5-16 Every 6 hours G74 Model Peak Downstream Contribution vs FLM Results - Denton West Location

Table 5-23 Number of IPSA Fault Level Values for Several Bins of % Difference against FLM Results - Denton West Location

% Difference Bin	Number of values (G74-1MVA)	Number of values (G74-2MVA)
0% to 1%	1	2
1% to 2%	0	3
2% to 5%	8	13
5% to 10%	9	20
10% to 20%	12	34
20% to 25%	8	17
25% to 30%	9	9
30% to 35%	17	12
35% to 40%	20	8
40% to 50%	44	13
50% to 75%	44	15
75% to 100%	3	8
100% to 500%	1	22

5.4.4 Irlam Location

Figure 5-17 shows the G74 model peak downstream results for the two cases (1 MVA and 2 MVA per 1 MVA of load respectively) against FLM results. The results suggest that for this location, the G74 model variation to provide 2 MVA fault contribution per 1 MVA of load is generally more compatible with the FLM results than the default G74 model.

Table 5-24 shows number of IPSA fault level values for several bins of % difference against FLM results. The 1 MVA G74 Model has the largest number of results within 40 % to 75 % difference from the FLM results, while for the 2 MVA G74 model, the 5 % to 25 % difference interval is the one with the largest number of results.

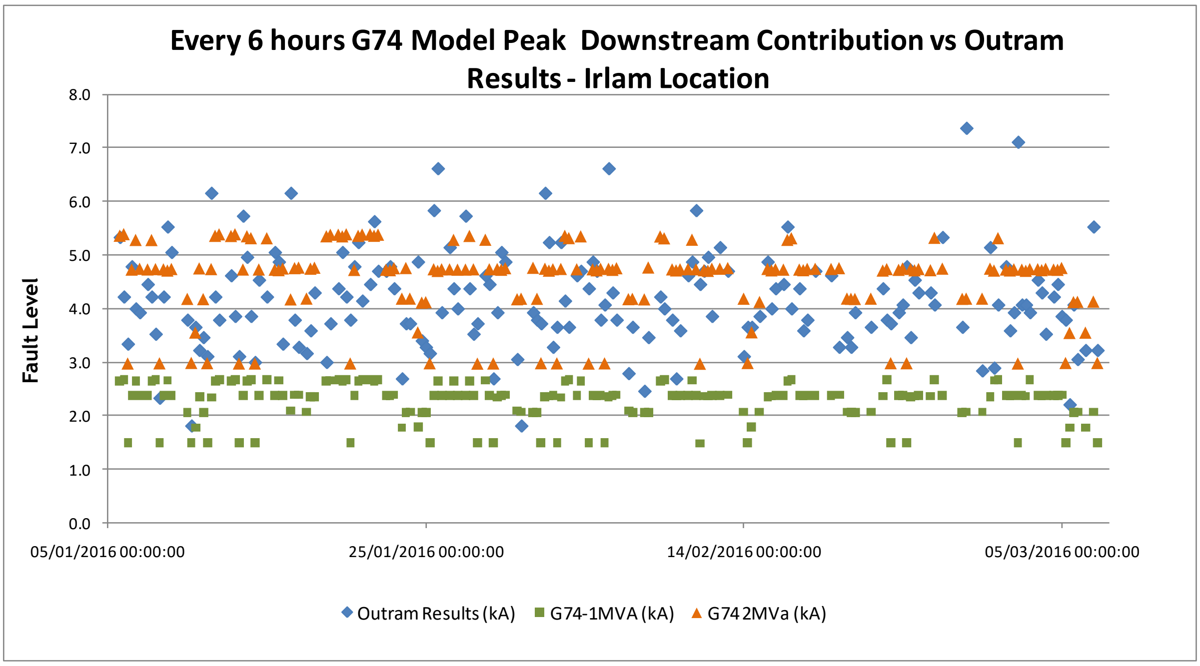


Figure 5-17 Every 6 hours G74 Model Peak Downstream Contribution vs FLM Results - Irlam Location

Table 5-24 Number of IPSA Fault Level Values for Several Bins of % Difference against FLM Results - Irlam Location

% Difference Bin	Number of values (G74-1MVA)	Number of values (G74-2MVA)
0% to 1%	0	7
1% to 2%	0	5
2% to 5%	0	17
5% to 10%	1	27
10% to 20%	6	30
20% to 25%	2	28
25% to 30%	10	18
30% to 35%	20	18
35% to 40%	26	6
40% to 50%	58	11
50% to 75%	52	7
75% to 100%	1	1
100% to 500%	0	1

5.4.5 Wigan Location

Figure 5-18 shows the G74 model peak downstream results for the two cases (1 MVA and 2 MVA per 1 MVA of load respectively) against FLM results. The results suggest that for this location, the default G74 model variation to provide 1 MVA fault contribution per 1 MVA of load is generally more compatible with the FLM results than the G74 model that provides 2 MVA/MVA fault infeed.

Table 5-25 shows number of IPSA fault level values for several bins of % difference against FLM results. The 1 MVA G74 Model has the largest number of results within 10 % and 30 % difference from the FLM results, while for the 2 MVA G74 model, the 40 % to 75 % difference interval is the one with the largest number of results.

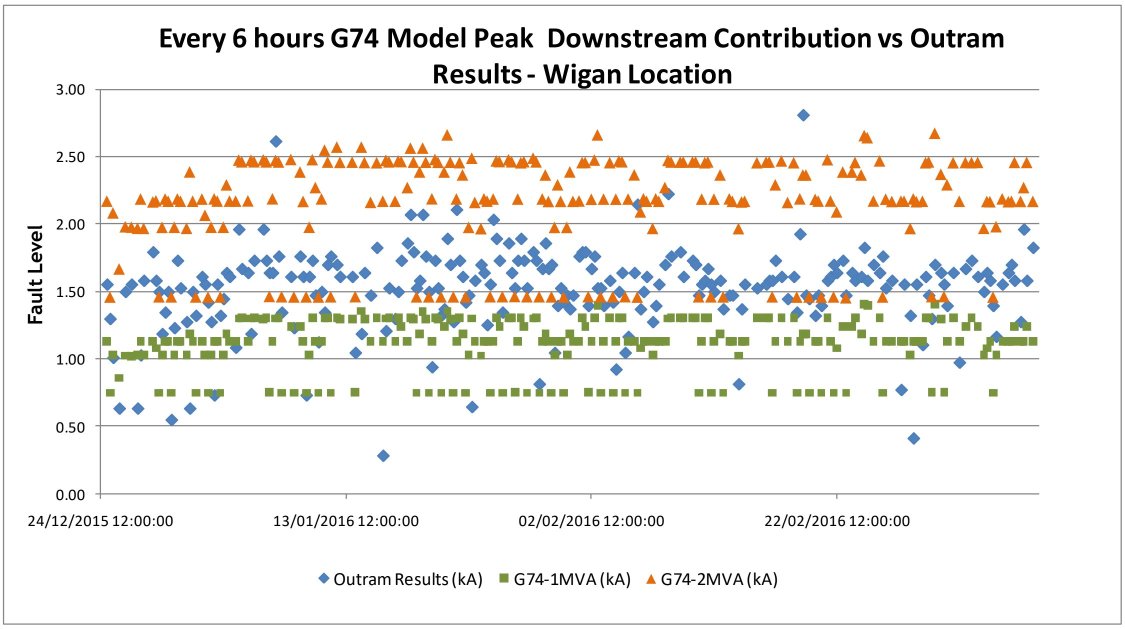


Figure 5-18 Every 6 hours G74 Model Peak Downstream Contribution vs FLM Results - Wigan Location

Table 5-25 Number of IPSA Fault Level Values for Several Bins of % Difference against FLM Results – Wigan Location

% Difference Bin	Number of values (G74-1MVA)	Number of values (G74-2MVA)
0% to 1%	0	2
1% to 2%	1	1
2% to 5%	6	13
5% to 10%	6	11
10% to 20%	40	18
20% to 25%	44	7
25% to 30%	43	10
30% to 35%	30	21
35% to 40%	12	22
40% to 50%	28	49
50% to 75%	18	53
75% to 100%	1	5
100% to 150%	1	11
150% to 350%	2	7
350% to 700%	0	2

5.5 Conclusions

5.5.1 Upstream Contribution Fault Component

Table 5-26 shows a summary of the differences between FLM and IPSA results, for upstream contributions, based on the results of Section 5.3. All the differences are percentage (%) related to FLM results.

Table 5-26 Summary of FLM vs. IPSA Upstream Contributions

Location	Load Scenario	Peak Make	RMS Break
		%	%
Broadheath	Maximum Load	-2.8%	-9.7%
	Modal Load	-3.5%	-9.1%
Denton West	Maximum Load	-6.7%	3.1%
	Modal Load	-7.3%	3.0%
Irlam	Maximum Load	-8.9%	-1.7%
	Modal Load	-10.1%	-1.0%
Wigan	Maximum Load	-35.0%	-10.2%
	Modal Load	-33.9%	-8.6%

Broadheath 11 kV location

In the case of RMS break, the differences are relatively high: 9.7 % for maximum load and 9.1 % for modal load scenario (Table 5-26). IPSA break results are larger than FLM estimated values.

However, in the case of peak make, the differences are smaller: 2.8 % for maximum load and 3.5 % for modal load scenario and represent the smallest peak make differences among all four locations. The IPSA model has more peak fault contribution from the upstream network.

The differences of fault levels between FLM and IPSA in Broadheath do not follow the same pattern as seen in other three locations, where differences in RMS break are smaller than the peak make ones. For Broadheath, the differences in RMS break between FLM and IPSA results (almost 1 kA) could be explained by the possible inconsistency of 132 kV grid in Altrincham area between the IPSA Master Network and the actual operating scheme during the period of measurements, the relative modest disturbance energy seen by the device and the larger room for interpretation of the results in Pronto software compared to the other locations.

The upstream contribution is not as largely dependent on load as the downstream contribution via the G74 models.

Denton West and Irlam 6.6 kV Locations

Denton West and Irlam locations have similar conclusions. In the case of break, the differences are generally small: 3.1 % for maximum load and 3.0 % for modal load scenarios in Denton West and 1.7 % for maximum load and 1.0 % for modal load scenarios in Irlam (Table 5-26). These results can be considered satisfactory and suggest a high level of confidence in the modelling of the network. IPSA break results are smaller than FLM estimated values in Denton West and larger in Irlam.

The differences in peak make are generally larger, 6.7 % for maximum load and 7.3 % for modal load scenarios in Denton West and 8.9 % for maximum load and 10.1 % for modal load scenarios in Irlam (Table 5-26). The IPSA model has more peak fault contribution from the upstream network than the value estimated by FLM. Break and peak currents are derived from the same data, break depends on the absolute value of impedance while the peak is influenced by the phase, being expected to be noisier than the RMS results.

The upstream contribution is not as largely dependent on load as the downstream contribution via the G74 models.

Wigan 33 kV Location

In Wigan case, results show large differences in both break and peak upstream values. In the case of break, the differences are 10.2 % for maximum load and 8.6 % for modal load scenario, while the differences in peak make are up to 35.0 % for maximum load and 33.9 % for modal load scenario (Table 5-26). Compared to

FLM upstream values, IPSA network model generates higher fault level values for both break and peak.

A possible explanation for the large differences could be the 132 kV network model of the Wigan area. Wigan Grid is supplied by Washway Farm GSP and Kirkby GSP via two 132/33 kV 90 MVA transformers. Recent changes in the 132 kV area upstream Wigan have been made to the IPSA Master Network, in particular the connection of the Kirkby new transformer which has most likely increased the general fault level in the area.

The operating scheme in the area modelled in the IPSA Master Network may not be consistent with the actual NGET operating diagram.

5.5.2 Downstream Contribution and G74 Models

The downstream contribution is mainly composed of the G74 models. There are no DG units with a capacity of more than 200 kW modelled in the Denton West and Wigan areas. In Broadheath and Irlam, a 210 kW mini CHP and a 250 kW solar park respectively are modelled in the HV network each having an estimated contribution of less than 0.1 kA peak make and less than 0.05 kA RMS break at the corresponding Primary buses.

As the fault contribution of the DG units in Broadheath and Irlam have been considered, it is very unlikely, assuming they have been operated throughout the entire period of measurements, that these generating units would have a much larger fault contribution to cause the fault current differences between IPSA and FLM results.

In all the locations, the IPSA fault level results are consistently smaller than the FLM values. The G74 model provides 1 MVA initial symmetrical fault contribution for each 1 MVA of load, consistent with the ER G74.

The maximum and modal load scenarios have been used for the comparison, and the minimum load has been added as a sensitivity analysis. Results show that the variation of load in the IPSA network affects the peak make downstream fault current while the RMS break fault remains generally constant. This is expected because the ENWL G74 model current contribution decays to zero before the 90 ms break time and the RMS break fault contribution is given by the DG units in the HV area, if present.

This poses relevant questions whether the ER G74 and ETR 120 guidelines are still valid for the network and load mix of today in the three areas studied.

The FLM does not provide results for the break level from downstream network.

Sensitivity analysis has been undertaken by considering a variation of the default G74 model modified to provide 2 MVA initial symmetrical fault contribution for each 1 MVA of load.

For Broadheath and Irlam, the results suggest that the G74 model variation (2 MVA/MVA of load) is more compatible with the FLM results than the default G74 model (1 MVA/MVA of load) for both maximum load and modal load scenarios.

For Denton West location, the results suggest that the G74 model variation (2 MVA/MVA of load) is more compatible with the FLM results than the default G74 model (1 MVA/MVA of load) for the modal load scenario. For the maximum load scenario, the FLM fault results are quite equidistant between the IPSA results of the two G74 models.

For Wigan, the results suggest that the G74 model variation (2 MVA/MVA of load) is more compatible with the FLM results than the default G74 model (1 MVA/MVA of load) for modal load scenario. For maximum load scenario, the default G74 model is more compatible with the FLM results than the G74 model variation.

The results suggest that, for these initial four locations, the G74 model peak make fault contribution may be underestimated and that the ER G74 may need to be revised to reflect the change in load mix of today. It should be noted that ER G74 was developed in 1992 and since then the load mix and appliances used in commercial and industrial environments may have changed.

The G74 model contribution modelled in the IPSA Master Network is highly dependent on the load. Therefore, it is important to carefully choose the load scenarios in the fault level studies.

5.5.3 Discussions Regarding the Accuracy of the IPSA Network Model

For the purpose of validating the IPSA network model, it is essential that the IPSA model should be representative of the actual network for the period of measurements, and that accurate information is used for modelling the network components, network topology, load profile, motors and distributed generation operation status and their fault contribution.

The factors which may have impact on accuracy of fault level calculations using the network model are summarized as follows:

- The modelling of the passive network components (transformers, lines). It is expected that modelling the passive network components in IPSA will not introduce large errors as they are represented based on the industry best practice.
- Network topology:
    - The most recent IPSA Master Network and DINIS models have been used and updated for the validation study. It is expected that the models are well representative of the actual network in real time operation for this period of measurements
    - It is understood that additional information may be provided to TNEI if any change in topology is suspected to have been undertaken during the period of measurements.

- EHV (132 kV, 33 kV) connected generator parameters and their fault contribution are not expected to introduce large errors as they are represented in the IPSA network model based on the industry best practice/generators datasheets. In addition, the impedance of the 132/33 kV transformers and 33/11 kV or 33/6.6 kV transformers at the specified sites will normally dominate the equivalent impedance of the network seen at the faulted point, thus a slight change of the EHV connected generator parameters will have insignificant impact on fault levels at the concerned 11 kV and 6.6 kV busbars.
- NG transmission network and equivalent generators connected to the transmission network will impact the fault levels in the EMWL distribution network. It is important that the NG transmission network model, which is integrated together with the ENWL 132 kV distribution network model, is updated in the ENWL IPSA model, representing the actual normal operating conditions in the NG transmission system.
- HV (11 kV and below) connected generators parameters and their fault contribution has been modelled based on the provided data. The missing information (e.g. fault level contribution, transformer parameters) has been assumed based on generic generator characteristics thus errors could occur; however, due to the fact that the DG units in the selected locations have small capacity (max. 250 kW), differences in actual parameters compared to estimated is not expected to have a material impact on the Primary bus fault level.
- Distributed generation status during the period of measurements
    - It has been assumed that all the EHV generation was in operation during the period of measurements, consistent with their status in the ENWL IPSA Master Network Model
    - It has been assumed that the HV DG units in the selected location operated during the period of measurements; a sensitivity case has been studied by considering them switched-off
- HV Motor fault contribution and status/operation: the ENWL G74 methodology has been preserved; any methodology that estimates parameters when actual data is not available can introduce errors; a sensitivity case has been studied by considering the G74 models to produce 2 MVA of initial symmetrical fault contribution per 1 MVA of general load.
- Load profile
    - Passive loads do not contribute fault level to a faulted point, but the parameters of the G74 models depend on the total MVA consumption of the feeders in the selected locations

- The consumption influences the pre-fault voltage profile in the area, which was taken into account in the IPSA fault level study
- The load scenarios chosen to be studied in IPSA have significant impact on the G74 model peak results

5.5.4 Sources of Uncertainty in Fault Level Measurements

Based on the FLM operating procedure provided by Outram, it is understood that results may be influenced by systematic errors due to incorrect assumptions, wrong CT settings, faulty sensors, cables etc.

The switchboard CTs and VTs will introduce error in both the measurement of magnitude and the measurement of angle. The FLM utilises magnitude measurements in the calculation of RMS fault level. The calculation of peak fault level utilises both the measurement of magnitude and angle (for X/R ratio calculation) and therefore contains two possible errors. It is stated in Outram literature that at high X/R ratios, 1 degree error in phase angle measurement can cause peak fault level to be wrongly calculated by 2.5 %.

The quality of the data presented to the Fault level Monitor's algorithms depends on the size and type of the disturbances (the larger and the more abrupt the disturbance or voltage step, the better). Thus the accuracy is influenced by a low disturbance level (lack of disturbances). According to the FLM operating procedure, the FLM is capable of successfully detecting the voltage steps down to about 0.15 %.

The device works with populations of results (a form of probability density function), over specified intervals. The probabilistic nature of the algorithm needs to be taken into account when interpreting the results.

The downstream contributions depend heavily on what motors or other downstream energy sources were present and in operation at the time of the upstream disturbances upon which the downstream assessments depend.

6 Conclusions

6.1 General Review of the ENWL Network Models

The comparison of asset parameters and fault level results produced by the ENWL IPSA Master Network Model against the November 2015 LTDS shows some differences, of which some are due to recent updates on the network model following publication of the 2015 LTDS. Other differences are highlighted in the relevant section.

The differences in the peak make values could be partially explained by the load differences between the two sources which triggers variation of the G74 model parameters. The G74 model is limited to 1 MVA increments thus a variation of e.g. 0.2 MVA can result in a 1 MVA variation of initial symmetrical fault contribution.

ENWL may wish to fully automate the export of the transformer data from IPSA in the specified LTDS format. It is believed that this automation activity will reduce time and minimise risk of errors.

Some inconsistencies between the IPSA Master Network and NGET ETYS 2015 are noticed in the Wigan – Kirkby - Orrell – Washway Farm 132 kV area. This suggests that the two sources of information are not correlated.

The fault contribution to the DNO distribution network is mainly from large generators connected to the NG transmission network and the equivalent NG transmission network impedance at the interface points between NG transmission network and ENWL distribution network plays an important role to accurate calculation of fault currents in the ENWL distribution network. It is thus recommended that ENWL update the NG transmission network topology and parameters in the IPSA Master Network model annually in accordance with the week 42 data provided by NG.

6.2 Validity of ENWL G74 Model in Relation with the Guidelines

The review of the G74 induction machine models represents an important aspect of this study. The G74 models are widely used in the industry by the distribution network operators to simulate the fault contribution from the general load, when asynchronous motors forming part of the general load are not individually identifiable. ER G74 and ETR 120 provide guidance on how to estimate the fault level contribution of these models and how to model their equivalent electrical parameters.

While the ENWL G74 model generally follows the indicative guidelines, the contribution from the ENWL model at break time (90 ms) is negligible, whereas a model calculated using the indicative G74 parameters has the contribution at the break time of 90 ms. This difference is a result of the smaller time constant applied in the ENWL model. Also, the ENWL model produces slightly smaller peak contribution values than the model using the G74 indicative parameters. If ENWL wish to follow the guidelines to a higher extent, the indicative figures provided in

G74 which are also reproduced in Section 3, need to be considered and applied. The parameters of the equivalent induction machines representing the G74 model can be replaced by the values provided by TNEI in the same section.

It is also worth commenting that the ENWL G74 fault infeed database components represent 1 MVA fault contributions, or typical fault infeed from 1 MVA of connected LV demand. Using these components the network model is limited to 1 MVA increments and a decision needs to be made if the connected demand is e.g. 1.5 MVA. ENWL may wish to increase the accuracy of the G74 model fault contribution by reducing the MVA increment. Some examples are presented below:

- the G74 model parameters can be calculated for each load either via an automated process or via spreadsheets; the values can then be pasted in the IPSA Master Network Model
- the fault level study can be undertaken via a script that reads the load at each bus and automatically calculates the fault contribution of the G74 models

6.3 Comparison of the IPSA and FLM Fault Level Results

The calculated fault current results using the updated ENWL IPSA network model have been compared to the fault level values provided by the FLM device. Differences between the calculated and the estimated fault levels have been identified and potential reasons for the differences were analysed. Please note that the conclusions drawn here are based on the limited subsets of four network models and measurements.

For the Broadheath 11 kV location, the results show relatively large differences in RMS break upstream values between IPSA and FLM, up to 9.7 %. The IPSA RMS break results are larger than the FLM values. The differences between FLM and IPSA at Broadheath do not follow the same patterns seen at the other three locations, where differences in RMS break are smaller than the peak make ones.

For this location, the differences in break (almost 1 kA) could be explained by the possible inconsistency in 132 kV grid in Altrincham area between the IPSA Master Network and the actual operating scheme during the period of measurements, the relative modest disturbance energy seen by the FLM and larger room for interpretation of the results in Pronto software compared to the other locations.

Nevertheless, ENWL may wish to check the 132 kV network in Altrincham – Carrington area and the 400/275 kV National Grid topology in the area in the IPSA Master Network model and compare with the FLM results again if the IPSA Master Network model needs update.

The differences in upstream peak make are the smallest among the four locations, up to 3.5 % between the simulated and the estimated values, depending on the load scenarios. The IPSA model has more peak make fault contribution from the upstream network than the FLM.

For the two 6.6 kV locations, Denton West and Irlam, the upstream RMS break results suggest a high level of confidence in modelling the network in IPSA (maximum difference of 3.1 % between IPSA and FLM results). The IPSA RMS break results are smaller than the FLM estimated values at Denton West, but larger at Irlam.

The differences in upstream peak make are generally larger, up to 10.1 %, depending on the load scenarios and location. The IPSA model has more peak make fault contribution from the upstream network than the FLM.

For the Wigan 33 kV location, the results show large differences of upstream values in both RMS break and peak make between IPSA and FLM. In the case of RMS break, the differences are up to 10.2 %, while the peak make are up to 35.0 %. Compared to the FLM values, the IPSA network model generates higher upstream fault level values for both RMS break and peak make.

The large differences could be due to the uncertainty in modelling the National Grid wider area that supplies Wigan grid. The operating scheme in the area modelled in the IPSA Master Network may not be consistent with the actual NGET operating diagram. We recommend to double check the 400/275 kV National Grid topology in the area in the IPSA Master Network model and compare with the FLM fault predictions again if the IPSA Master Network model is updated.

The Outram FLM device is an innovative solution to predict the fault level in the electrical networks and can be used for numerous applications, including the validation of the fault level models of the network. It is the first commercially available[27] fault monitor developed to use natural disturbances from the network to generate its results.

When comparing the FLM with network modelling, one should acknowledge and be aware of underlying differences. A network model is a mathematical representation of electrical network; it is expected that computer-based fault level simulations use worst case assumptions and provide results on the conservative side, based on which grid operators plan their decisions. On the other hand, the FLM results are based on real current and voltage measurements, on the natural changes in the actual network during the trial period.

The Denton West 6.6 kV and Irlam 6.6 kV results suggest a high level of confidence in the network model of the studied areas by showing a good alignment with the FLM results. The relative modest disturbance energy during the trial period for Broadheath 11 kV location may explain the higher differences with the IPSA upstream fault results compared to Denton West and Irlam. Wigan 33 kV location also sees higher differences in the upstream fault contribution and this may be

[27] http://www.outramresearch.co.uk/flm/pages/product_outram_fault_level_monitors.shtml

explained by the uncertainty in modelling of the National Grid wider area that supplies Wigan grid and sees recent changes.

6.4 Conclusions and Recommendations Regarding the G74 ENWL Model

For all locations, the distribution generation connected to HV network did not have a significant impact at the location of the FLM devices, due to its low capacity; therefore the downstream fault contribution is mainly from the equivalent motors of the G74 models.

The results of the four trial locations consistently suggest the peak make fault contribution from the G74 models is most likely underestimated and that the ER G74 may need to be revised to reflect the change in load mix of today. This report provides useful information by studying a variation of the G74 model having a double fault contribution compared the one suggested by the guideline and currently used by ENWL.

It should be noted that ER G74 was developed in 1992 and since then the load mix and appliances used in commercial and industrial environments may have changed.

The industry practice is to employ the same G74 model, irrespective of the mix of load in each location or area. This is understandable as it is difficult for the distribution operators to separate consumers or areas of consumers in different categories, i.e. predominantly households, predominantly industrial.

Appendix A - RESPOND Trial Site Locations

RESPOND SITES V7.3

Final List; barring future major faults that require large scale asset replacement (post Hindley Green Removal and Denton West Insertion)

Substation	S/S Number	Voltage at Site	Protection at Site	Installation year of equipment	Worst Performer Feeder Ranking	Number of faults in 2012/2013	Faults outside fault level	CB Maintenance	Is Limiter Insert change	Technology to be Deployed	Fault Level reason	Cores/ phase	
BAMBER BRIDGE	400201	11kV	Numerical / Microprocessor	2006	315	7	2		2	HV Is Limiter - bus section - 1	Existing arrangements at site	NA	
BROADHEATH	**100134**	11kV	Electromechanical		401	10	3	1	2	HV Is Limiter - Incomer - 2	RMU on outgoing feeder	NA	
ATHLETIC ST	400052	6.6kV, 33kV	6.6kV - Electromechanical 33kV - Electromechanical	1964	294	28	8			EHV Is sensing equipment - 1	RMU on outgoing feeder	**1**	Cable external diameter 55mm
Wigan BSP (Gidlow CCT No 1)	**200421**	6.6kV, 33kV	6.6kV - Electromechanical 33kV - Electromechanical	1993	145	20	6			EHV Is sensing equipment - 2	RMU on outgoing feeder	**1**	Cable external diameter 55mm
LONGRIDGE	400416	6.6kV	Mixture	1967	135	36	11			HV Is sensing equipment - 1	RMU on outgoing feeder	**4**	Cable external diameter 45mm
HAREHOLME	400092	6.6kV	Static Electronic	1994	257	20	6			HV Is sensing equipment - 2	RMU on outgoing feeder	**2**	Cable external diameter 45mm
NELSON	400044	6.6kV	Electromechanical	1965	131	17	5			HV Is sensing equipment - 3	RMU on outgoing feeder	**4**	Cable external diameter 45mm
MOUNT ST	100622	6.6kV, 33kV	6.6kV - Electromechanical 33kV - Electromechanical	1966	223	10	3	1		EHV adaptive protection - 1	RMU on outgoing feeder	NA	
OFFERTON	**302872**	6.6kV, 33kV	6.6kV - Electromechanical 33kV - Electromechanical	1966	719		0	0		EHV adaptive protection - 2	Can run in // with 3x BSPs	NA	
ATHERTON TOWN CENTRE	205318	11kV	Static Electronic	1994	7	29	9	2		HV adaptive protection - 1	Substation equipment	NA	
DENTON WEST	**100111**	33kV, 6.6kV	Electromechanical	1967?						HV adaptive protection - 2	Replacement for Hindley Green	NA	
BLACKBULL	400403	6.6kV	Numerical / Microprocessor	2007	303	17	5	1		HV adaptive protection - 3	RMU on outgoing feeder	NA	
IRLAM	**100615**	6.6kV	Static Electronic	1989	275	7	2			HV adaptive protection - 4	RMU on outgoing feeder	NA	
LITTLEBOROUGH	304884	6.6kV	Electromechanical	1966	336	13	4	1		HV adpative protection - 5	RMU on outgoing feeder	NA	

Reference: File 'Final Respond Site Selection V 7.3'

Appendix B - Comparison of the Network Assets against LTDS Data in the Selected Locations

Appendix B.1 Broadheath Area

Table B.1.1 Line Data

IPSA Master Network					LTDS November 2015					Difference		
From Busbar	To Busbar	Resistance (pu)	Reactance (pu)	Susceptance (pu)	From Busbar	To Busbar	Resistance (pu)	Reactance (pu)	Susceptance (pu)	Resistance (pu)	Reactance (pu)	Susceptance (pu)
bowdon_33_t11	altrin_33_b	0.0319	0.0242	0.0038	BOWDON T11	ALTRINCHAM	0.0319	0.0242	0.0041	0.0000	0.0000	-0.0003
bowdon_33_t12	altrin_33_a	0.0327	0.0243	0.0038	BOWDON T12	ALTRINCHAM	0.0328	0.0243	0.0040	0.0000	0.0000	-0.0002
greenl_33_t11	altrin_33_b	0.0292	0.0170	0.0038	GREEN LANE T11 - Altrincham	ALTRINCHAM	0.0288	0.0167	0.0043	0.0004	0.0003	-0.0005
altrin_33_a	greenl_33_t12	0.0316	0.0379	0.0017	ALTRINCHAM	GREEN LANE T12 - Altrincham	0.0316	0.0379	0.0017	0.0000	0.0000	0.0000
altrin_33_b	broadh_33_t11	0.0006	0.0008	0.0001	ALTRINCHAM	BROADHEATH T11	0.0006	0.0008	0.0001	0.0000	0.0000	0.0000
altrin_33_b	broadh_33_t12	0.0007	0.0008	0.0001	ALTRINCHAM	BROADHEATH T12	0.0007	0.0008	0.0001	0.0000	0.0000	0.0000
altrin_33_b	broadh_33_t13	0.0007	0.0009	0.0001	ALTRINCHAM	BROADHEATH T13	0.0007	0.0009	0.0001	0.0000	0.0000	0.0000

Table B.1.2 Transformer Data

IPSA Master Network								LTDS November 2015							Difference			
From Busbar	To Busbar	Name	Resistance (pu)	Reactance (pu)	Rating (MVA)	Minimum Tap (%)	Maximum Tap (%)	From Busbar	To Busbar	Resistance (pu)	Reactance (pu)	Rating (MVA)	Minimum Tap (%)	Maximum Tap (%)	Resistance (pu)	Reactance (pu)	Minimum Tap (%)	Maximum Tap (%)
bowdon_33_t12	bowdon_11_b	bowdon_t12	0.04	1	11.5 / 23	-17.2	5.7	BOWDON	BOWDON	0.04	1.000	11.5 / 23	-18.6	4.3	0	0.000	1.4	1.4
bowdon_33_t11	bowdon_11_a	bowdon_t11	0.04	1	11.5 / 23	-17.2	5.7	BOWDON	BOWDON	0.04	1.000	11.5 / 23	-18.6	4.3	0	0.000	1.4	1.4
greenl_33_t11	greenl_11_a	greenl_t11	0.04	1.143	11.5 / 23	-17.2	5.7	GREEN LANE	GREEN LANE	0.04	1.000	11.5 / 23	-17.2	5.7	0	0.143	0.0	0.0
greenl_33_t12	greenl_11_b	greenl_t12	0.04	1.162	11.5 / 23	-17.2	5.7	GREEN LANE	GREEN LANE	0.04	1.000	11.5 / 23	-17.2	5.7	0	0.162	0.0	0.0
broadh_33_t11	broadh_11_a	altrin_t11	0.04	1	11.5 / 23	-17.2	5.7	BROADHEATH	BROADHEATH	0.04	1.000	11.5 / 23	-18.6	4.3	0	0.000	1.4	1.4
broadh_33_t12	broadh_11_b	altrin_t12	0.04	0.9	10 / 15	-10.5	3	BROADHEATH	BROADHEATH	0.04	1.04	10 / 15	-15.0	4.5	0	-0.140	4.5	-1.5
broadh_33_t13	broadh_11_b	altrin_t13	0.04	1	11.5 / 23	-17.2	5.7	BROADHEATH	BROADHEATH	0.04	1.000	11.5 / 23	-18.6	4.3	0	0.000	1.4	1.4
altrin_132_gt1	altrin_33_gt1	altrin_gt1	0.007	0.252	90	-20	10	altrincham 1	altrincham	0.007	0.252	90	-20	+10	0	0.000	0.0	0.0
altrin_132_gt2	altrin_33_gt2	altrin_gt2	0.007	0.249	90	-20	10	altrincham 2	altrincham	0.007	0.249	90	-20	+10	0	0.000	0.0	0.0

Table B.1.3 Load Data

IPSA Master Network			LTDS November 2015:	Max load 2014-2015			Max load 2015-2016 forecast		Difference	
Busbar	Real Power (MW)	Reactive Power (MVAr)	Busbar	Voltage (kV)	Real Power (MW)	Reactive Power (MVAr)	Real Power (MW)	Reactive Power (MVAr)	Real Power (MW)	Reactive Power (MVAr)
broadh_11_a	13.81	0.2	BROADHEATH	11	14.15	0.20	14.36	0.20	-0.55	0.00
broadh_11_b	13.81	0.2	BROADHEATH	11	14.15	0.20	14.36	0.20	-0.55	0.00
bowdon_11_b	7.99	0.54	BOWDON	11	8.18	0.56	8.28	0.56	-0.29	-0.02
bowdon_11_a	7.99	0.54	BOWDON	11	8.18	0.56	8.28	0.56	-0.29	-0.02
greenl_11_a	9.87	0.39	GREEN LANE-Altrincham	11	10.11	0.40	10.21	0.41	-0.34	-0.01
greenl_11_b	9.87	0.39	GREEN LANE-Altrincham	11	10.11	0.40	10.21	0.41	-0.34	-0.01

Appendix B.2 Denton West Area

Table B.2.1 Line Data

IPSA Master Network					LTDS November 2015					Difference		
From Busbar	To Busbar	Resistance (pu)	Reactance (pu)	Susceptance (pu)	From Busbar	To Busbar	Resistance (pu)	Reactance (pu)	Susceptance (pu)	Resistance (pu)	Reactance (pu)	Susceptance (pu)
opensh_33_t11	droyls_33_b	0.0289	0.0442	0.0046	-	-	-	-	-	-	-	-
droyls_33_a	dreast_33_t11	0.0044	0.0038	0.0005	DROYLSDEN	DROYLSDEN EAST T11	0.0044	0.0038	0.0005	0.0000	0.0000	0.0000
snipe_tee	dreast_33_t12	0.0048	0.0044	0.0004	DROYLSDEN	DROYLSDEN EAST T12	0.0048	0.0044	0.0004	0.0000	0.0000	0.0000
droyls_33_a	snipe_33_t11	0.0222	0.0266	0.0012	DROYLSDEN	SNIPE T11	0.0222	0.0266	0.0012	0.0000	0.0000	0.0000
droyls_33_b	dentea_33_b	0.0321	0.0417	0.0056	DROYLSDEN	DENTON EAST	0.0292	0.0315	0.0064	0.0029	0.0102	-0.0008
dentea_33_a	dentwe_33_b	0.0203	0.0187	0.0035	DENTON EAST	DENTON WEST B	0.0203	0.0187	0.0035	0.0000	0.0000	0.0000
dentwe_33_b	droyls_33_a	0.0764	0.0488	0.0026	DENTON WEST B	DROYLSDEN	0.0763	0.0428	0.0028	0.0001	0.0060	-0.0002
dentwe_33_t11	droyls_33_a	0.0710	0.0527	0.0044	DROYLSDEN	DENTON WEST A	0.0766	0.0429	0.0028	-0.0056	0.0098	0.0017
dentwe_33_a	opensh_33_t11	0.0283	0.0347	0.0042	-	-	-	-	-	-	-	-
opensh_33_t12	droyls_33_a	0.0266	0.0372	0.0041	OPENSHAW T12	DROYLSDEN	0.0266	0.0206	0.0035	0.0000	0.0166	0.0006
snipe_tee	snipe_33_t12	0.0211	0.0253	0.0011	DROYLSDEN	SNIPE T12	0.0211	0.0253	0.0011	0.0000	0.0000	0.0000
-	-	-	-	-	DROYLSDEN	OPENSHAW T11 / STUART ST Tee	0.0143	0.0124	0.0015	-	-	-
-	-	-	-	-	OPENSHAW T11 / STUART ST Tee	OPENSHAW T11	0.0127	0.0099	0.0017	-	-	-
-	-	-	-	-	STUART STREET	OPENSHAW T11 / STUART ST Tee	0.0164	0.0143	0.0017	-	-	-
-	-	-	-	-	DENTON WEST A	DROYLSDEN	0.0506	0.0440	0.0052	-	-	-

Table B.2.2 Transformer Data

IPSA Master Network								LTDS November 2015							Difference			
From Busbar	To Busbar	Name	Resistance (pu)	Reactance (pu)	Rating (MVA)	Minimum Tap (%)	Maximum Tap (%)	From Busbar	To Busbar	Resistance (pu)	Reactance (pu)	Rating (MVA)	Minimum Tap (%)	Maximum Tap (%)	Resistance (pu)	Reactance (pu)	Minimum Tap (%)	Maximum Tap (%)
droyls_132_gt2	droyls_33_gt2	droyls_gt2	0.006	0.187	90	-20	10	droylsden 2	droylsden	0.006	0.187	90	-20	+10	0.000	0.000	0.000	0.000
droyls_132_gt1	droyls_33_gt1	droyls_gt1	0.006	0.189	90	-20	10	droylsden 1	droylsden	0.006	0.189	90	-20	+10	0.000	0.000	0.000	0.000
snipe_33_t11	snipe_6.6_a	snipe_t11	0.04	1	11.5 / 23	-17.2	5.7	DROYLSDEN	SNIPE	0.04	1.040	11.5 / 23	-17.2	5.7	0.000	-0.040	-0.040	-0.020
dreast_33_t12	dreast_6.6_b	dreast_t12	0.04	0.97	11.5 / 23	-17.2	5.7	DROYLSDEN EAST	DROYLSDEN EAST	0.04	1.000	11.5 / 23	-17.2	5.7	0.000	-0.030	0.000	0.000
dreast_33_t11	dreast_6.6_a	dreast_t11	0.04	0.98	11.5 / 23	-17.2	5.7	DROYLSDEN EAST	DROYLSDEN EAST	0.04	1.000	11.5 / 23	-17.2	5.7	0.000	-0.020	0.000	0.000
opensh_33_t11	opensh_6.6_a	opensh_t11	0.04	1.04	10 / 14	-15	4.5	OPENSHAW	OPENSHAW	0.04	1.040	10 / 14	-15.0	4.5	0.000	0.000	0.000	0.000
dentea_33_b	dentea_6.6_b	dentea_t11	0.04	1	10 / 14	-15	4.5	DENTON EAST	DENTON EAST	0.04	1.040	10 / 14	-15.0	4.5	0.000	-0.040	0.000	0.000
dentea_33_a	dentea_6.6_a	dentea_t12	0.04	1	10 / 14	-15	4.5	DENTON EAST	DENTON EAST	0.04	1.040	10 / 14	-15.0	4.5	0.000	-0.040	0.000	0.000
dentwe_33_t11	dentwe_6.6_a	dentwe_t11	0.04	1	11.5 / 23	-17.2	5.7	DENTON WEST	DENTON WEST	0.04	1.000	11.5 / 23	-18.6	4.3	0.000	0.000	1.400	1.400
dentwe_33_b	dentwe_6.6_b	dentwe_t12	0.04	1	11.5 / 23	-17.2	5.7	DENTON WEST	DENTON WEST	0.04	1.000	11.5 / 23	-18.6	4.3	0.000	0.000	1.400	1.400
opensh_33_t12	opensh_6.6_b	opensh_t12	0.04	1.04	10 / 14	-15	4.5	OPENSHAW	OPENSHAW	0.04	1.040	10 / 14	-15.0	4.5	0.000	0.000	0.000	0.000
snipe_33_t12	snipe_6.6_b	snipe_t12	0.04	1	11.5 / 23	-17.2	5.7	DROYLSDEN	SNIPE	0.04	1.040	11.5 / 23	-17.2	5.7	0.000	-0.040	-0.040	-0.020

Table B.2.3 Load Data

IPSA Master Network			LTDS November 2015	Max load 2014-2015			Max load 2015-2016 forecast		Comparison	
Busbar	Real Power (MW)	Reactive Power (MVAr)	Busbar	Voltage (kV)	Real Power (MW)	Reactive Power (MVAr)	Real Power (MW)	Reactive Power (MVAr)	Real Power (MW)	Reactive Power (MVAr)
dreast_6.6_a	8.79	1.26	DROYLSDEN EAST	6.6	9.00	1.30	9.07	1.31	-0.28	-0.04
dreast_6.6_b	8.79	1.26	DROYLSDEN EAST	6.6	9.00	1.30	9.07	1.31	-0.28	-0.04
opensh_6.6_a	7.51	1.55	OPENSHAW	6.6	7.69	1.59	7.79	1.61	-0.28	-0.04
opensh_6.6_b	7.51	1.55	OPENSHAW	6.6	7.69	1.59	7.79	1.61	-0.28	-0.04
dentea_6.6_b	7.07	0.1	DENTON EAST	6.6	7.24	0.10	7.30	0.10	-0.23	0.00
snipe_6.6_a	7.5	1.34	SNIPE	6.6	7.69	1.37	7.77	1.39	-0.27	-0.03
dentwe_6.6_a	7.35	1.05	DENTON WEST	6.6	7.53	1.07	7.60	1.08	-0.25	-0.02
snipe_6.6_b	7.5	1.34	SNIPE	6.6	7.69	1.37	7.77	1.39	-0.27	-0.03
dentea_6.6_a	7.07	0.1	DENTON EAST	6.6	7.24	0.10	7.30	0.10	-0.23	0.00
dentwe_6.6_b	7.35	1.05	DENTON WEST	6.6	7.53	1.07	7.60	1.08	-0.25	-0.02

Appendix B.3 Irlam Area

Table B.3.1 Line Data

IPSA Master Network					LTDS November 2015					Difference		
From Busbar	To Busbar	Resistance (pu)	Reactance (pu)	Susceptance (pu)	From Busbar	To Busbar	Resistance (pu)	Reactance (pu)	Susceptance (pu)	Resistance (pu)	Reactance (pu)	Susceptance (pu)
carrin_33_a	mancrd_33_tee	0.0147	0.0130	0.0013	-	-	-	-	-	-	-	-
carrin_33_b	nwgpar_33_t12	0.0123	0.0107	0.0013	CARRINGTON	NWGB PARTINGTON T12	0.0123	0.0107	0.0013	0.0000	0.0000	0.0000
carrin_33_a	airpro_33_t11	0.0015	0.0013	0.0002	CARRINGTON	AIR PRODUCTS T11	0.0015	0.0013	0.0002	0.0000	0.0000	0.0000
carrin_33_b	airpro_33_t12	0.0019	0.0016	0.0002	CARRINGTON	AIR PRODUCTS T12	0.0019	0.0016	0.0002	0.0000	0.0000	0.0000
carrin_33_b	irlamp_33_t12	0.0204	0.0433	0.0047	CARRINGTON	IRLAM T12	0.0202	0.0428	0.0047	0.0002	0.0005	0.0001
carrin_33_a	irlamp_33_t11	0.0258	0.0333	0.0034	CARRINGTON	IRLAM T11	0.0389	0.0313	0.0035	-0.0130	0.0020	-0.0001
mancrd_33_tee	nwgpar_33_t11	0.0114	0.0127	0.0014	-	-	-	-	-	-	-	-
-	-	-	-	-	CARRINGTON	NWGB PARTINGTON T11	0.0123	0.0107	0.0013	-	-	-

Table B.3.2 Transformer Data

IPSA Master Network								LTDS November 2015							Difference			
From Busbar	To Busbar	Name	Resistance (pu)	Reactance (pu)	Rating (MVA)	Minimum Tap (%)	Maximum Tap (%)	From Busbar	To Busbar	Resistance (pu)	Reactance (pu)	Rating (MVA)	Minimum Tap (%)	Maximum Tap (%)	Resistance (pu)	Reactance (pu)	Minimum Tap (%)	Maximum Tap (%)
irlamp_33_t11	irlamp_6.6_a	irlamp_t11	0.052	1.146	11.5 / 23	-17.16	5.72	IRLAM PRIMARY	IRLAM PRIMARY	0.052	1.146	11.5 / 23	-17.2	5.7	0	0	0.040	0.020
irlamp_33_t12	irlamp_6.6_b	irlamp_t12	0.053	1.150	11.5 / 23	-17.16	5.72	IRLAM PRIMARY	IRLAM PRIMARY	0.052	1.146	11.5 / 23	-17.2	5.7	0.00017	0.00392	0.040	0.020
carrin_132_gt1	carrin_33_gt1	carrin_gt1a	0.012	0.280	60	-20	10	carrington 1	carrington bsp	0.012	0.280	60	-20	+10	-3E-07	-1E-09	0.000	0.000
nwgpar_33_t11	nwgpar_6.6_a	nwgpar_t11	0.050	1.000	10 / 14	-15	4.5	NWGB PARTINGTON	NWGB PARTINGTON	0.040	1.040	10 / 14	-15.0	4.5	0.01	-0.04	0.000	0.000
nwgpar_33_t12	nwgpar_6.6_b	nwgpar_t12	0.040	0.997	10 / 14	-15	4.5	NWGB PARTINGTON	NWGB PARTINGTON	0.040	1.040	10 / 14	-15.0	4.5	0	-0.043	0.000	0.000
airpro_33_t12	airpro_6.6_b	airpro_t12	0.030	0.970	11.5 / 23	-17.2	5.7	-	-	-	-	-	-	-	-	-	-	-
airpro_33_t11	airpro_6.6_a	airpro_t11	0.030	0.960	11.5 / 23	-17.2	5.7	-	-	-	-	-	-	-	-	-	-	-
carrin_132_gt2	carrin_33_gt2	carrin_gt2a	0.012	0.281	60	-20	10	carrington 2	carrington bsp	0.012	0.281	30	-20	+10	5E-07	-4E-07	0.000	0.000

Table B.3.3 Load Data

IPSA Master Network			LTDS November 2015:	Max load 2014-2015			Max load 2015-2016 forecast		Comparison	
Busbar	Real Power (MW)	Reactive Power (MVAr)	Busbar	Voltage (kV)	Real Power (MW)	Reactive Power (MVAr)	Real Power (MW)	Reactive Power (MVAr)	Real Power (MW)	Reactive Power (MVAr)
irlamp_6.6_a	8.78	1.19	IRLAM	6.6	9.03	1.22	9.15	1.24	-0.37	-0.03
aiprod_6.6_a	8.47	5.14	-	-	-	-	-	-	-	-
britga_6.6_a	0.08	0	-	-	-	-	-	-	-	-
britga_6.6_b	0.08	0	-	-	-	-	-	-	-	-
irlamp_6.6_b	8.78	1.19	IRLAM	6.6	9.03	1.22	9.15	1.24	-0.37	-0.03
aiprod_6.6_b	8.47	5.14	-	-	-	-	-	-	-	-
nwgpar_6.6_a	2.81	0	NWGB PARTINGTON	6.6	2.87	0.00	2.91	0.00	-0.10	0.00
nwgpar_6.6_b	2.81	0	NWGB PARTINGTON	6.6	2.87	0.00	2.91	0.00	-0.10	0.00

Appendix B.4 Wigan Area

Table B.4.1 Line Data 33 kV

IPSA Master Network					LTDS November 2015					Difference		
From Busbar	To Busbar	Resistance (pu)	Reactance (pu)	Susceptance (pu)	From Busbar	To Busbar	Resistance (pu)	Reactance (pu)	Susceptance (pu)	Resistance (pu)	Reactance (pu)	Susceptance (pu)
gidlow_33_a	wigan_33_a	0.0161	0.0292	0.0032	GIDLOW A	WIGAN	0.0161	0.0292	0.0032	0.0000	0.0000	0.0000
gidlow_33_b	wigan_33_b	0.0161	0.0292	0.0032	GIDLOW B	WIGAN	0.0161	0.0292	0.0032	0.0000	0.0000	0.0000
worsme_33_t11	wigan_33_a	0.0131	0.0118	0.0013	WORSLEY MESNES T11	WIGAN	0.0131	0.0118	0.0013	0.0000	0.0000	0.0000
worsme_33_t12	wigan_33_b	0.0131	0.0118	0.0012	WORSLEY MESNES T12	WIGAN	0.0129	0.0116	0.0013	0.0002	0.0001	0.0000
greens_33_t13	wigan_33_a	0.0042	0.0045	0.0004	GREEN ST T13	WIGAN	0.0041	0.0044	0.0004	0.0000	0.0001	0.0000
hindly_33_tee	greens_33_t12	0.0042	0.0045	0.0004	WIGAN	GREEN ST T12	0.0041	0.0044	0.0004	0.0001	0.0001	0.0000

Table B.4.2 Line Data 132 kV

IPSA Master Network					LTDS November 2015					Difference		
From Busbar	To Busbar	Resistance (pu)	Reactance (pu)	Susceptance (pu)	From Busbar	To Busbar	Resistance (pu)	Reactance (pu)	Susceptance (pu)	Resistance (pu)	Reactance (pu)	Susceptance (pu)
washwa_132_sgt2	wigan_132_te2	0.0002	0.0006	0.0003	Washway Farm GSP	Skelmersdale 2 / Wigan 2 Tee	0.0002	0.0006	0.0003	0.0000	0.0000	0.0000
wigan_132_te2	skelme_132_gt2	0.0004	0.0017	0.0007	Skelmersdale 2 / Wigan 2 Tee	Skelmersdale 2	0.0004	0.0017	0.0007	0.0000	0.0000	0.0000
wigan_132_te1	wigan_132_gt1	0.0178	0.0457	0.0177	Skelmersdale 1 / Wigan 1 Tee	Wigan 1	0.0178	0.0457	0.0177	0.0000	0.0000	0.0000
wigan_132_te2	orrell_132_gt1	0.0094	0.0241	0.0000	Skelmersdale 2 / Wigan 2 Tee	-	-	-	-	-	-	-
wigan_132_te1	washwa_132_sgt1	0.0002	0.0006	0.0003	Skelmersdale 1 / Wigan 1 Tee	Washway Farm GSP	0.0002	0.0006	0.0003	0.0000	0.0000	0.0000
wigan_132_te1	skelme_132_gt1	0.0004	0.0017	0.0007	Skelmersdale 1 / Wigan 1 Tee	Skelmersdale 1	0.0004	0.0017	0.0007	0.0000	0.0000	0.0000
kirkby_132_sgt5	orrell_132_gt2	0.0059	0.0220	0.0313	-	-	-	-	-	-	-	-
orrell_132_gt2	wigan_132_gt2	0.0083	0.0215	0.0004	-	Wigan 2	-	-	-	-	-	-

Table B.4.3 33/6.6 kV Transformer Data

IPSA Master Network								LTDS November 2015							Difference			
From Busbar	To Busbar	Name	Resistance (pu)	Reactance (pu)	Rating (MVA)	Minimum Tap (%)	Maximum Tap (%)	From Busbar	To Busbar	Resistance (pu)	Reactance (pu)	Rating (MVA)	Minimum Tap (%)	Maximum Tap (%)	Resistance (pu)	Reactance (pu)	Minimum Tap (%)	Maximum Tap (%)
gidlow_33_a	gidlow_6.6_a	gidlow_t11	0.04	1.00	11.5/23	-17.2	5.7	GIDLOW	GIDLOW	0.04	1.00	11.5 / 23	-18.6	4.3	0	0.00	1.4	1.4
gidlow_33_b	gidlow_6.6_b	gidlow_t12	0.04	1.00	11.5/23	-17.2	5.7	GIDLOW	GIDLOW	0.04	1.00	11.5 / 23	-18.6	4.3	0	0.00	1.4	1.4
worsme_33_t11	worsme_6.6_a	worsme_t11	0.04	1.00	11.5/23	-17.2	5.7	WORSLEY MESNES	WORSLEY MESNES	0.04	1.00	11.5 / 23	-18.6	4.3	0	0.00	1.4	1.4
worsme_33_t12	worsme_6.6_b	worsme_t12	0.04	1.00	11.5/23	-17.2	5.7	WORSLEY MESNES	WORSLEY MESNES	0.04	1.00	11.5 / 23	-18.6	4.3	0	0.00	1.4	1.4
greens_33_t13	greens_6.6_c	greens_t13	0.04	1.02	11.5/23	-17.2	5.7	GREEN ST	GREEN ST	0.04	1.00	11.5 / 23	-17.2	5.7	0	0.02	0.0	0.0
greens_33_t12	greens_6.6_b	greens_t12	0.04	1.00	11.5/23	-17.2	5.7	GREEN ST	GREEN ST	0.04	1.00	11.5 / 23	-18.6	4.3	0	0.00	1.4	1.4

Table B.4.4 GT and SGT Transformer Data

IPSA Master Network								LTDS November 2015/TYS November 2015							Difference			
From Busbar	To Busbar	Name	Resistance (pu)	Reactance (pu)	Rating (MVA)	Minimum Tap (%)	Maximum Tap (%)	From Busbar	To Busbar	Resistance (pu)	Reactance (pu)	Rating (MVA)	Minimum Tap (%)	Maximum Tap (%)	Resistance (pu)	Reactance (pu)	Minimum Tap (%)	Maximum Tap (%)
washwa_275_sgt1	washwa_132_sgt1	washwa_sgt1	0.00197	0.07970	180	-15	15	WASF21	WASF12	0.00197	0.07970	180	0.0	0.0	0	0.000	-15.0	15.0
washwa_275_sgt2	washwa_132_sgt2	washwa_sgt2	0.00196	0.07833	180	-15	15	WASF22	WASF11	0.00197	0.07970	180	0.0	0.0	-0.00001	-0.001	-15.0	15.0
skelme_132_gt2	skelme_33_gt2	skelme_gt2	0.00705	0.25190	90	-20	10	skelmersdale 2	skelmersdale	0.007049	0.25190	90	-20	+10	0	0.000	0.0	0.0
skelme_132_gt1	skelme_33_gt1	skelme_gt1	0.00717	0.25190	90	-20	10	skelmersdale 1	skelmersdale	0.007172	0.25190	90	-20	+10	0	0.000	0.0	0.0
wigan_132_gt2	wigan_33_gt2	wigan_gt2	0.00634	0.33005	90	-20	10	wigan 2	wigan	0.006335	0.33005	90	-20	+10	0	0.000	0.0	0.0
wigan_132_gt1	wigan_33_gt1	wigan_gt1	0.00570	0.27650	90	-20	10	wigan 1	wigan	0.005702	0.27650	90	-20	+10	0	0.000	0.0	0.0
kirkby_275_sgt5	kirkby_132_sgt5	washwa_sgt2	0.00150	0.08000	180	-15	15	KIBY21	WASF1*	0.001221	0.08047	240	0.0	0.0	0.000279	-0.000467	-15.0	15.0
orrell_132_gt2	orrell_33_gt2	orrell_gt2	0.00565	0.27920	90	-20	10	Orrell 2	Orrell	0.0056467	0.27920	90	-20	+10	0	0.000	0.0	0.0
orrell_132_gt1	orrell_33_gt1	orrell_gt1	0.00565	0.27920	90	-20	10	Orrell 1	Orrell	0.0056467	0.27920	90	-20	+10	0	0.000	0.0	0.0

Table B.4.5 Load Data

IPSA Master Network			LTDS November 2015:	Max load 2014-2015			Max load 2015-2016 forecast		Difference	
Busbar	Real Power (MW)	Reactive Power (MVAr)	Busbar	Voltage (kV)	Real Power (MW)	Reactive Power (MVAr)	Real Power (MW)	Reactive Power (MVAr)	Real Power (MW)	Reactive Power (MVAr)
gidlow_6.6_b	9.01	1.26	GIDLOW	6.6	9.23	1.29	9.32	1.30	-0.31	-0.03
gidlow_6.6_a	9.01	1.26	GIDLOW	6.6	9.23	1.29	9.32	1.30	-0.31	-0.03
worsme_6.6_a	4.64	0.09	WORSLEY MESNES	6.6	4.75	0.09	4.79	0.10	-0.15	0.00
greens_6.6_b	9.19	1.37	GREEN ST T12 & T13	6.6	9.41	1.40	9.52	1.42	-0.33	-0.03
greens_6.6_c	9.19	1.37	GREEN ST T12 & T13	6.6	9.41	1.40	9.52	1.42	-0.33	-0.03
worsme_6.6_b	4.64	0.09	WORSLEY MESNES	6.6	4.75	0.09	4.79	0.10	-0.15	0.00

Note: All impedances in p.u. on 100 MVA base

Appendix C – List of Feeders Connected to the Primary Substations

Appendix C.1. Broadheath Primary

1 ALTRINCHAM GRID : L3088 ATLANTIC ST (MADANS
2 ALTRINCHAM GRID : L2238 KEARNS/ALTRINCHAM R
3 ALTRINCHAM GRID : L2239 LINOTYPE/BUDENBERG
4 ALTRINCHAM GRID : L2240 RECORD ELECTRICAL
5 ALTRINCHAM GRID : L3060 HARCOURT RD/NAVIGAT
6 ALTRINCHAM GRID : L2247 T21/WOODCOTE RD
7 ALTRINCHAM GRID : L2242 BROADHEATH O/D
8 ALTRINCHAM GRID : L2241 B&Q ATLANTIC ST
9 ALTRINCHAM GRID : L2245 ALTRINCHAM RET PK N
10 ALTRINCHAM GRID : L2246 MANCHESTER RD
11 ALTRINCHAM GRID : L3123 ATLANTIC ST NO3
12 ALTRINCHAM GRID : L2243 THE FLEET

Reference: File ‘FLA data Broadheath 1103 to 1606.xlsx’ via email from Kieran Bailey dated 27/06/2016

Appendix C.2. Denton West Primary

1 DENTON WEST : F547 CORNHILL LN
2 DENTON WEST : F47 CORONATION ST
3 DENTON WEST : F149 KENSINGTON GR
4 DENTON WEST : F452 MCWW DENTON (normally open)
5 DENTON WEST : F1332 ASHBROOK AVE
6 DENTON WEST : F549 E PASS & CO /PARKWAY
7 DENTON WEST : F243 GRANADA RD
8 DENTON WEST : F1519 DEBDALE PK
9 DENTON WEST : F1460 DENTON WEST NETWORK
10 DENTON WEST : F3168 WRIGHT ROBINSON SPO
11 DENTON WEST : F351 GORTON/DEAN RD GORTO

Reference: File ‘FLA data Denton West 18012016’ via email from Kieran Bailey dated 23/02/2016

Appendix C.3. Irlam Primary

1 IRLAM : F76 TRANSPORT YARD/GRIDCO
2 IRLAM : F3999 WERIT UK/CATERPILLA
3 IRLAM : F3900 WERIT UK
4 IRLAM : F3636 ENVIRONMENTAL POLYM
5 IRLAM : F3145 TRAMWAY RD
6 IRLAM : F2504 DEAN RD EMBEDDED
7 IRLAM : F1566 MONA WAY
8 IRLAM : F1174 ROSEWAY AVE
9 IRLAM : F1125 SOAPSTONE WAY/CWS B
10 IRLAM : F1112 VICTORIA RD
11 IRLAM : F1111 TESCO IRLAM

Reference: File ‘FLA data Irlam 18012016’ via email from Kieran Bailey dated 23/02/2016

Appendix D – Amendments Made to Some HV Loads in the Selected Locations

The tables below show the loads for which the rating was not initially specified in the DINIS files. Additional information about the customers type and corresponding transformer rating has been received from ENWL.

Appendix D.1. Broadheath Primary

s/s N o.	Substation mame	TX rating	Customer Type	s/s N o.	Substation mame	TX rating	Customer Type
172280	WHITEHEADS OCEAN STREET	0.5MVA	Standard				
171035	ATLATIC ST	0.75MVA	Standard				
178697	ATLANTIC ST SUPERMARKET	0.5MVA	HV CUSTOMER				
172613	BROAD PRINT BARLOW RD	0.5MVA	HV CUSTOMER				
172345	ATLANTIC ST (MADANS)	→		178483	Halo Furnishings (Cons)	0.5MVA	COMA
171126	B&D STEELS	0.5MVA	HV CUSTOMER				
172544	MIM DAVENPORT LN	0.5MVA	HV CUSTOMER				
177218	NOVA GROUP ALTRINCHAM NO2	→		178211	Nova Groups (Cons) No. 2	1MVA	COMA
172520	NOVA GROUP	1MVA	COMA				
172244	ALTRINCHAM METROLINK	0.5MVA	HV CUSTOMER				
171037	ATTENBURYS LANE SWITCH	→		171094	**Bollin Dr**	0.5MVA	Standard
171935	TIMPERLEY METROLINK	0.5MVA	HV CUSTOMER				
171015	ALTRINCHAM SEWAGE	0.5MVA	HV CUSTOMER				

Note: For customer identified as HV or IDNOs, a default value of 0.5 MVA has been used

Appendix D.2. Denton West Primary

s/s N o.	Substation mame	TX rating	Customer Type
178016	DENTON HALL FM	0.5MVA	HV CUSTOMER
177095	SYSTEM 3 WINDMILL LN	1.4MVA	HV CUSTOMER
172365	J&J HARVEY	0.75MVA	COMA
178552	ALPHAGATE DR	0.8MVA	Standard
172368	GORTON POOL	0.63MVA	COMA
178238	BOOTH DALE RD	0.5MVA	IDNO
178393	DUCHESS DR	0.5MVA	IDNO
178653	KINGS RD AUDENSHAW	0.5MVA	IDNO

Note: For customer identified as HV or IDNOs, a default value of 0.5 MVA has been used

Appendix D.3. Irlam Primary

s/s N o.	Substation mame	TX rating	Customer Type	s/s N o.	Substation mame	TX rating
167885	DEAN RD EMBEDDED	0.5MVA	HV Customer			
166594	C.W.S. BOTTLING	0.5MVA	HV Customer			
166574	MSC CANAL BRIDGE	0.5MVA	HV Customer			
165400	TESCO ~~HYPERMARKET~~ IRLAM	0.5MVA	HV Customer			
171503	GRIDCO NO. 1	0.5MVA	HV Customer			
166684	M/CR.BLAST CLEAN	0.5MVA	HV Customer			
168468	ROSEWAY AVE	0.5MVA	IDNO			
165390	KELLOGGS IRLAM			166785	Bonar Cereal Packaging No.1	1.25MVA
167603	WERIT UK			168669	Werit Uk No.1 (Cons)	0.8MVA+1.25MVA
	LANCS TAR B	1MVA				
167258	M62 SUPPLY CAD MOSS RD	0.1MVA	Standard			
166877	BUTCHERSFIELD GENERATION	Two HV metered exit points, however at this time the customer only has one operational generator. Electricity North West Butchersfield Generation Substation (166877). 1 x 150kW LV synchronous generator (data sheet requested from site). Via 1250kVA, Dyn11 TX				

Note: For customer identified as HV or IDNOs, a default value of 0.5 MVA has been used

Reference: The information has been extracted from file 'Loads without rating value KB150316.xlsx', via e-mail dated 15/03/2016 (RE TNEI - IPSA+ Model), at TNEI request

Appendix E – Distributed Generation Additional Data

Appendix E.1. The Winery Fairhills Rd Irlam (PV)

Generator/Site Data

	One TRIO 27.6 inverter	All site
Rated power (kW)	27.6	220.8
Maximum power (kW)	30.0	240.0
Voltage (kV)	0.4	0.4
Rated current (A)	43.3	346.4
Maximum current (A)	45.0	360.0

Note:

- The rated values have been provided by ENWL, document 'PowerOne Trio-27.6'

Generator Fault Contribution

	One TRIO 27.6 inverter	All site
Maximum current (A)	45.0	360.0
RMS Break current (A)	45.0	360.0
RMS Break current (p.u.)	1.04	1.04
Peak make current (p.u.)	2.62	2.62
Peak make current (A)	113.4	907.6

Note:

- The maximum current of the inverter given in the document 'PowerOne Trio-27.6' has been interpreted as break current contribution (controlled by the converter)
- The peak current has been assumed based on in-house information of inverter of similar structure, Huawei Sun2000-33KTL, document 'fault behaviour.xps'

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TYPE CERTIFICATE – ANNEX 4

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Results of the type tests of the generating unit

1 General

The measurements were performed at a SUN2000-33KTL photovoltaic inverter of Huawei Technologies Co., Ltd. The components and the software versions are described in annex 2 of this certificate. The measurement results of the Low Voltage Ride Through- tests are documented in the measurement report GLGH-4280 15 12947 294-A-0001-A and the measurement results of the control behaviour and power quality tests are documented in the measurement report GLGH-4280 15 12947 294-A-0001-A. Specific results of the measurements of the generating unit are stated in the following sections and the extracts from the measurement report which is attached to this certificate:

GLGH-4280 15 12947 294-S-0001-A	Extract from the test report "Determination of the electrical properties of the HUAWEI SUN2000-33KTL". (pages 21/26 to 26/26 of this appendix)

Details if the measurement reports can also be found in our certification reports CR-GCC-TR8-00131-A066-0 and CR-GCC-TR8-00131-A067-0.

2 Behaviour of the Generating Unit during Two-phase and Three-phase Faults

In the measurement report GLGH-4280 15 12947 294-A-0001-A the short circuit currents were determined based on the measurements at the Huawei SUN2000-33KTL. In the following table the required values of FGW TG3 are summarised. The values shown are as follows:

- half-period root mean square (RMS)-value (first column of short circuit currents) and peak value (second column) at t_0 (fault occurrence);
- one-period positive (first column) and negative phase sequence value (second column) at t_1 (150 ms after fault occurrence);
- one-period positive (first column) and negative phase sequence value (second column) at t_2 (20 ms before voltage return).

The RMS- and peak values are the maximum of the three phases which were determined at the connection terminal of the generating unit (400 V) during two-phase and three-phase voltage dip tests performed at partial and rated power and scaled to a rated current of $I_{n,AC}$ = 47,63 A. Due to the technical equality these maximum short circuit currents can also be used for the inverter with 30 kW, scaled to the rated current of $I_{n,AC}$ = 43,30 A.

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Table 2-1: Maximum short circuit currents during three-phase voltage with k=2.

Point in Time	Remaining Voltage	k-factor	Short Circuit Currents [p.u.]	
t_0 = 0 s (RMS-value and peak value)	0%	2	1,18	2,62
t_1 = 150 ms (pos. and neg. sequence)			1,02	0,02
t_2 = 20 ms before voltage return (pos. and neg. sequence)			1,02	0,01
t_0 = 0 s (RMS-value and peak value)	25%	2	1,11	2,60
t_1 = 150 ms (pos. and neg. sequence)			1,03	0,01
t_2 = 20 ms before voltage return (pos. and neg. sequence)			1,03	0,01
t_0 = 0 s (RMS-value and peak value)	50%	2	1,09	2,16
t_1 = 150 ms (pos. and neg. sequence)			0,94	0,01
t_2 = 20 ms before voltage return (pos. and neg. sequence)			0,95	0,01
t_0 = 0 s (RMS-value and peak value)	75%	2	1,06	1,93
t_1 = 150 ms (pos. and neg. sequence)			0,79	0,01
t_2 = 20 ms before voltage return (pos. and neg. sequence)			0,80	0,01

Reference: Document '*fault behavior.xps*'

Transformer Data

Transformer		Source
Capacity (MVA):	0.250	assumed
Primary Voltage (kV):	6.60	provided
Secondary Voltage (kV):	0.40	provided
Vector Group:	Dyn11	assumed
Impedance Losses (kW)	3.250	In-house data
Impedance Voltage (%)	4.00	In-house data
Impedance Calculation:		
System MVA Base:	100	
Zbase (ohm):	0.436	
RT (ohm):	2.265	
ZT (ohm):	6.970	
XT(ohm)	6.591	
ZT (pu):	16.000	
RT (pu):	5.200	
XT (pu):	15.131	
X/R Ratio	2.910	

Note:

- In-house data taken from http://www.meksantrafo.com.tr/en/node/16

Appendix E.2. Urban Splash (Mini CHP)

Generator Data

Max apparent power (kVA)	120.0
Voltage (kV)	0.4
Rated current (A)	173.2
RMS Break current (A)	195.0
RMS Break current (p.u.)	1.13
Peak make current (p.u.)	2.62
Peak make current (A)	453.8

Note:

- The maximum current of the unit given in the document 'D11234 02 Electrical Protection' has been interpreted as RMS break current contribution (controlled by the converter)
- The peak current has been assumed based on in-house information of units connected via power electronics, Huawei Sun2000-33KTL, document 'fault behaviour.xps' (see Appendix E.1)

Transformer Data

Transformer		Source
Capacity (MVA):	1.25	provided
Primary Voltage (kV):	11	
Secondary Voltage (kV):	0.40	
Vector Group:	Dyn11	
Impedance Losses (kW)	11.0	In-house data
Impedance Voltage (%)	6.00	provided
Impedance Calculation:		
System MVA Base:	100	
Zbase (ohm):	1.21	
RT (ohm):	0.852	
ZT (ohm):	5.808	
XT(ohm)	5.745	
ZT (pu):	4.800	
RT (pu):	0.7040	
XT (pu):	4.7481	
X/R Ratio	6.744	

Note:

- In-house data taken from document 'ABB Transformer Datasheet, 1250kVA, 11kV'

Appendix F – FLM Device - Explanations of Populations and Bins

Explanation of Bins and Populations

Populations and their presentations are used to try to offer quality or confidence information in a set of results without making assumptions as to their validity. They are particularly useful in allowing multiple different conditions to be shown uncompromised by averaging.

Fault Level Value	1	2	3	4	5	6	7	8	9	10
Interval 1	0	0	0	0	0	0	0	0	0	0
Interval 2	0	0	0	0	3	2	0	0	0	0
Interval 3	0	0	0	2	1	4	2	1	0	0
Interval 4	0	0	1	2	3	4	1	0	0	0
Interval 5	0	0	0	0	0	0	0	0	0	0
Interval 6	0	0	0	0	0	0	0	0	0	0
total	0	0	1	4	7	10	3	1	0	0

Figure 1-6 Tabular representation of 'populations' and 'bins'

Say that over 6 intervals, a total of 26 events occur. Each has a weight of 1 unit, and its Fault Level value is distributed as shown in the table above, Figure 1-6. During interval 2, three events occurred of value 5, and two of value 6. During interval 3, one event occurred of value 5, and four of value 6 (plus a further five events) and so on. Each of the value columns 1 to 10 accumulates all of the events that lie on their value, so it is said that there are 10 'bins' accumulating events, one bin corresponding to each value. After 1 interval, bin 5 has no entries (because there were no events of value 5 during interval 1). After 2, 3 and 4 intervals, bin 5 contains three, four and finally seven entries respectively, and that is still the total after all 6 intervals. If we graph the total at the end we can see how the full 26 events were distributed, see Figure 1-7. The 26 events constitute the total 'population' of results, and the graph shows the distribution of that population.

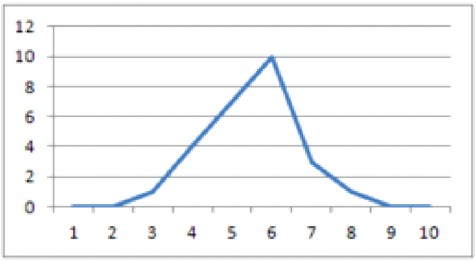

Figure 1-7 Graphical representation of 'populations' and 'bins'

The graph shows the same information as in the table, but much easier to see, especially when the numbers are large and there are many bins. Imagine also that we should allow for variable weights so that a heavily weighted result raises the relevant bin content by more than the average. This method of data presentation makes no assumptions, and does not manipulate the data, but nevertheless, it is possible to see at a glance that the highest number of events (10) had value 6, and none of the other bins came close. If we choose to look at other than just the peak, we might observe that the average event value was 5.5.

The FLM operates this 'bin' accumulation system to build and then describe the more complex population distributions. Each 'bin' is spaced approximately 1.81% above it's preceding neighbour which means the total distribution is logarithmic and 512 bins describe 4 decades of Fault Level.

Consider the following:

For any given operational situation, the Fault Level will remain static and the FLM (given disturbances to evaluate) will obtain a set of results clustered around the correct value. How close each result is to the correct value at any given time will depend on sources of error, principally noise, disturbance size, etc., and how much notice should be taken of it (its weight) may depend on the size and quality of the disturbance. The set of results is termed a population of results, and it may be plotted graphically with result value on the X-axis, and number and weight of results on the Y-axis. The overall height of the distribution is then indicative of the number and weight of results obtained, and the lateral spread indicative of the noise observed. A narrow, high distribution is the best, where there is little doubt of the average Fault Level value. A wide flat-top distribution is worst. Figure 1-8 (on the next page) is an example of a single population.

However, the Fault Level in some parts of the network may change as, for instance, additional generation is added or removed, linking breakers are opened/ closed, etc. for operational reasons. After the Fault Level changes from one value to another, a second population may build up describing the second Fault Level value. Both populations are valid, and ideally one should not contaminate the other, since each may then be scrutinised independently to arrive at the most likely Fault Level applicable for the two distinct periods of time. See Figure 1-9 (also on the next page) for an example of two distinct populations.

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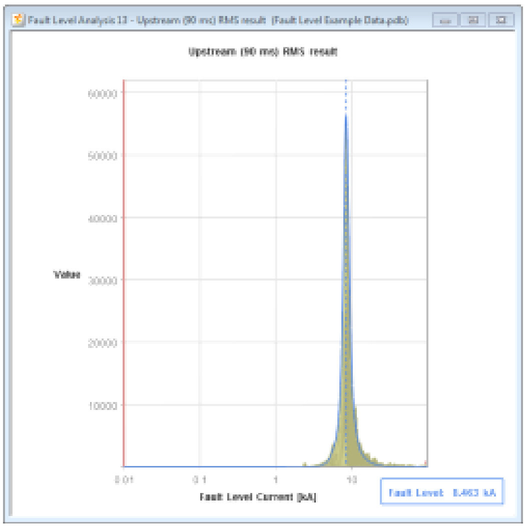


Figure 1-8 A single population of Fault Level results

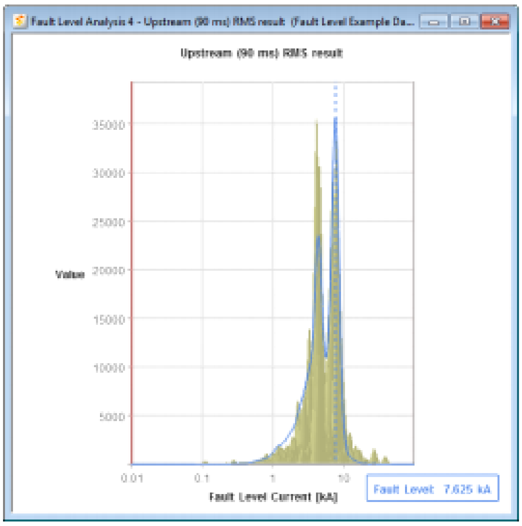


Figure 1-9 Two distinct populations of Fault Level results

During each collation interval, all the results for one parameter are accumulated into a set of 'bins' representing all realistically possible Fault Levels. For the graph above the bins spanned 0.01kA to 100kA. The times at which each result was obtained is not kept. Thus at the end of the interval, the resulting bin contents can be graphed. This will show the number and quality of populations, but not when they were obtained within the interval. Thus the times of Fault Level changes can be resolved to an interval, but probably not better.

Reference: File 'Outram PM7000FLM Operating Procedure'

Appendix G – Summary of the Load Flow Processed Data

Appendix G.1 Loads on Each Feeder (in Amps) and Power Factor for Maximum, Modal and Minimum Load Scenarios

Broadheath Primary

Max load	ipsa current (A)
ALTRINCHAM GRID L2241 B&Q ATLANTIC ST	46.1
ALTRINCHAM GRID L2240 RECORD ELECTRICAL	192.7
ALTRINCHAM GRID L2238 KEARNSALTRINCHAM R	100.0
ALTRINCHAM GRID L3123 ATLANTIC ST NO3	36.2
ALTRINCHAM GRID L2246 MANCHESTER RD	130.6
ALTRINCHAM GRID L3088 ATLANTIC ST (MADANS	123.9
ALTRINCHAM GRID L2243 THE FLEET	159.3
ALTRINCHAM GRID L3060 HARCOURT RDNAVIGAT	145.1
ALTRINCHAM GRID L2239 LINOTYPEBUDENBERG	80.5
ALTRINCHAM GRID L2247 T21WOODCOTE RD	85.0
ALTRINCHAM GRID L2245 ALTRINCHAM RET PK N	43.4
ALTRINCHAM GRID L2242 BROADHEATH OD	86.6
Power factor at the Primary	0.99
Time	04/29/16 11:00
Modal load	**ipsa current (A)**
ALTRINCHAM GRID L2241 B&Q ATLANTIC ST	20.5
ALTRINCHAM GRID L2240 RECORD ELECTRICAL	72.0
ALTRINCHAM GRID L2238 KEARNSALTRINCHAM R	31.3
ALTRINCHAM GRID L3123 ATLANTIC ST NO3	32.4
ALTRINCHAM GRID L2246 MANCHESTER RD	44.1
ALTRINCHAM GRID L3088 ATLANTIC ST (MADANS	55.4
ALTRINCHAM GRID L2243 THE FLEET	63.3
ALTRINCHAM GRID L3060 HARCOURT RDNAVIGAT	53.4
ALTRINCHAM GRID L2239 LINOTYPEBUDENBERG	17.9
ALTRINCHAM GRID L2247 T21WOODCOTE RD	54.4
ALTRINCHAM GRID L2245 ALTRINCHAM RET PK N	17.2
ALTRINCHAM GRID L2242 BROADHEATH OD	48.4
Power factor at the Primary	1.00
Time	03/19/16 04:30
Minimum load	**ipsa current (A)**
ALTRINCHAM GRID L2241 B&Q ATLANTIC ST	16.0
ALTRINCHAM GRID L2240 RECORD ELECTRICAL	52.8
ALTRINCHAM GRID L2238 KEARNSALTRINCHAM R	24.4
ALTRINCHAM GRID L3123 ATLANTIC ST NO3	29.3
ALTRINCHAM GRID L2246 MANCHESTER RD	30.6
ALTRINCHAM GRID L3088 ATLANTIC ST (MADANS	49.0
ALTRINCHAM GRID L2243 THE FLEET	42.6

ALTRINCHAM GRID L3060 HARCOURT RDNAVIGAT	40.5
ALTRINCHAM GRID L2239 LINOTYPEBUDENBERG	14.3
ALTRINCHAM GRID L2247 T21WOODCOTE RD	32.1
ALTRINCHAM GRID L2245 ALTRINCHAM RET PK N	13.1
ALTRINCHAM GRID L2242 BROADHEATH OD	27.3
Power factor at the Primary	1.00
Time	06/05/16 05:30

Denton West Primary

Max load	ipsa current (A)
DENTON WEST F1332 ASHBROOK AVE	128.6
DENTON WEST F47 CORONATION ST	202.7
DENTON WEST F1519 DEBDALE PK	112.6
DENTON WEST F547 CORNHILL LN	63.8
DENTON WEST F149 KENSINGTON GR	78.8
DENTON WEST F1460 DENTON WEST NETWORK	188.2
DENTON WEST F351 GORTONDEAN RD GORTO	174.2
DENTON WEST F3168 WRIGHT ROBINSON SPO	161.5
DENTON WEST F243 GRANADA RD	147.2
DENTON WEST F549 E PASS & CO PARKWAY	22.5
Power factor at the Primary	0.99
Time	20/01/2016 18:00
Modal load	**ipsa current (A)**
DENTON WEST F1332 ASHBROOK AVE	108.2
DENTON WEST F47 CORONATION ST	184.4
DENTON WEST F1519 DEBDALE PK	68.3
DENTON WEST F547 CORNHILL LN	32.1
DENTON WEST F149 KENSINGTON GR	68.9
DENTON WEST F1460 DENTON WEST NETWORK	123.7
DENTON WEST F351 GORTONDEAN RD GORTO	134.0
DENTON WEST F3168 WRIGHT ROBINSON SPO	105.5
DENTON WEST F243 GRANADA RD	90.3
DENTON WEST F549 E PASS & CO PARKWAY	45.6
Power factor at the Primary	0.99
Time	19/01/2016 09:00
Minimum load	**ipsa current (A)**
DENTON WEST F1332 ASHBROOK AVE	26.3
DENTON WEST F47 CORONATION ST	82.2
DENTON WEST F1519 DEBDALE PK	50.8
DENTON WEST F547 CORNHILL LN	32.0
DENTON WEST F149 KENSINGTON GR	51.0
DENTON WEST F1460 DENTON WEST NETWORK	60.1
DENTON WEST F351 GORTONDEAN RD GORTO	92.9
DENTON WEST F3168 WRIGHT ROBINSON SPO	50.7

DENTON WEST F243 GRANADA RD	44.7
DENTON WEST F549 E PASS & CO PARKWAY	10.0
Power factor at the Primary	0.98
Time	24/01/2016 05:00

Irlam Primary

Max load	ipsa current (A)
IRLAM F1112 VICTORIA RD	228.6
IRLAM F76 TRANSPORT YARDGRIDCO	10.7
IRLAM F3636 ENVIRONMENTAL POLYM	4.8
IRLAM F1566 MONA WAY	169.1
IRLAM F1125 SOAPSTONE WAYCWS B	195.0
IRLAM F3145 TRAMWAY RD	126.0
IRLAM F1111 TESCO IRLAM	52.7
IRLAM F2504 DEAN RD EMBEDDED	268.9
IRLAM F3900 WERIT UK	18.1
IRLAM F3999 WERIT UKCATERPILLA	163.3
IRLAM F1174 ROSEWAY AVE	242.3
Power factor at the Primary	0.98
Time	18/01/2016 17:00
Modal load	**ipsa current (A)**
IRLAM F1112 VICTORIA RD	90.5
IRLAM F76 TRANSPORT YARDGRIDCO	10.7
IRLAM F3636 ENVIRONMENTAL POLYM	4.7
IRLAM F1566 MONA WAY	61.0
IRLAM F1125 SOAPSTONE WAYCWS B	112.0
IRLAM F3145 TRAMWAY RD	55.3
IRLAM F1111 TESCO IRLAM	37.1
IRLAM F2504 DEAN RD EMBEDDED	153.7
IRLAM F3900 WERIT UK	24.9
IRLAM F3999 WERIT UKCATERPILLA	69.4
IRLAM F1174 ROSEWAY AVE	94.6
Power factor at the Primary	0.99
Time	23/01/2016 06:30
Minimum load	**ipsa current (A)**
IRLAM F1112 VICTORIA RD	75.0
IRLAM F76 TRANSPORT YARDGRIDCO	10.7
IRLAM F3636 ENVIRONMENTAL POLYM	4.7
IRLAM F1566 MONA WAY	60.2
IRLAM F1125 SOAPSTONE WAYCWS B	94.4
IRLAM F3145 TRAMWAY RD	49.3
IRLAM F1111 TESCO IRLAM	34.4
IRLAM F2504 DEAN RD EMBEDDED	132.4
IRLAM F3900 WERIT UK	24.6
IRLAM F3999 WERIT UKCATERPILLA	50.9
IRLAM F1174 ROSEWAY AVE	82.5
Power factor at the Primary	0.99
Time	24/01/2016 04:30

Appendix G.2 Loads on Each Transformer and Power Factor for Maximum, Modal and Minimum Load Scenarios in Wigan 33 kV Location

Wigan Grid

Max load	ipsa current (A)
wigan_gt1-wigan_33_a	481.9
wigan_gt2-wigan_33_b	336.4
Power factor at the 33kV bus	0.99
Time	24/02/2016 18:00
Modal load	**ipsa current (A)**
wigan_gt1-wigan_33_a	234.2
wigan_gt2-wigan_33_b	116.0
Power factor at the 33kV bus	1.00
Time	09/03/2016 02:00
Minimum load	**ipsa current (A)**
wigan_gt1-wigan_33_a	203.7
wigan_gt2-wigan_33_b	89.5
Power factor at the 33kV bus	1.00
Time	27/12/2015 05:30

Appendix H – Fault Level Results along the Feeders

Appendix H.1 Broadheath Location

Feeder / Busbar name of loads	Peak@10ms	RMS Break@90ms
	kA	kA
ALTRINCHAM GRID : L3088 ATLANTIC ST (MADANS		
ALTRINCHAM BUS PK NO 1	20.143	9.240
ALTRINCHAM BUS PK NO 2	19.877	9.180
ALTRINCHAM RETAIL PARK NO 2	14.968	7.843
ATLANTIC ST (MADANS)	29.945	10.714
CRAVEN ROAD	14.359	7.643
ALTRINCHAM GRID : L2238 KEARNS/ALTRINCHAM R		
ALTRINCHAM RETAIL PK NO3	30.440	10.819
ATLANTIC ST SUPERMARKET	22.575	9.784
ATLANTIC ST	20.579	9.402
B&D STEELS	18.937	9.200
BARLOW RD 14	19.088	9.233
BARLOW ROAD 52	16.201	8.543
BROAD PRINT BARLOW RD	16.506	8.631
BUDENBERG	19.031	9.201
DOWDING AND MILLS	19.284	9.125
HANOVER BUSINESS PARK NO.1	12.739	7.410
HANOVER ROAD	13.430	7.673
KEARNS	25.260	10.227
WHITEHEADS OCEAN STREET	17.642	8.793
ALTRINCHAM GRID : L2239 LINOTYPE/BUDENBERG		
budenberg hse	27.863	10.578
LADY KELVIN ROAD	18.737	9.316
LINOTYPE	24.858	10.252
LOCK ROAD	18.390	9.229
MIM DAVENPORT LN	19.352	9.206
NOVA GROUP ALTRINCHAM NO2	22.200	9.916
NOVA GROUP	20.335	9.621
P I CASTINGS	19.828	9.317
ALTRINCHAM GRID : L2240 RECORD ELECTRICAL		
ATLANTIC POINT	19.943	9.625
ATLATIC ST	12.781	7.506
BACK LANE	5.431	3.495
BALDWIN AND FRANCIS	14.503	8.197
BRADGATE ROAD	7.554	4.809
CHARCOAL RD	6.831	4.381

Feeder / Busbar name of loads	Peak@10ms	RMS Break@90ms
	kA	kA
DENZELL HOSPITAL	7.985	5.065
DUNHAM HALL	5.441	3.501
DUNHAM MASSEY VISITOR CTR	5.900	3.794
BONVILLE RD	9.749	6.026
GREEN LANE FARM	3.185	1.980
GROVEHOUSE FARM	4.543	2.902
HARRINGTON RD	7.028	4.502
HUNTSHAM CLOSE	9.623	6.033
LYON RD TURBOTECH	16.287	8.847
MCWW DUNHAM	8.799	5.501
MERLIN CT ATLANTIC ST	14.324	8.127
NORTH QUAYS BUSINESS PK	14.382	8.150
OLDFIELD LANE	9.146	5.744
OLDFIELD ROAD	10.230	6.284
PACIFIC RD NO2	11.614	6.984
PACIFIC RD	11.693	7.021
RECORD ELECTRICAL	27.938	10.583
RED BEECH FARM	4.001	2.534
SCHOOL LANE DUNHAM	5.132	3.299
SCRAGG E	13.574	7.842
SEAMONS ROAD	11.220	6.789
SINDERLAND GRN	3.158	1.962
SINDERLAND HOUSE FARM	3.318	2.070
TAYLOR ROAD	9.238	5.777
WHITEHOUSE FARM	3.290	2.050
WOODEND BRADGATE RD.	9.263	5.802
WOODHOUSE LN COMPACT	5.948	3.825
WOODHOUSE LN	5.981	3.846
ALTRINCHAM GRID : L3060 HARCOURT RD/NAVIGAT		
ALTRINCHAM METROLINK	15.498	8.137
BURLINGTON HSE	16.807	8.550
BARRINGTON ROAD	18.815	9.021
BREWERY STREET	13.847	7.606
BREWERY STREET	13.844	7.603
HARCOURT ROAD	23.486	9.977
HAZEL ROAD	16.258	8.428
NAVIGATION RD TRAFALGAR H	23.806	10.052
NORWEST CO-OP	14.445	7.813
RACKHAMS	14.812	7.933
SOUTHMARK HOUSE	16.611	8.451

Feeder / Busbar name of loads	Peak@10ms	RMS Break@90ms
	kA	kA
SPRINGFIELD RD	13.204	7.409
STAMFORD NEW ROAD	15.395	8.103
STATION BUILDINGS	12.846	7.237
VICTORIA ST ALT	13.704	7.558
WOODLANDS LANE	10.483	6.377
ALTRINCHAM GRID : L2247 T21/WOODCOTE RD		
ALMA RD	6.062	3.295
CHERRY LANE	4.985	2.815
CLOUGH AVE	4.928	2.799
COPPICE AVENUE	4.640	2.644
FIELDVALE ROAD	8.357	4.023
MEADWAY	5.972	3.252
OVERTON CRESCENT	5.446	3.029
RAGLAN ROAD	6.050	3.277
THE DRIVE	7.406	3.796
WALTON ROAD EASTWAY	7.351	3.739
WASHWAY ROAD 307	7.514	3.791
ALTRINCHAM GRID : L2242 BROADHEATH O/D		
BOOTH ROAD	12.229	6.952
BROADHEATH OUTDOOR	32.204	11.101
DEVISDALE	11.014	6.434
GREY RD	13.129	7.310
HIGHER DOWNS	9.672	5.808
LYNNFIELD HS CHURCH ST	18.440	8.988
OLDFIELD ROAD EAST	9.905	5.998
STAMFORD GRANGE	13.620	7.510
TOWNFIELD ROAD SCHOOL	16.035	8.313
ALTRINCHAM GRID : L2241 B&Q ATLANTIC ST		
B&Q ATLANTIC ST	25.108	10.391
BROADHEATH BRIDGE	22.587	10.033
DEANSGATE LN	12.200	7.237
MELDRUMS GR	12.559	7.403
RYALANDS	16.920	8.867
ALTRINCHAM GRID : L2245 ALTRINCHAM RET PK N		
ALTRINCHAM RETAIL PARK NO 1	24.369	10.302
DAVENPORT ROAD	23.714	10.211
SINDERLAND ROAD O/D SAT	14.237	8.291
VIADUCT RD	17.982	9.189
WATERHOUSE J	20.284	9.617
ALTRINCHAM GRID : L2246 MANCHESTER RD	#N/A	#N/A

Feeder / Busbar name of loads	Peak@10ms	RMS Break@90ms
	kA	kA
ATTENBURY LN NETWORK	11.364	6.789
ATTENBURYS LANE SWITCH	11.667	6.931
BOLLIN DRIVE	10.810	6.550
FRIESTON ROAD	9.088	5.717
HAWTHORN AVENUE	8.142	5.177
MALPAS DRIVE	13.156	7.530
MANCHESTER RD ALTRINCHAM	17.797	8.947
PARK GREENWAY	9.188	5.738
PARK ROAD 64	10.464	6.375
SOUTH TRAFFORD COLLEGE	14.556	8.040
TIMPERLEY METROLINK	8.011	5.098
WOODCOTE ROAD	15.694	8.363
ALTRINCHAM GRID : L3123 ATLANTIC ST NO3		
11 kV	9.737	5.658
6.6 kV	7.911	3.797
ALTRINCHAM SEWAGE	12.307	6.756
ATLANTIC ST NO 3	29.037	10.605
CATTERICK AVENUE	8.229	4.942
CEMEX	25.009	10.082
CHEPSTOW AVENUE	9.484	5.542
HURST AVE. 171	8.642	5.158
HURST AVE. 172	8.643	5.159
HURST AVE 38	9.119	5.380
LINGFIELD AVENUE	10.456	5.992
WESTBURY AVE 37	9.852	5.734
WOODHOUSE LANE	7.828	4.727
ALTRINCHAM GRID : L2243 THE FLEET		
BACK GRAFTON STREET	11.397	6.586
CHAPEL STREET	9.728	5.913
UNICORN	16.165	8.296
HIGH STREET ALT	12.104	6.880
GROBY RD	13.328	7.408
HIGH ST BUS PK	12.427	7.015
PRIVATE NETWORK	12.104	6.879
THE FLEET	21.741	9.644
THE GRAFTONS	10.501	6.245
TOWN HALL DEVT	14.615	7.815
WOOLWORTHS ALTRINCHAM	13.298	7.355

Appendix H.2 Denton West Location

Feeder / Busbar name of loads	Peak@10ms	RMS Break@90ms
	kA	kA
DENTON WEST : F547 CORNHILL LN		
BOOTH DALE RD	5.40	3.38
CORNHILL LANE	13.82	8.42
DUCHESS DR	7.84	5.01
KINGS RD AUDENSHAW	7.72	4.93
M60 PILLAR PMT KINGS RD	9.10	5.82
MANCHESTER RD AUDENSHAW	5.87	3.70
DENTON WEST : F47 CORONATION ST		
CORONATION ST	13.48	7.98
DENTON HALL	8.15	5.11
DENTON WWTW	9.03	5.65
EDMC0019J7 (CATHERINE ST WEST)	12.75	7.63
FAREBROTHER WINDMILL LN	8.35	5.23
GORTON CRESCENT	9.00	5.64
JACKSONS WINDMILL LN	7.77	4.89
W C B DENTON	9.32	5.90
DENTON WEST : F149 KENSINGTON GR		
ALPHAGATE DR	13.65	8.10
J&J HARVEY	11.01	6.77
J.SAINSBURY DENTON	10.81	6.66
KENSINGTON GROVE	22.04	11.08
PETCARE	9.59	5.99
DENTON WEST : F1332 ASHBROOK AVE		
EDMC0019KE (ASHBROOK AVENUE)	24.51	11.22
THOMPSON RD	15.93	9.20
SYSTEM 3 WINDMILL LN	16.95	9.03
DENTON WEST : F549 E PASS & CO /PARKWAY		
PARKWAY DENTON	11.05	6.81
PARKWAY	10.68	6.61
PASS E AND CO	12.96	7.79
DENTON WEST : F243 GRANADA RD		
DANE BANK	12.30	7.47
DENTON HALL FM	9.34	5.85
FAIRVIEW ROAD	7.42	4.74
GRANADA RD	21.11	10.79
HULME RD	14.74	8.59
WINDERMERE AVENUE	9.04	5.76
DENTON WEST : F1519 DEBDALE PK		
DEAN RD GORTON	11.11	6.85

DEBDALE PK	17.93	9.80
RYDER BROW RD	9.86	6.10
WALL WAY	13.21	7.92
DENTON WEST : F1460 DENTON WEST NETWORK		
ASHKIRK ST	6.48	4.08
DENTON DRAINAGE	11.10	6.85
DENTON WEST NETWORK	38.34	13.52
THORNLEY PARK	19.58	10.31
DENTON WEST : F3168 WRIGHT ROBINSON SPO		
ABBEY HEY LANE 352	10.72	6.42
BELLAMY COURT	9.92	6.01
FALMER ST	13.35	7.67
JETSON ST	12.17	7.11
WRIGHT ROBINSON SPORTS COLL	13.95	7.94
DENTON WEST : F351 GORTON/DEAN RD GORTO		
BEECH HURST HSG	8.74	5.39
GORTON POOL	9.35	5.72
GORTON	14.15	7.88
HIGH BANK	11.66	6.84
HYDE RD 550	9.70	5.91
HYDE RD RETAIL GORTON	10.47	6.30
TESCO GORTON	10.39	6.26

Appendix H.3 Irlam Location

Feeder / Busbar name of loads	Peak@10ms	RMS Break@90ms
	kA	kA
IRLAM : F76 TRANSPORT YARD/GRIDCO		
GRIDCO NO. 1	11.66	6.69
TRANSPORT YARD	10.97	6.36
IRLAM : F3999 WERIT UK/CATERPILLA		
BRINELL DR NO 1	15.99	8.28
CATERPILLAR	19.70	9.40
CHEMICAL STORAGE	13.60	7.45
CPI MORTARS	14.61	7.78
IRLAM SEWAGE WORKS	13.08	7.20
KELLOGGS IRLAM	13.42	7.32
MANCHESTER INVESTMENT CASTINGS	16.33	8.39
MARTENS RD	14.15	7.61
OMEGA TECHNOLOGY 1	15.93	8.28
OMEGA TECHNOLOGY 2	14.43	7.74
OPAL TELECOM SITE NO 2	12.98	7.15

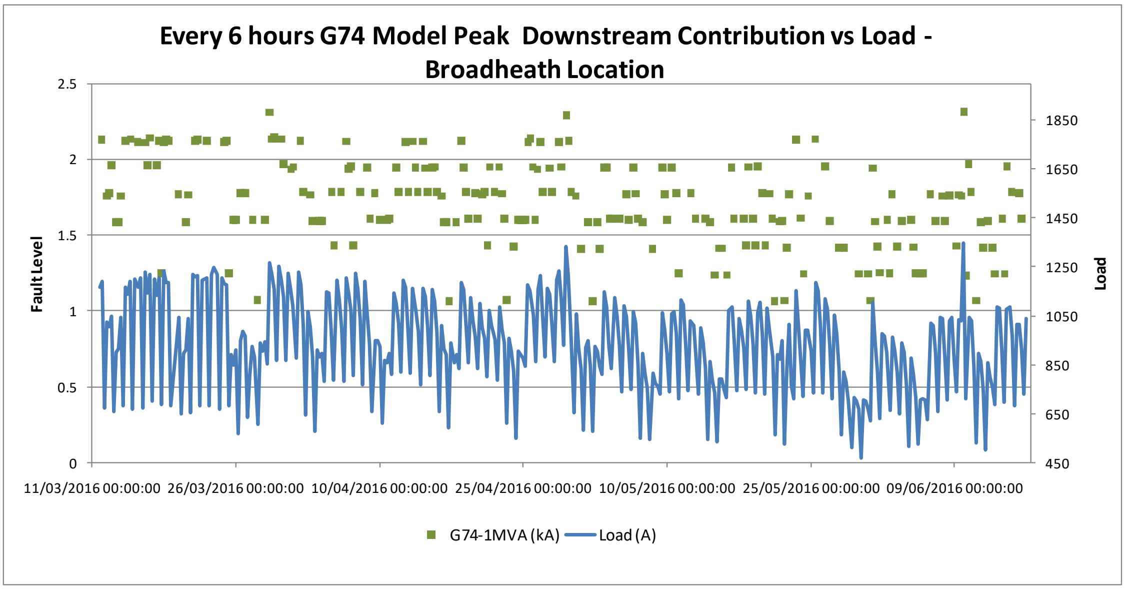
Feeder / Busbar name of loads	Peak@10ms	RMS Break@90ms
	kA	kA
IRLAM : F3900 WERIT UK		
WERIT UK	18.38	9.02
IRLAM : F3636 ENVIRONMENTAL POLYM		
ENVIRONMENTAL POLYMERS	26.80	10.99
IRLAM : F3145 TRAMWAY RD		
ASTLEY RD	9.29	5.78
BARTON GRANGE FM	1.67	0.85
BARTON MOSS FM	1.69	0.87
BIRCH COTTAGE	2.55	1.44
CAD MOSS RD	3.54	2.10
CELL SITE 129A	1.90	1.01
FOUR LANE ENDS COTTAGES	3.04	1.76
HEPHZIBAH	3.56	2.11
IRLAM & CADISHEAD SCH	13.58	7.67
LARKHILL COTTAGES	2.70	1.53
LARKHILL FARM	3.25	1.90
M62 ASTLEY RD SUPPLY	4.56	2.79
M62 SUPPLY RASPBERRY LN	1.76	0.92
MANOR FM	1.65	0.84
MOSS FARM	2.12	1.15
MOSS HOUSE FARM	3.19	1.86
MOSSLAND	2.69	1.53
NEW FARM	2.85	1.64
OAKFIELD	2.28	1.25
OXCHEEK COTTAGE	1.85	0.98
PROSPECT GRANGE	5.52	3.42
PROSPECT RD	7.61	4.81
RED BARN PEAT WORKS	2.20	1.20
ROSE FARM	6.70	4.21
TRAMWAY RD	34.87	11.79
WESTHOLME	3.54	2.10
WOODBARN FARM	2.28	1.26
WOODSTOCK FARM	3.97	2.38
WORSLEY VIEW	4.74	2.91
IRLAM : F2504 DEAN RD EMBEDDED		
BESSEMER ROAD	9.07	5.34
BRINELL HS	12.10	6.77
DEAN RD EMBEDDED	18.04	8.87
DEAN RD	15.90	8.22
FERROUS WAY	8.88	5.24

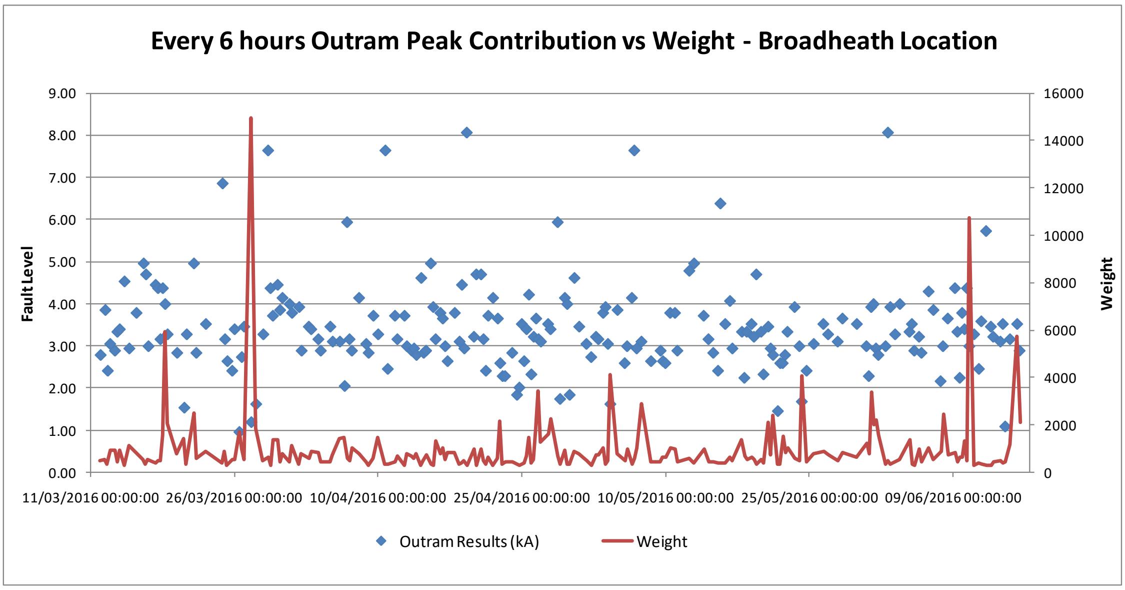
Feeder / Busbar name of loads	Peak@10ms	RMS Break@90ms
	kA	kA
FLUOROCARBON IRLAM	8.15	4.86
GILCHRIST RD.	9.41	5.52
MCR.BLAST CLEAN	8.67	5.13
OPAL TELECOM	14.00	7.53
VARN PRODUCTS	10.30	5.97
IRLAM : F1566 MONA WAY		
CURLEW DRIVE	7.42	4.49
CUTNOOK LANE	8.36	4.91
FERRY ROAD	12.83	7.00
FERRYHILL RD	11.30	6.35
HERON DRIVE	8.83	5.15
MONA WAY	17.19	8.56
SANDY LANE	10.28	5.88
SCHOOL LANE	9.58	5.53
IRLAM : F1174 ROSEWAY AVE		
AMOCO	9.11	5.53
BUTCHERSFIELD GENERATION	4.82	2.92
CADISHEAD SEWAGE WORKS	6.24	3.86
CUMBERLAND AVE	6.95	4.29
EDMC001VRC (LANCS TAR)	8.40	5.15
EDMC001VRE (LANCS TAR B)	8.41	5.15
EDMC002EKO (LORDS ST CADISHEAD)	7.47	4.61
FAIRFIELD RD CADISHEAD	6.57	4.05
FIR ST WEST	5.17	3.20
FIR STREET EAST	6.10	3.75
GRAHAM CRESCENT	6.01	3.72
MOSS LANE	5.55	3.40
NEW MOSS RD	4.90	3.00
ROSEWAY AVE	11.06	6.52
IRLAM : F1125 SOAPSTONE WAY/CWS B		
BOYSNOPE P.M.T.	5.92	3.64
C.W.S. BOTTLING	16.45	8.67
CADISHEAD WAY	11.58	6.79
FAIRHILLS RD IND EST	7.86	4.84
FIDDLERS LANE	7.99	4.83
FLUID MOTION LAB	4.82	2.94
MAKRO	5.39	3.31
MORGAN WALLWORKS	7.01	4.27
MSC CANAL BRIDGE	12.57	7.22
NAPIERS	5.92	3.63

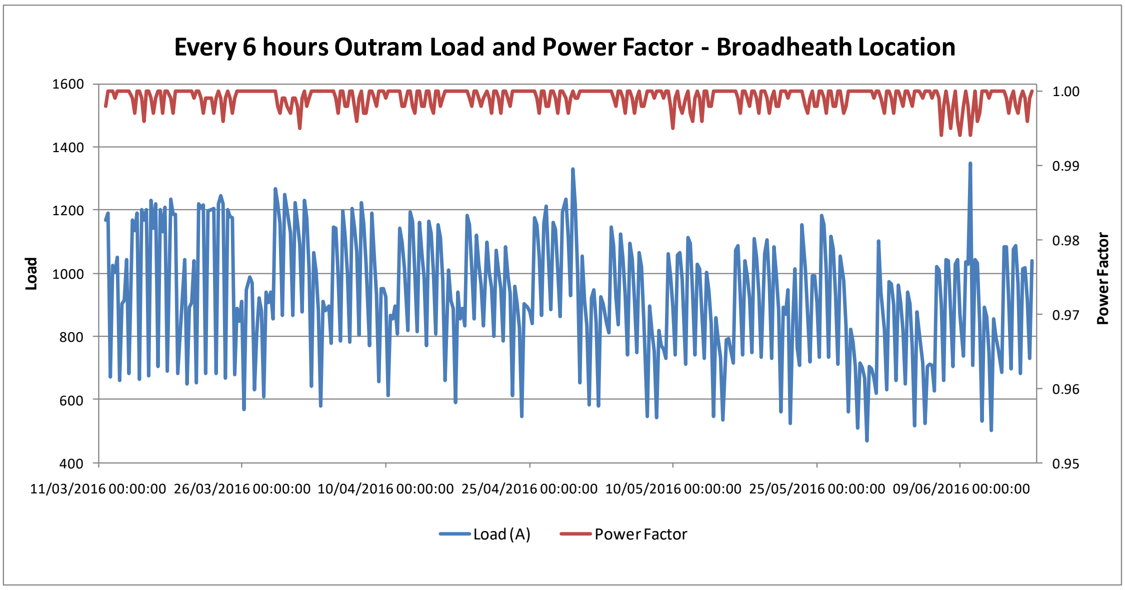
Feeder / Busbar name of loads	Peak@10ms	RMS Break@90ms
	kA	kA
SANDYWARPS	9.26	5.63
SOAPSTONE WAY	16.01	8.53
IRLAM : F1112 VICTORIA RD		
BEECH AVENUE	7.74	4.76
BOAT LANE	8.98	5.47
BROADWAY IRLAM	11.48	6.73
FAIRHILLS RD	5.09	3.13
GRAZING DRIVE	8.25	5.06
ROSCOE RD	4.73	2.89
ST JOHN ST	11.71	6.84
VICTORIA RD IRLAM	14.12	7.85
WOODROW WAY	4.74	2.90
IRLAM : F1111 TESCO IRLAM		
FLIXTON SEWAGE	11.85	6.88
IRLAM WHARF RD	11.09	6.43
TESCO HYPERMARKET IRLAM	20.11	9.68

Appendix I – Peak Downstream Detailed Analysis - Additional Results

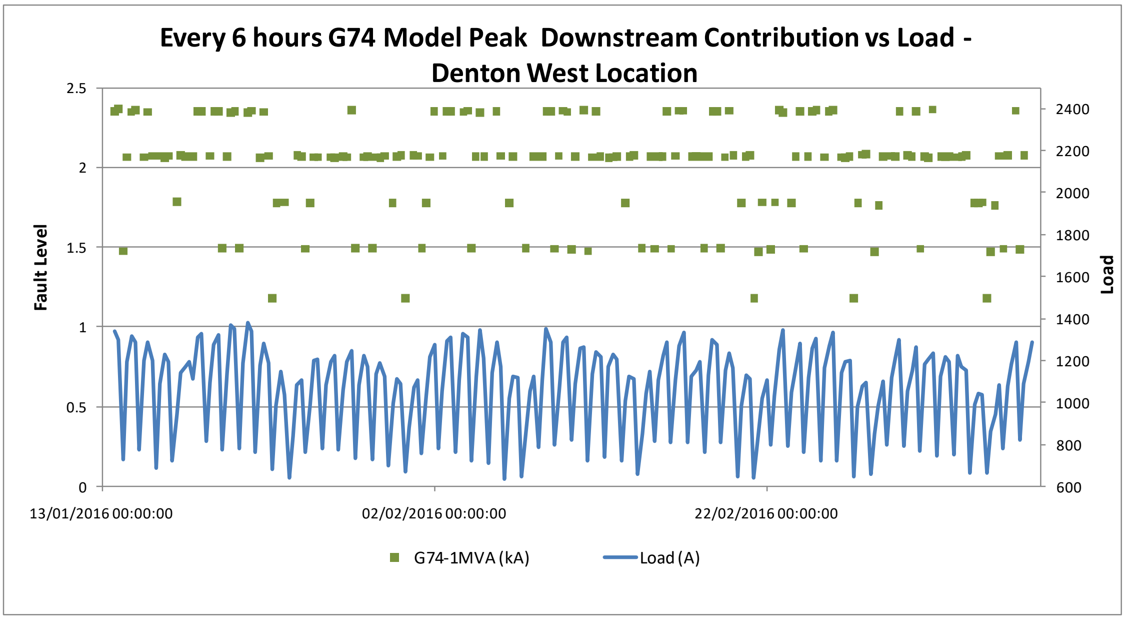
Appendix I.1 Broadheath Location

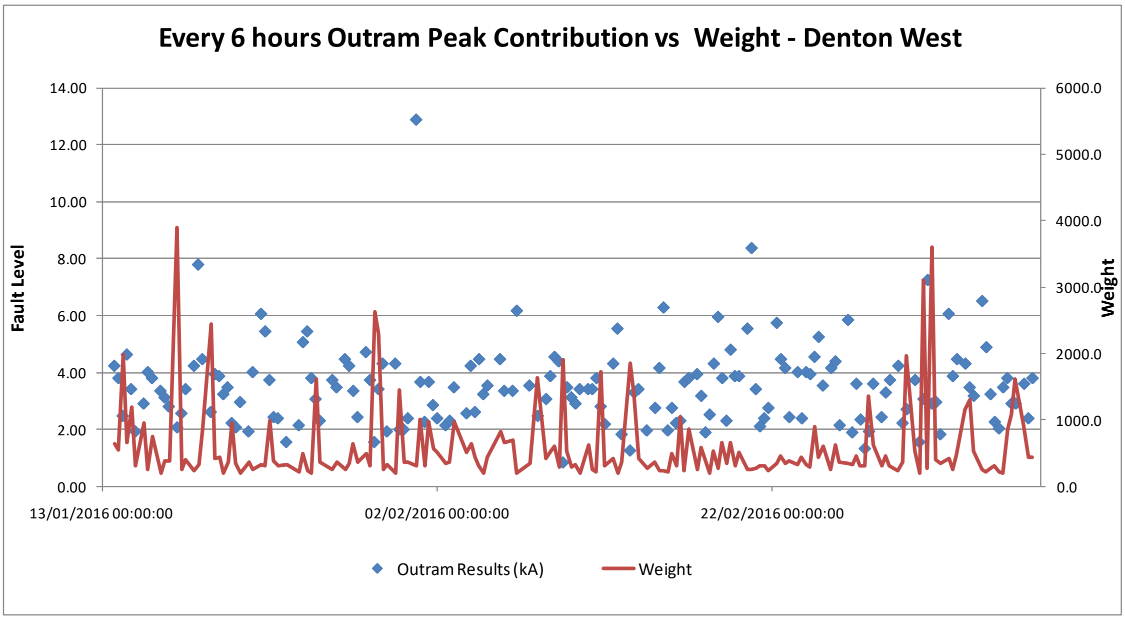


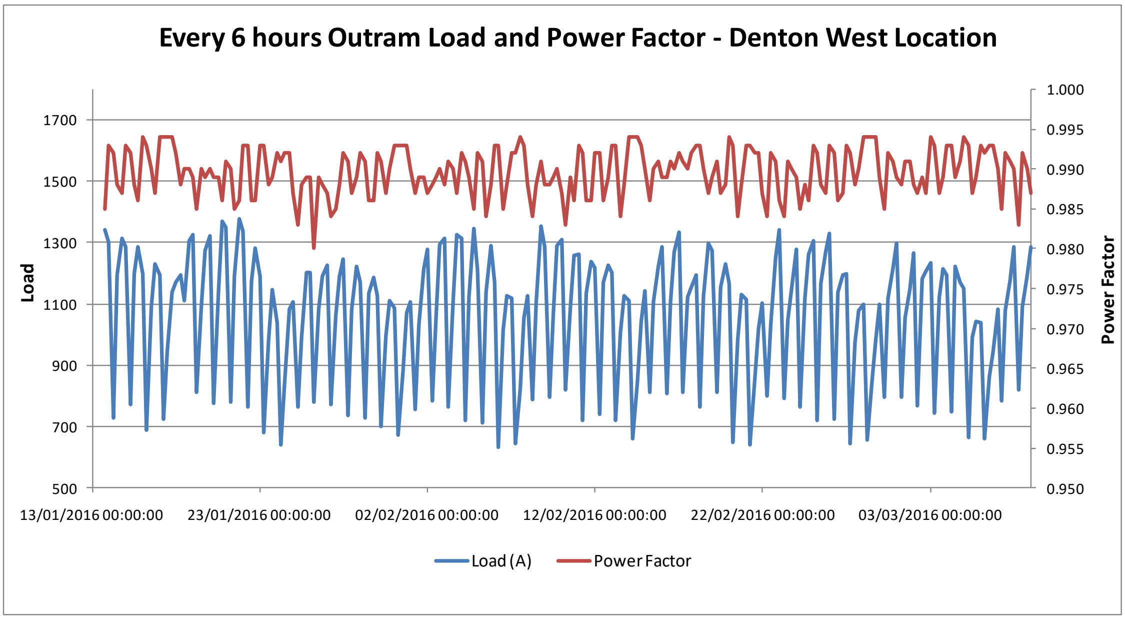




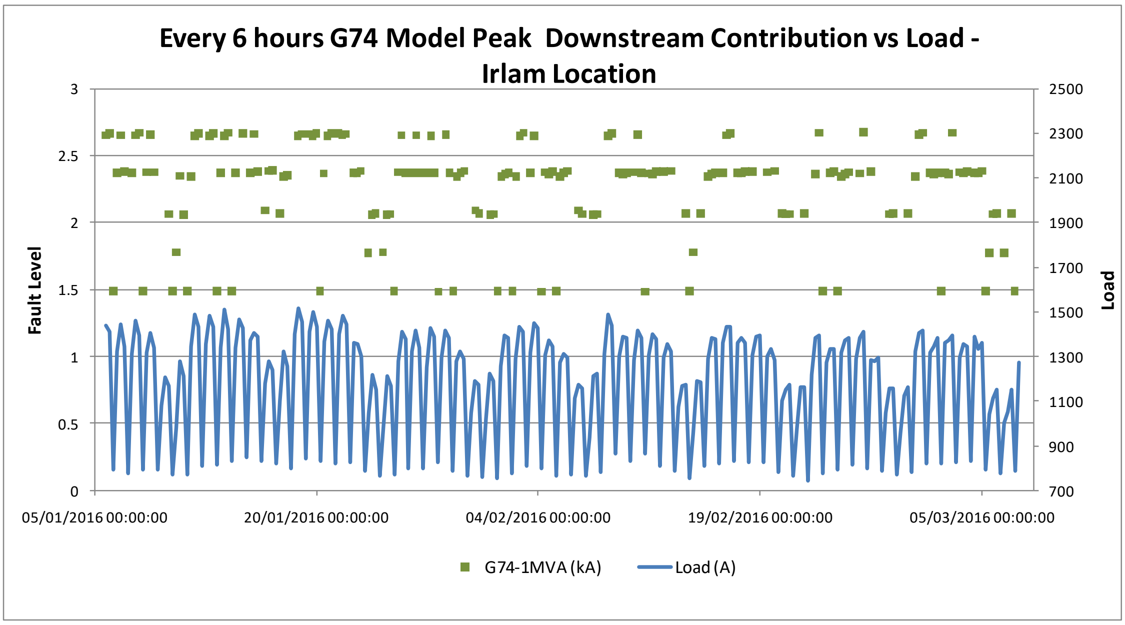
Appendix I.2 Denton West Location

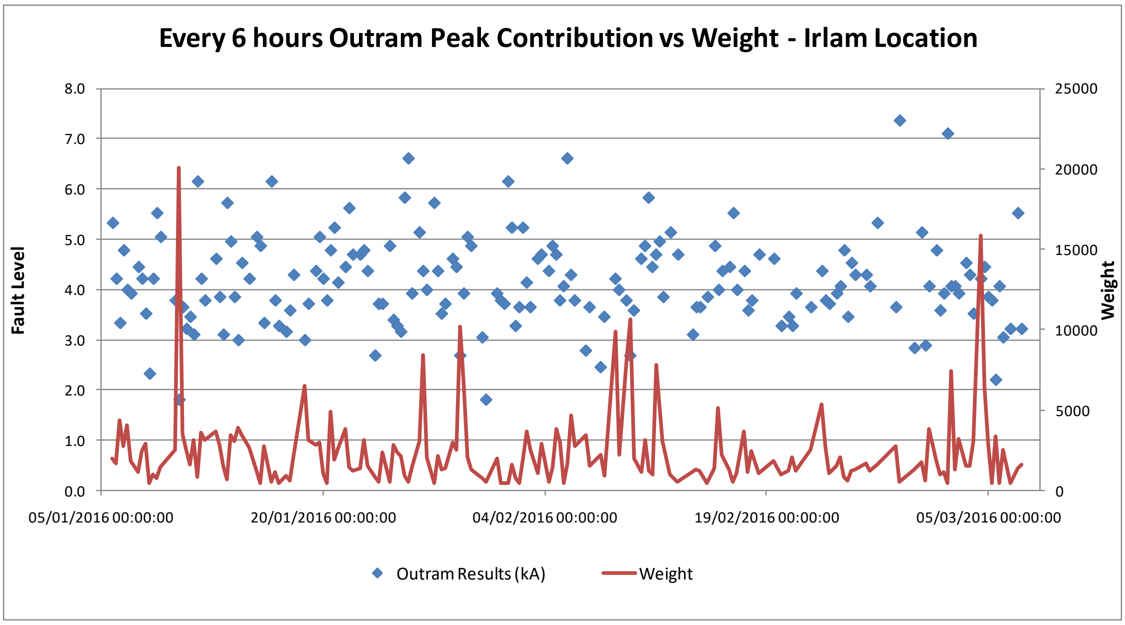


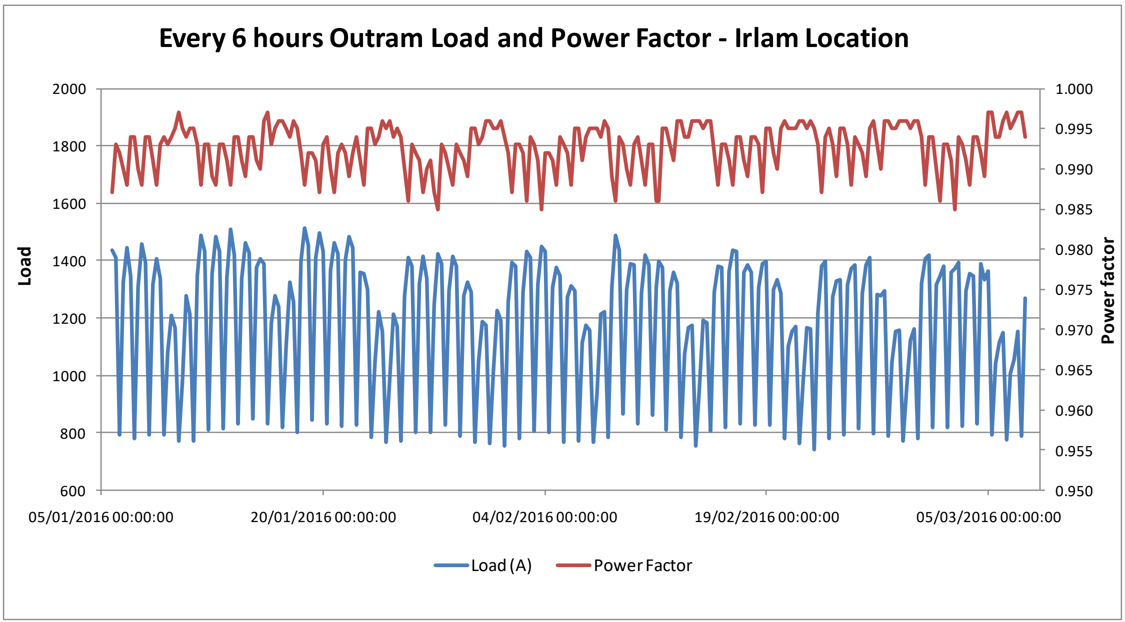

Every 6 hours Outram Peak Contribution vs Weight - Denton West
Fault Level
Weight
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
6000.0
5000.0
4000.0
3000.0
2000.0
1000.0
0.0
13/01/2016 00:00:00
02/02/2016 00:00:00
22/02/2016 00:00:00
Outram Results (kA)
Weight


Every 6 hours Outram Load and Power Factor - Denton West Location
Load
Power Factor
1700
1500
1300
1100
900
700
500
1.000
0.995
0.990
0.985
0.980
0.975
0.970
0.965
0.960
0.955
0.950
13/01/2016 00:00:00
23/01/2016 00:00:00
02/02/2016 00:00:00
12/02/2016 00:00:00
22/02/2016 00:00:00
03/03/2016 00:00:00
Load (A)
Power Factor

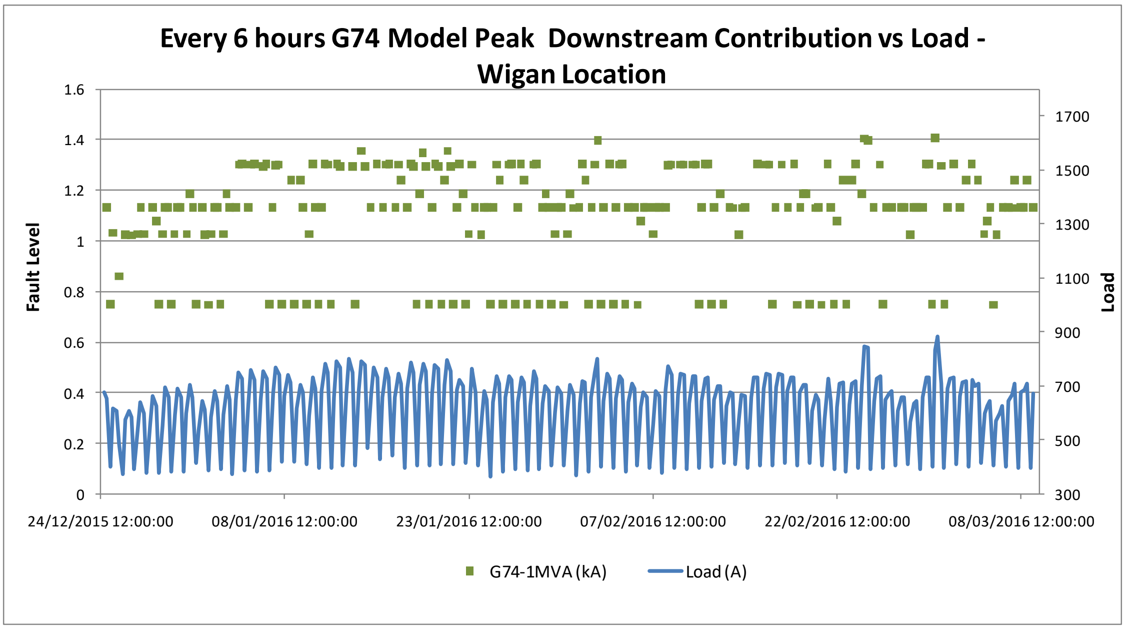
Appendix I.3 Irlam Location

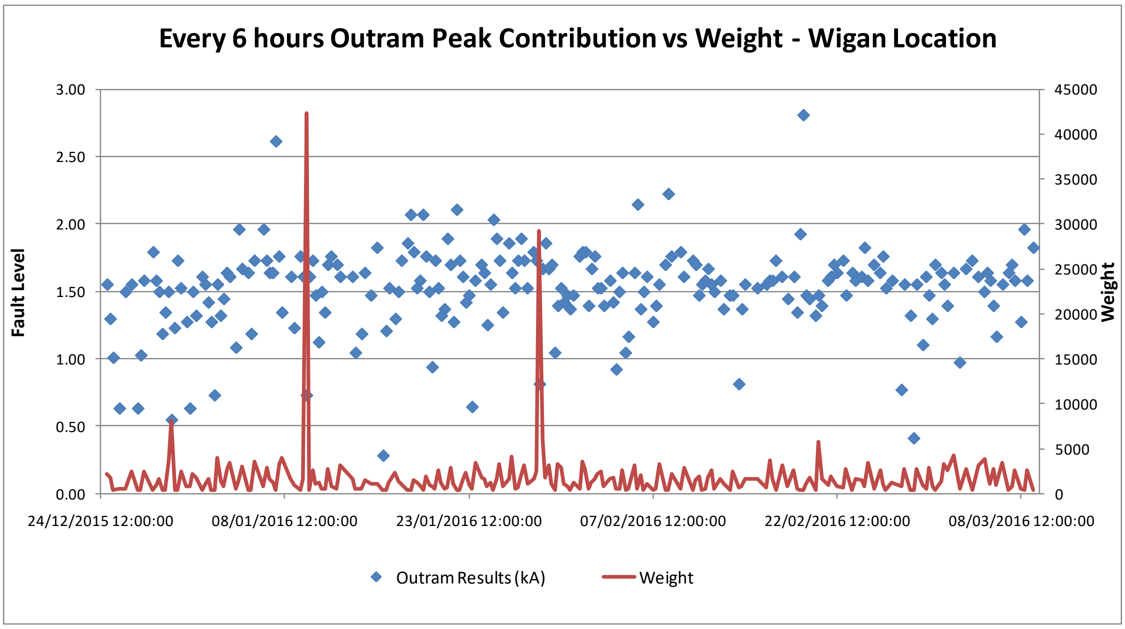


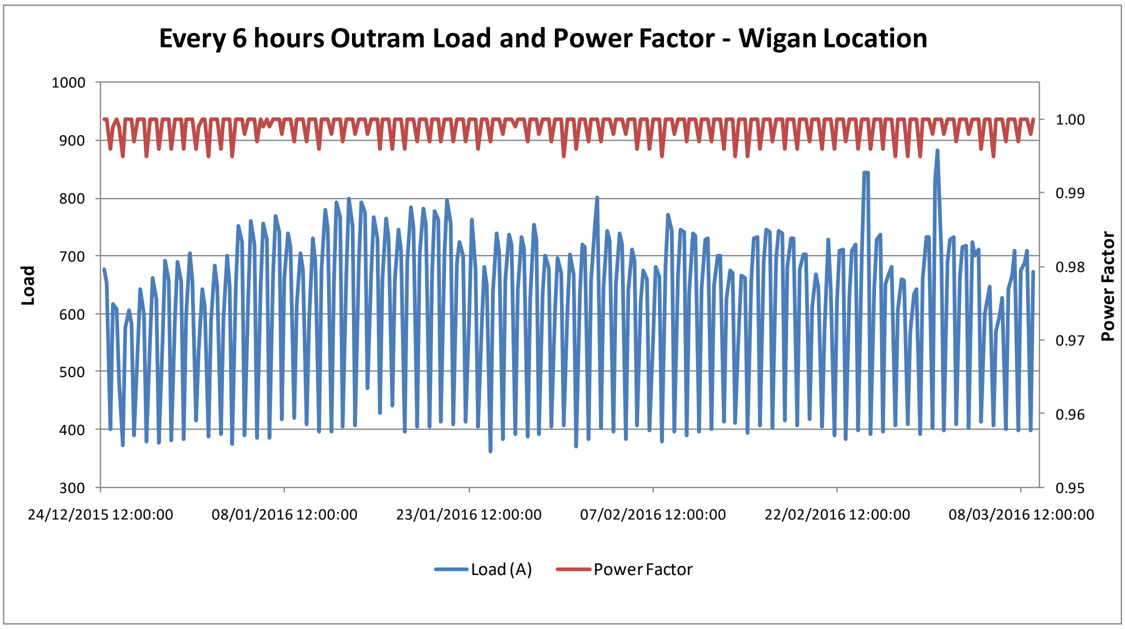




Appendix I.4 Wigan Location




Every 6 hours Outram Peak Contribution vs Weight - Wigan Location
Fault Level
Weight
3.00
2.50
2.00
1.50
1.00
0.50
0.00
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
24/12/2015 12:00:00
08/01/2016 12:00:00
23/01/2016 12:00:00
07/02/2016 12:00:00
22/02/2016 12:00:00
08/03/2016 12:00:00
Outram Results (kA)
Weight


Every 6 hours Outram Load and Power Factor - Wigan Location
Load
Power Factor
1000
900
800
700
600
500
400
300
1.00
0.99
0.98
0.97
0.96
0.95
24/12/2015 12:00:00
08/01/2016 12:00:00
23/01/2016 12:00:00
07/02/2016 12:00:00
22/02/2016 12:00:00
08/03/2016 12:00:00
Load (A)
Power Factor