Customer-Led Network Revolution

CLNR Power Quality Assessment

Impacts of Low Carbon Technologies

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Customer-Led Network Revolution

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Executive Summary

This report describes the results of power quality measurements made to assess the impact of new 'Low Carbon Technologies' (LCTs) such as Heat Pumps, Photovoltaic Generation, microCHP and Electric Vehicles as well as the effects of network interventions such as Electric Energy Storage and Voltage Regulators on the distribution networks to which they have been applied.

Two heat pump clusters were monitored with slightly different results although the heat pumps employed on each were the same. Neither of the clusters resulted in excessive values of flicker being generated as a result of the operation of the heat pumps. Measurement of individual heat pump customers yielded variable results which appear to be dependent upon both the characteristics of the heat pump itself and the network to which it is connected.

The individual British Gas Customer measurements showed no adverse Power Quality effects with the heat pumps exhibiting very gentle starting characteristics. However monitoring of a single heat pump installation following a voltage complaint showed very different results in terms of the operating characteristics of the heat pump and the impact upon the network. The issues experienced in this case were a combination of the high starting current exhibited by the heat pump motor and the fact that the connection point was in a rural location where a higher supply impedance would be expected compared to more urban locations. The heat pump in question had a normal operating current of 16.07A, without any form of soft start applied the motor is stated by the manufacturer to have a starting current of up to 130A, even with the soft start facilities offered by the manufacturer a starting current of up to 48A was specified.

In the forthcoming review of ENA Engineering Recommendation P28 clear guidance on the requirements for connection of heat pumps must be developed. It is clear from the measurements which have been made and reviewed in this project that there is significant variation between the operating characteristics of different heat pump designs which will make some designs unsuitable for locations with a lower fault level and it is the assessment of this that this guidance must address. Any such guidance must take account of the requirements of the applicable EU directives.

The harmonised standards (IEC 61000-3-3 ed 3.0 2013 Electromagnetic Compatibility (EMC) Part 3-3: Limits – Limitation of voltage changes voltage fluctuations and flicker in public low voltage supply systems, for equipment with rated current ≤16A per phase and not subject to conditional connection & IEC 61000-3-11 ed 1.0 2000: Electromagnetic Compatibility (EMC) – Part 3-11 Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems – Equipment with rated current ≤75A and subject to conditional connection) which govern the permissible voltage disturbances from equipment under the terms of the Electromagnetic Compatibility (EMC) Directive do not at present contain detailed requirements for the testing of heat pumps in particular those which employ auxiliary electric heating elements where they may have a separate electrical supply but are switched on from a single controller. It is stated in the EMC Directive that such arrangements should be tested as a single unit. However, some manufacturers are claiming that since the auxiliary heater need not be one of their units they should be tested and assessed

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separately for compliance with the requirements of the standards drawing an analogy with a computer and a printer. This approach effectively gives the whole system two bites at the emissions cherry and may lead to systems being wrongly declared compliant with the requirements of EN 61000-3-3 allowing unconditional connection. It is essential, if we are to avoid situations where equipment is declared suitable for unconditional connection due to a test regime which is apparently at odds with the EMC Directive guidance and subsequently causes problems in real life operation, that this loophole must be closed with defined testing requirements at the very least requiring the testing of such units as one whole system in line with the requirements of the EMC directive. To achieve this it is necessary for the UK Electricity Industry to effectively engage with appropriate standards committees and to seek a coordinated approach from Eurelectric.

Photovoltaic generators should present less direct concern in this regard as the threshold where the requirements of the governing EMC standards change coincides with the capacity limit for the inform and fit process described in Engineering Recommendation G83 and enshrined in the Electricity Safety Quality and Continuity Regulations. As such any larger capacity installations which hope to benefit from Feed in Tariff payments should have gone through the process of applying for a connection under G59/3 even if it is proposed to use type tested equipment which does not require witness testing as part of the connection process.

Electric Vehicles may present an interesting challenge in regard to preparing guidance on the provision of connections to control harmonic emissions and voltage disturbances on the network. In the clusters and in the case of each of the individual customers monitored the charger was limited to 16A capacity and as such the car and charger should be tested against EN 61000-3-2 and EN 61000-3-3 using the reference supply impedance, which according to IEC TR 60725 >95% of UK customers have a supply impedance at or below this value, to determine compliance. However in the case of a higher capacity charger the standards require either testing with the reference supply impedance demonstrating that the disturbance and harmonic emissions remain below limits or determination of the maximum supply impedance at which the acceptable limits are achieved. However, the charging point is largely a passive element in this arrangement with the power electronics controlling the charge of the batteries being located in the car. There arises therefore a question of how, if indeed it proves to be necessary at all, a DNO will be able to manage the connection of such a car to their network. The charging point having been installed, if and when the customer subsequently changes their car for another model the characteristics of the car may be different rather than the charging point which is essentially passive. It should be noted that as this project has not measured any charging conditions in excess of the 16A capacity there is no evidence that higher capacity chargers will necessarily present any particular power quality challenges and that the issue may be more a question of managing the current capacity of the network as the energy capacity of batteries increases as it must inevitably do if the range capacity of EVs is to be substantially increased, but nevertheless the existing approach to managing connection of distorting and/or disturbing loads and ensuring that the proposed connection point has a suitably low supply impedance doesn't work well if that load is by its very nature movable.

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The initial connection of the Electrical Energy storage devices was noticed during commissioning to have a small beneficial effect in terms of the harmonic emissions at the point of connection as the internal filters associated with the units acted to mitigate existing background levels by a small but measurable amount.

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1 Introduction

A key aspect of the Customer Led Network Revolution (CLNR) project is to understand the effects of clusters of Low Carbon Technologies (LCTs) and a range of network interventions on existing distribution networks. This report examines the results of the power quality monitoring programme put in place to monitor the effects of clusters of Photovoltaic generation, Heat Pumps and Electric Vehicles and the effects network interventions such as Electrical Energy Storage devices.

The monitoring scheme comprised measurements at individual domestic customers' premises with one of the following LCTs, Heat Pumps, Electric Vehicles, MicroCHP, or Photovoltaic Generation. In addition a number of customers without any LCTs in both rural and urban networks were monitored to provide a control group.

In addition to the clusters of LCTs on the Low Voltage (LV) distribution networks the effects of network interventions which may mitigate some of the anticipated effects were also trialled and monitored.

The monitoring requirements to demonstrate the effective operation of elements of the CLNR programme were outlined at the outset of the project. These generic requirements were refined and applied to the situation of the actual network locations selected.

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2 Methodology and Assumptions

All of the Power Quality Monitoring was carried out using Power Standards Laboratories PQubes. These are Class A power quality meters compliant with the specified method of power quality measurement laid down in IEC 61000-4-30 ed 2.0 2008: Electromagnetic Compatibility (EMC_ Part 4-30: Testing and Measurement Techniques – Power Quality Measurement Methods. Minimum, Average and Maximum values of Voltage Current and Active and Reactive Power were recorded every minute based on ½ cycle rms values. Values for the individual Voltage Current and Harmonics were recorded over 10 minute averages in line with the requirements of BS EN 50160 and IEC 61000-4-30. Similarly values of short term and long term flicker Pst and Plt were recorded.

The measurements of the individual LCTs were made at British Gas Domestic Customers' premises using a PQube configured to measure two currents and the infeed voltage(s). Two connection arrangements were employed. The first arrangement measures the gross premises current on one CT whilst the second CT measures the current associated with the LCT being monitored. This arrangement is illustrated in Figure 1 below, this represented the least intrusive requirement for installation.

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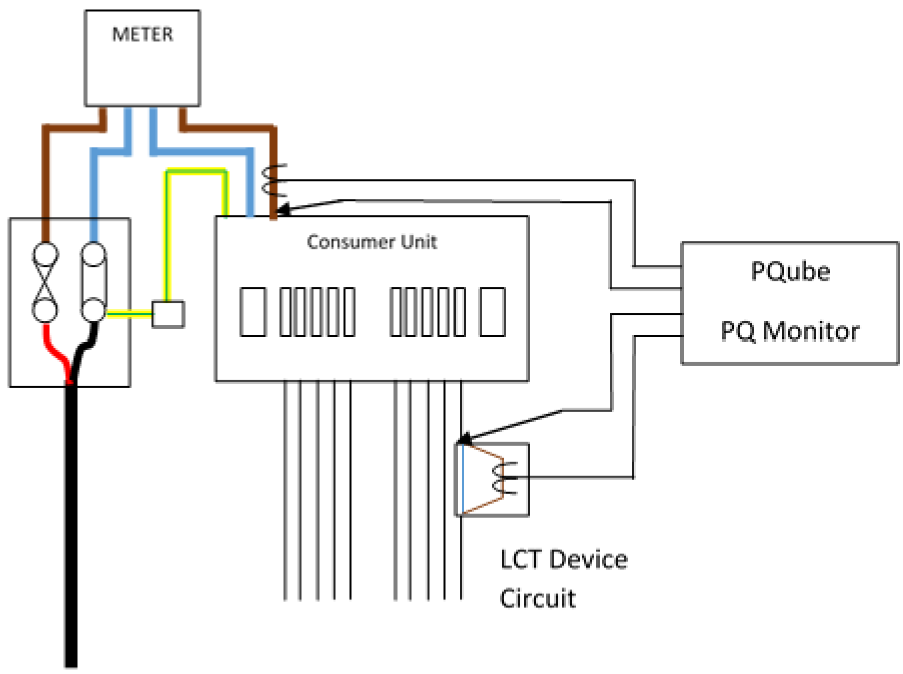

Figure 1 Connection to premises with a single consumer unit for individual customer monitoring

A second method which measured the general house current separately from the LCT current was also employed this is illustrated in Figure 2 below.

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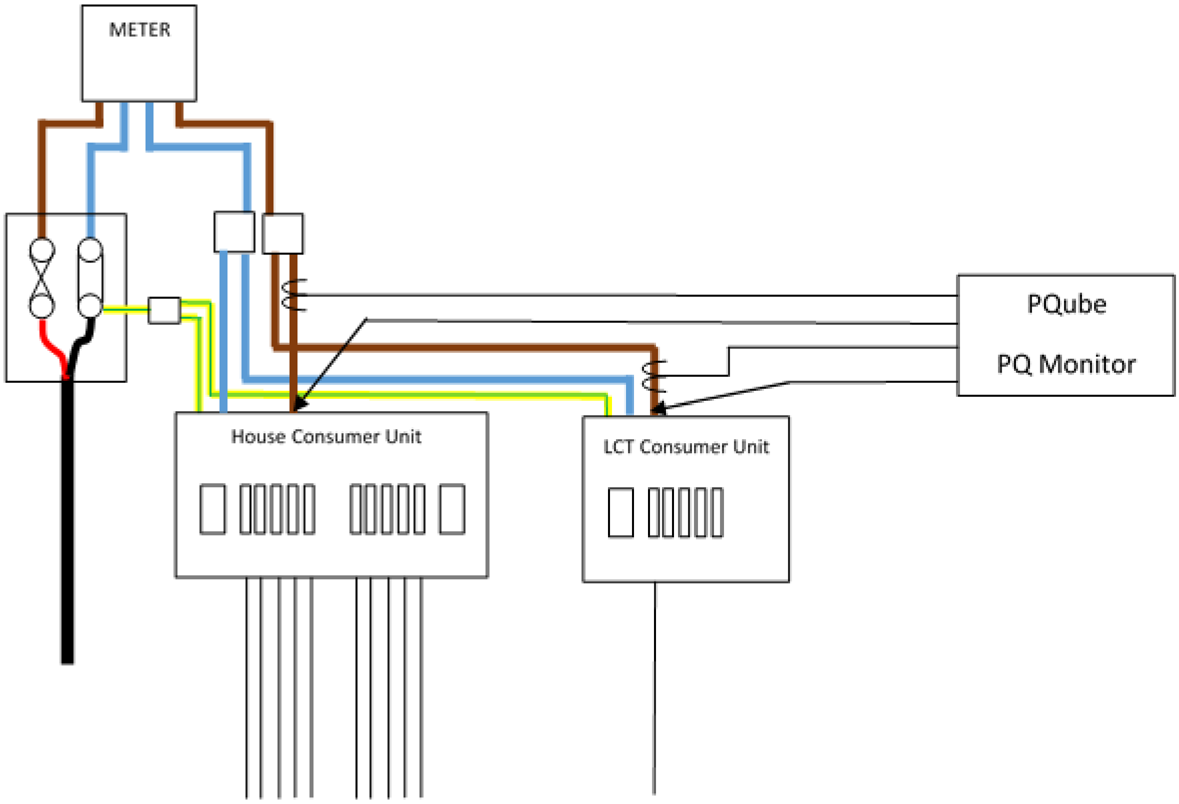

Figure 2 Connection to premises with two consumer units for individual customer monitoring

Measurements on the network were made at the source LV boards in the substations and at mid-point and feeder end positions along selected LV feeders using Prysmian Linkboxes designed to house the PQube. Measurements at the source and mid-point of feeders include current measurements whilst clearly there is no current measured at the end point of a feeder. The three phase measurements available on the network monitoring devices also allow the level of voltage unbalance to be measured.

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3 PQ Monitoring Results for Individual LCTs

The following sections describe the results obtained for the individual monitoring of the LCTs being examined under this project.

3.1 Heat Pump

Measurements were made at four British Gas Domestic Customers' premises to assess the effect of the operation of heat pumps at the point of connection. The results of the operation of the heat pumps over the winter 2013/14 is described in the sections below. The focus was on obtaining measurement over the winter period as this represents the most onerous conditions for the heat pump.

3.1.1 Heat Pump 1

The trace of the gross current drawn by the premises and the current drawn by the heat pump is shown in Figure 3 below. This plot also includes a measure of the voltage total harmonic distortion (THD) during the period. Although it can be seen that the levels of harmonic distortion rise and fall in a cyclic manner with the variation in load the magnitude of voltage harmonic distortion is well below the planning level of 5% at LV.

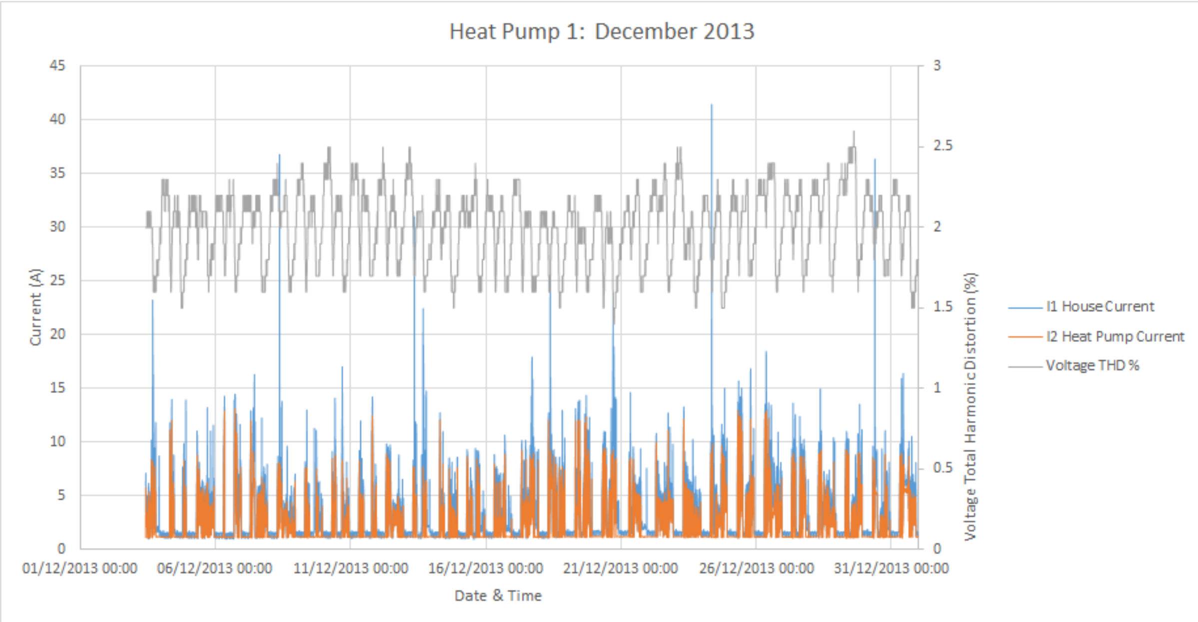

Figure 3 House & Heat Pump Current and Voltage THD – December 2013

It can be seen in figure 4 below that the heat pump is the dominant load over the course of a day. There are some short term high loads but for the majority of the day the overall house load follows the profile of the heat pump operation, which repeatedly cycles throughout the day presumably

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once the premises have reached the desired temperature. The value of voltage THD varies with little or no observable correlation between the operation of the heat pump and the level of distortion.

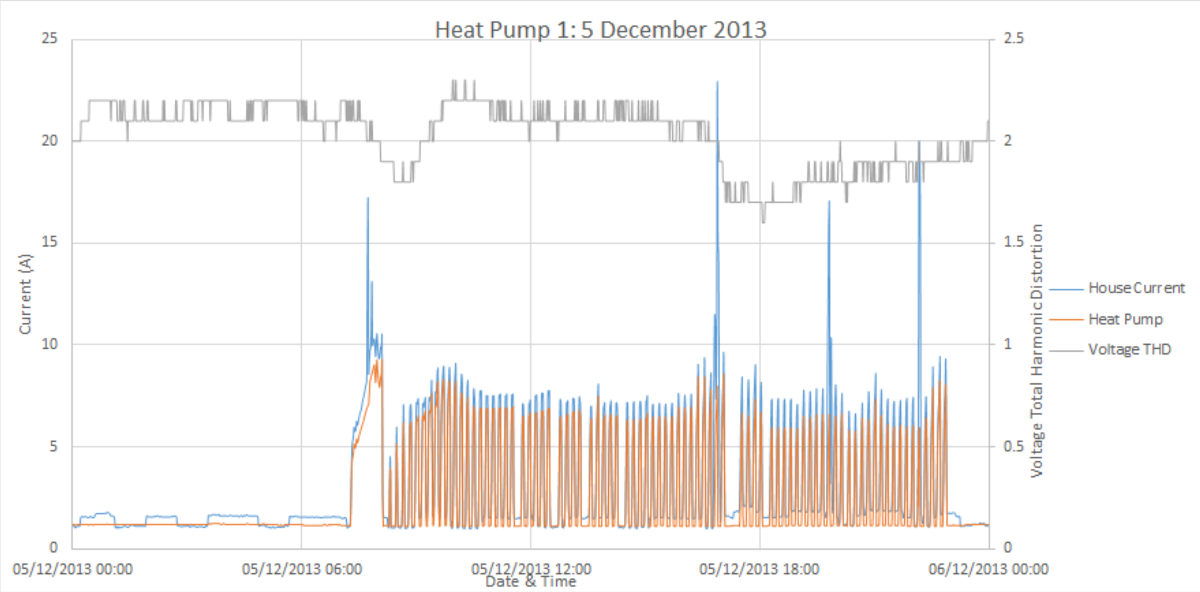

Figure 4 House & Heat Pump Current and Voltage THD – 5 December 2013

However the heat pump can be seen to have a very effective soft start facility applied to the motor as there is no evidence of a sharp peak of current when the heat pump starts, this is evident from the further expanded trace in Figure 5 which shows the maximum, minimum and average currents during each 1 minute period based on ½ cycle rms values. There is no significant spike as the heat pump starts which suggests a soft start applied to the motor control.

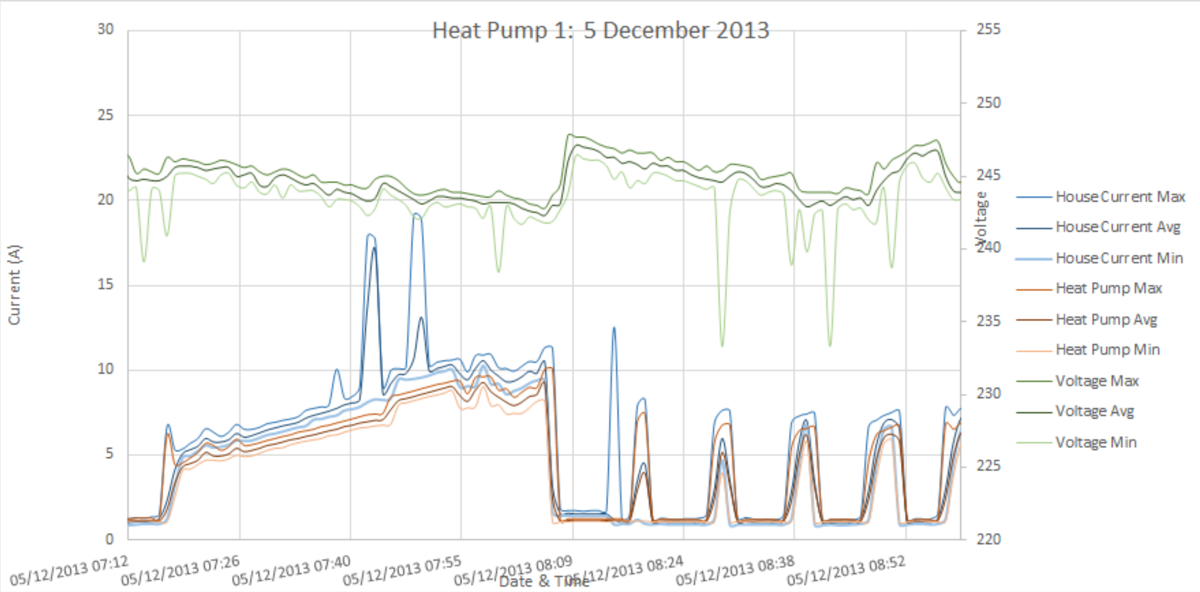

Figure 5 Supply Voltage Variation, Min Avg & Max currents – 5 December 2013 (pm)

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The flicker levels recorded are not shown on these graphs as they at a very low level with a maximum value of 0.03 being recorded, and are almost constant throughout the operation of the heat pump. It can be seen from the trace above that the voltage variation within each one minute average period is typically less than 2V between the maximum and minimum levels or only a 1% voltage change. The changes in current observed in this monitoring as the heat pump starts operates and stops are not sufficient in terms of either the magnitude or frequency of the change to cause flicker problems. It should be noted that the maximum operating current of the heat pump observed during the overall monitoring period is 13.7A.

During the day once the initial morning heating cycle has brought the premises up to the target temperature the heat pump appears to cycle approximately every 5-6 minutes.

3.1.2 Heat Pump 2

Figure 6 shows the results of the heat pump 2 operation. Similar to the first example the heat pump is the dominant load for the majority of the time it is operating. There are again examples of shorter duration high current for the house at the beginning of a cycle when the heat pump has been idle for a period. However these peaks of current are not reflected in the trace for the heat pump, suggesting that if they are in some way related to the operation of the heat pump that they are the result of a second load fed separately from the consumer unit.

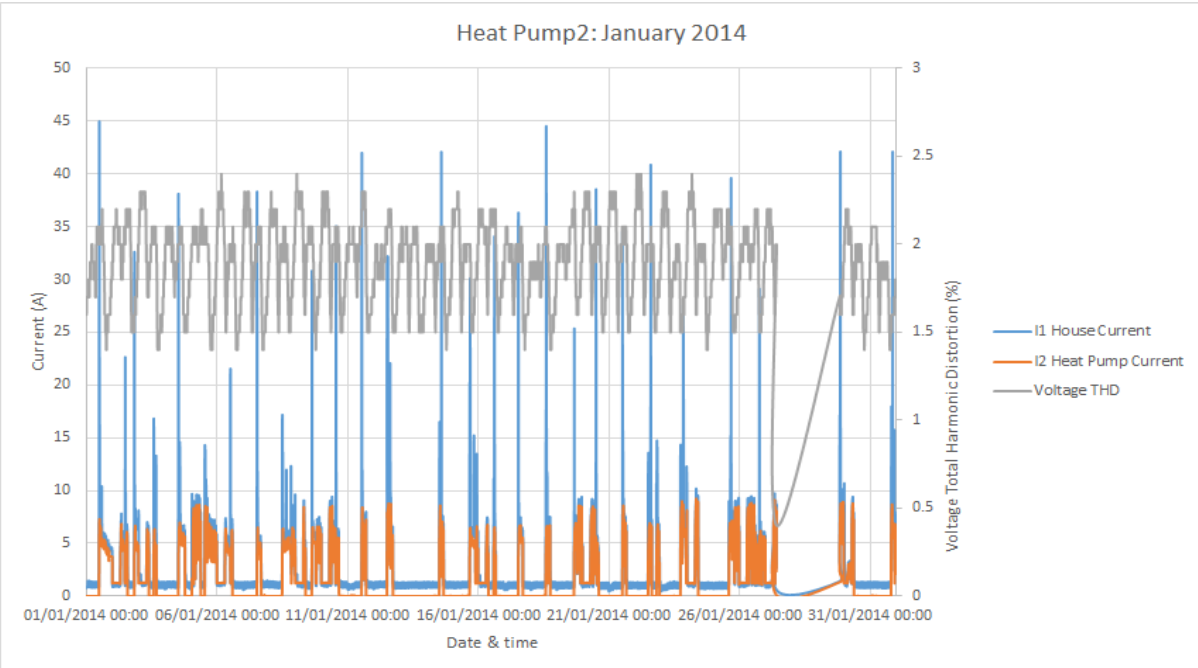

Figure 6 House and Heat Pump Current and Voltage THD – January 2014

In this case the heat pump exhibits both short term cycling and more extended periods of operation as can be seen in figure 7 below. The heat pump exhibited soft start characteristics with no

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significant current surge at start up. The flicker levels measured at the point of connection were very low and consistent. There is no correlation between the variation in the levels of voltage harmonic distortion and the operation of the heat pump. The maximum heat pump current recorded during the monitoring period was 10.97A.

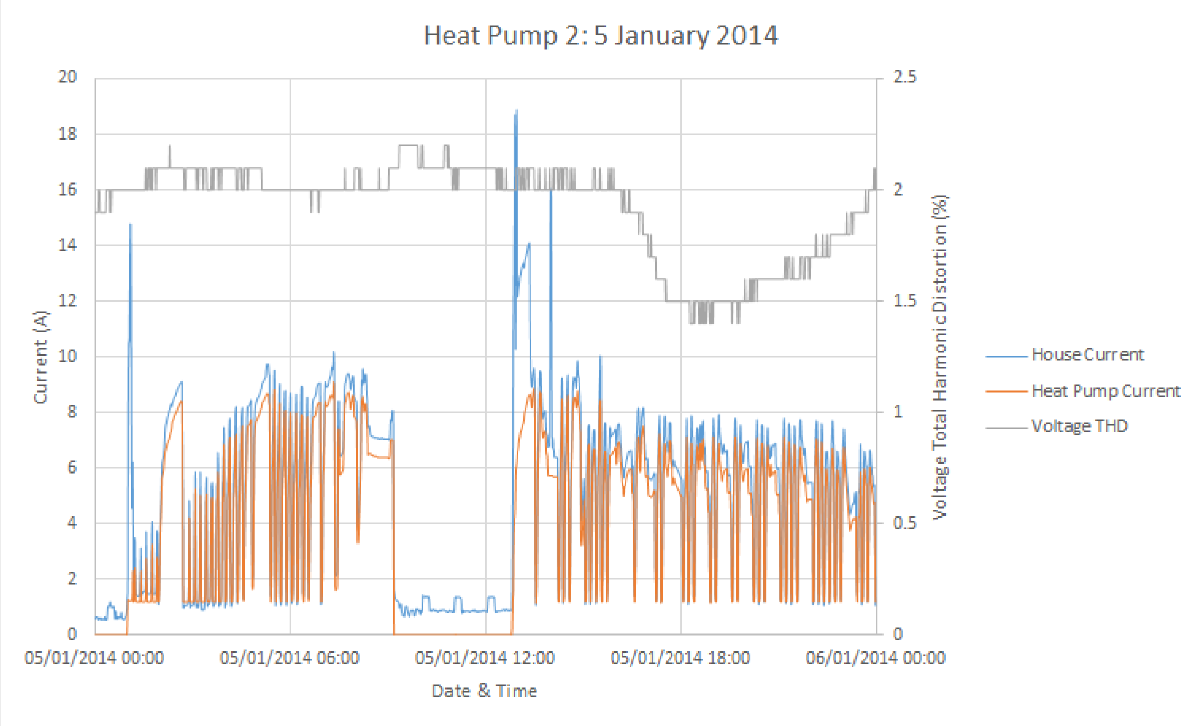

Figure 7 House & Heat Pump Current and Voltage THD – 5 January 2014

3.1.3 Heat Pump 3

Figures 8 and 9 below illustrate the house and heat pump current and the voltage harmonic distortion for the month of December 2013 and 11 December 2013 respectively. The heat pump demand is the dominant load although to a lesser degree in this case than in the first two examples. There are again short duration high current loads seen in the general house load which are not replicated in the heat pump demand record. There are both sustained periods of operation at different current levels perhaps indicative of changing heat demands and periods of cyclic operation. There is no correlation between the level of the voltage harmonic distortion and the operation of the heat pump. The maximum current drawn by the heat pump during the monitoring period is 11.59A.

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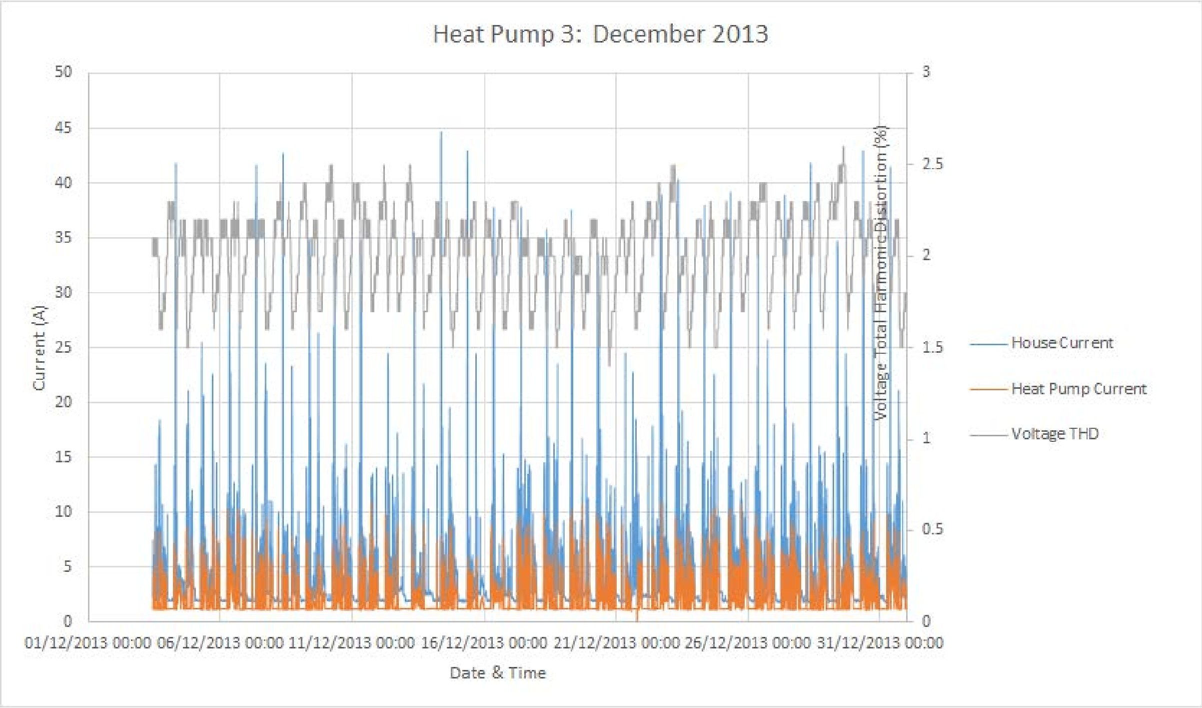

Figure 8 House and Heat Pump Current and Voltage THD – December 2013

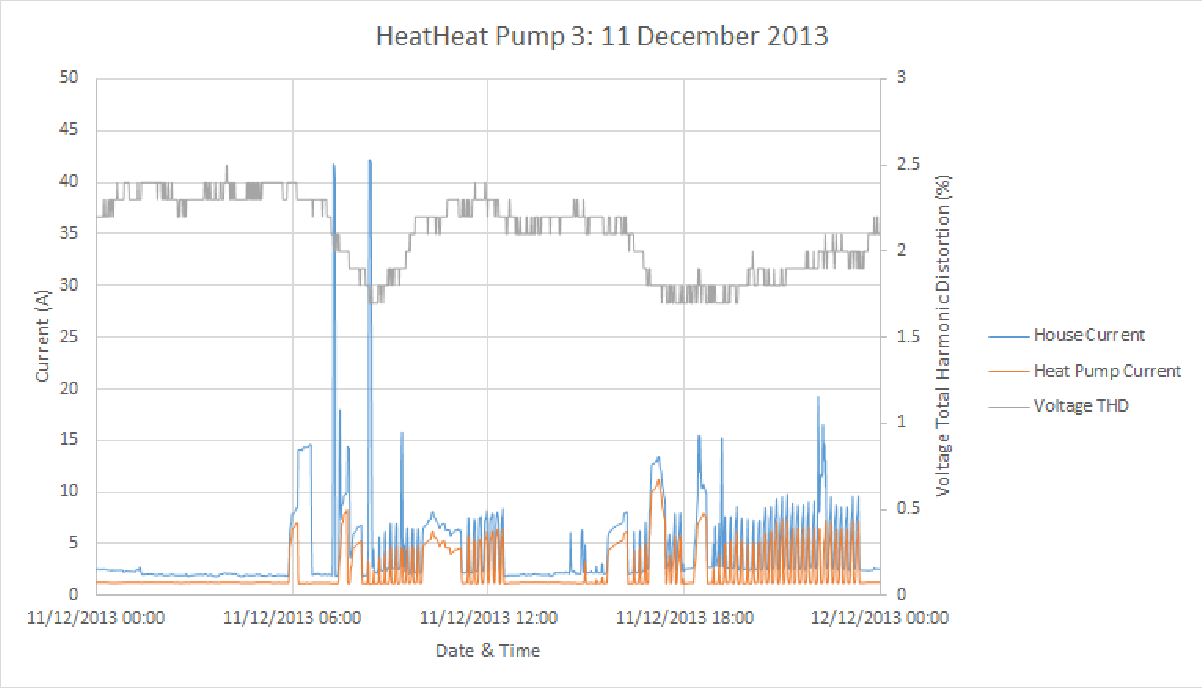

Figure 9 House & Heat Pump Current & Voltage THD – 11 December 2013

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3.1.4 Heat Pump 4

The fourth heat pump demonstrates similar characteristics to the other three examined in this monitoring programme, the heat pump is the dominant load exhibiting both sustained operation at times but more commonly repetitive cycling. There is no correlation between the variation of the voltage harmonic distortion and the operation of the heat pump. The maximum current drawn by the heat pump during the monitoring period was 8.8A. The heat pump exhibited characteristics of having soft start fitted. The levels of flicker recorded were very low and constant with no discernible effect of the starting of the heat pump motor.

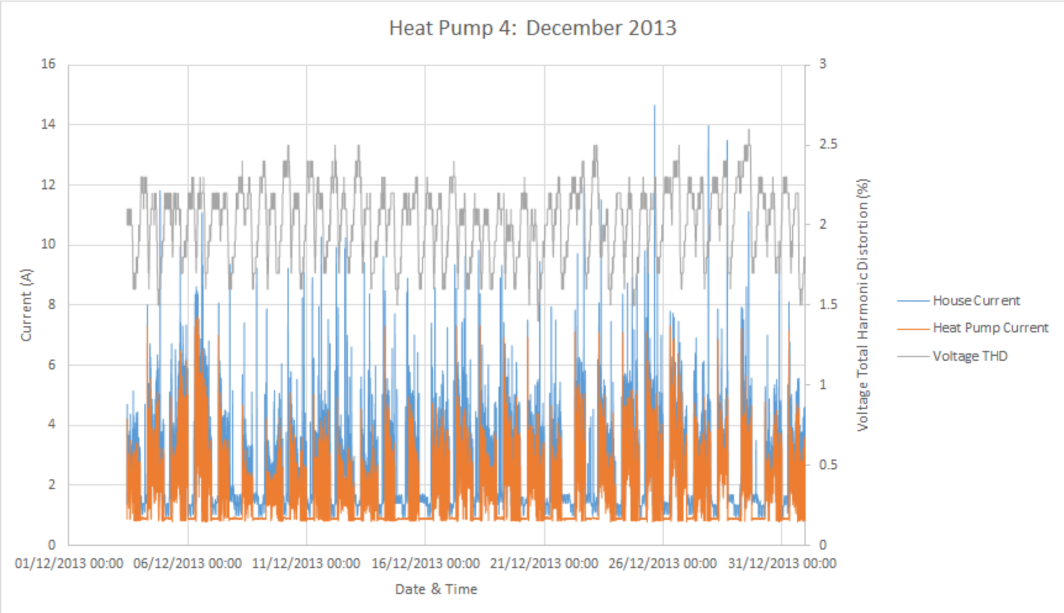

Figure 10 House & Heat Pump Current and Voltage THD – December 2013

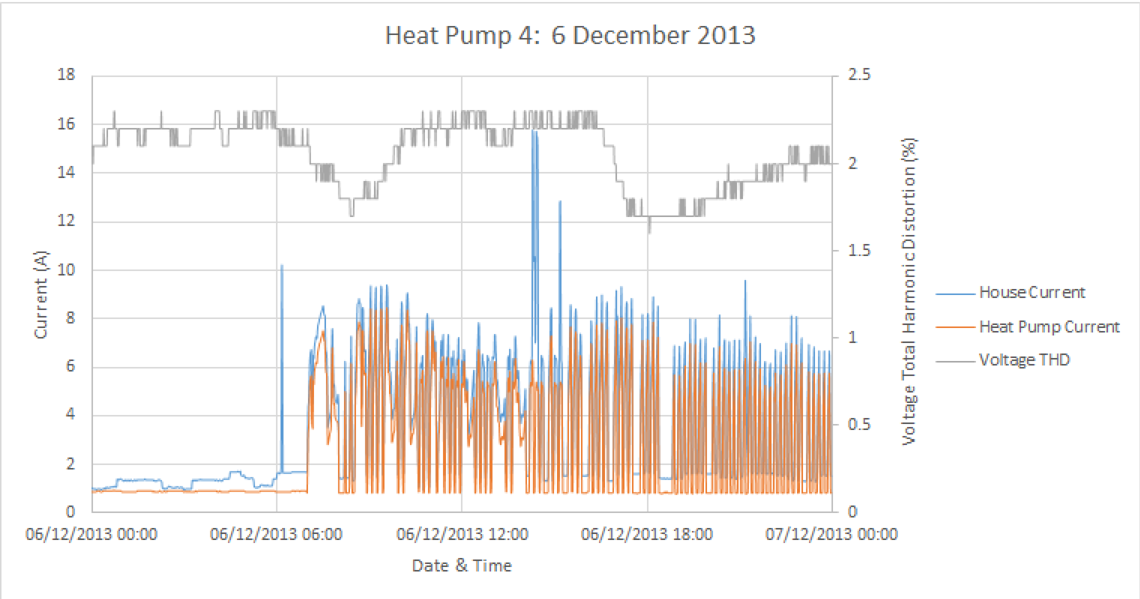

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Figure 11 House & Heat Pump Current and Voltage THD – 6 December 2013

3.1.5 Flicker

With a motor there is potential for starting current to create voltage disturbances which may lead to flicker, the units which were monitored through the British Gas monitoring programme did not exhibit any evidence of elevated starting currents, indeed the starting current of these units seems to barely have exceeded the maximum running current, based on measurements of ½ cycle rms values. That is not to say that all heat pumps will be so benign in their impact upon the network, one of the key marketplaces for heat pumps will be amongst customers who are not connected to the gas distribution system. It might be expected that many such customers will be located in the more remote parts of a DNO's licence area where the electrical network conditions might be characterised by a reduced fault level compared to urban areas, in such locations high starting currents and cyclic operation may lead to unacceptable levels of disturbance.

During the course of the CLNR project there has been an example of a heat pump whose operating characteristics were such as to generate a complaint from a neighbouring property about the disturbances resulting from the operation of the heat pump. In this case the heat pump had two possible staring operating conditions, in one where the staring current was unregulated the heat pump which had a rated operating current of 16.07A could be expected to draw up to 130A on start-up, in the second scenario where a soft starter was applied to the motor the starting current should be only 43A. In this case the soft starter did not appear to be functioning correctly as currents of up to 80A were recorded. It is worth noting that the individual short term flicker values (Pst) recorded during the testing of the unit were almost all below the limit of 1.0. As a whole the measurements were within the values set out in BS EN 50160 which requires that for a period of one week the long term flicker should be less than or equal to 1 for 95% of measurements. However Engineering Recommendation P28 sets a more stringent limit of 1.0 for Pst and 0.8 for Plt. It should be remembered that occurrences of faults on the transmission and distribution networks which result in voltage dips will generate higher than normal levels of short term flicker, however these values should be flagged under the requirements of IEC 61000-4-30 which describes the measurement processes for power quality phenomena. Flagged events such as these should be considered for disregarding for the assessment of flicker levels due to the operation of equipment connected to the network.

In the case being considered it is perhaps fortunate that the rated operating current of the heat pump exceeded 16A as this placed the device directly under the auspices of IEC 61000-3-11 rather than IEC 61000-3-3. Devices with a rated current of greater than 16A can either demonstrate compliance with the voltage disturbance requirements of IEC 61000-3-3, and thereby claim unconditional connection, or they must demonstrate the maximum supply impedance at which they can meet the voltage disturbance requirements and declare this in the installation instructions; such devices are then subject to conditional connection with the agreement of the DNO.

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There is some ambiguity regarding the testing of devices such as this one which have both a motor for the heat pump and an auxiliary heater for times when the external temperature is too low for the heat pump alone to develop enough heat energy. Some manufacturers claim that since the auxiliary heater need not be of their manufacture that the unit should not be tested as a whole, this lessens the impact seen during the tests of the unit and does not reflect the worst case conditions. This is contrary to the requirements of the EMC directive which requires that equipment which may be sold as a unit should be tested as a unit. The analogy which the manufacturers often use is that of a computer and printer which are operated together but are never tested as a whole unit for combined harmonic emissions. This is a little disingenuous as such things are rarely if ever offered by the manufacturer as a combined unit whilst without the auxiliary heater the heat pump will not meet its design performance.

The question of how to control the connection of heat pumps was touched upon in the Heat Pump Case Study into the flicker problems experienced. Above 16A rated current it is quite possible that many heat pumps will struggle to meet the voltage disturbance limits when connected to the reference supply impedance of 0.25 +j0.25 ohms (approximately 0.35 ohms) and as such they become subject to conditional connection with the agreement of the DNO only at those points in the network where the supply impedance to the customer is less than or equal to the maximum impedance stated by the manufacturer.

For any units which are able to meet the requirements of IEC 61000-3-3 regardless of their rated operating current then they are supposed to be subject to unconditional connection having satisfied the requirements of a harmonised standard.

It is not permitted under the Low Voltage Directive to place more stringent safety requirements on the connection of equipment which has satisfied the requirements of article 3 of the Low Voltage Directive.

In the review of Engineering Recommendation P28 consideration may need to be given to the potentially competing requirements of the EMC and Low Voltage directives which promote the free movement of equipment which meet certain conditions and those of the Distribution Code DPC 5.

3.1.6 Heat Pump Conclusion

The four units monitored at individual customer premises show quite benign operating characteristics with minimal effects upon the power quality parameters.

During the course of the CLNR project there has been an example of a heat pump which did not exhibit such benign characteristics which resulted in what were determined to be unacceptable levels of disturbance on the LV network.

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3.2 Electric Vehicles

Measurements were made at the premises of four British Gas Domestic Customers to examine the effects of an Electric Vehicle (EV) charger on the conditions at the point of connection. The operation of an EV is largely independent of the time of year and no specific time of year was required for the measurements to be made unlike with heat pumps where clearly the colder months are likely to be of greater interest. Not all of the EV charging monitoring systems have been installed in the manner outlined in figure 1 in section 2 Methodology & Assumptions. Rather than the first current monitoring channel recording the total premises load including that of the EV charger it can be seen from the traces for EV1, EV3 and EV4 that the premises load has been recorded excluding the EV charger, this arrangement would be consistent with the connection arrangement outlined in Figure 2 of section 2. The second trace in each case is just the EV charger.

3.2.1 Electric Vehicle 1

It can readily be seen in Figure 12 below that the charger has been employed relatively infrequently and exhibits a more or less constant load for a sustained period when the vehicle is connected.

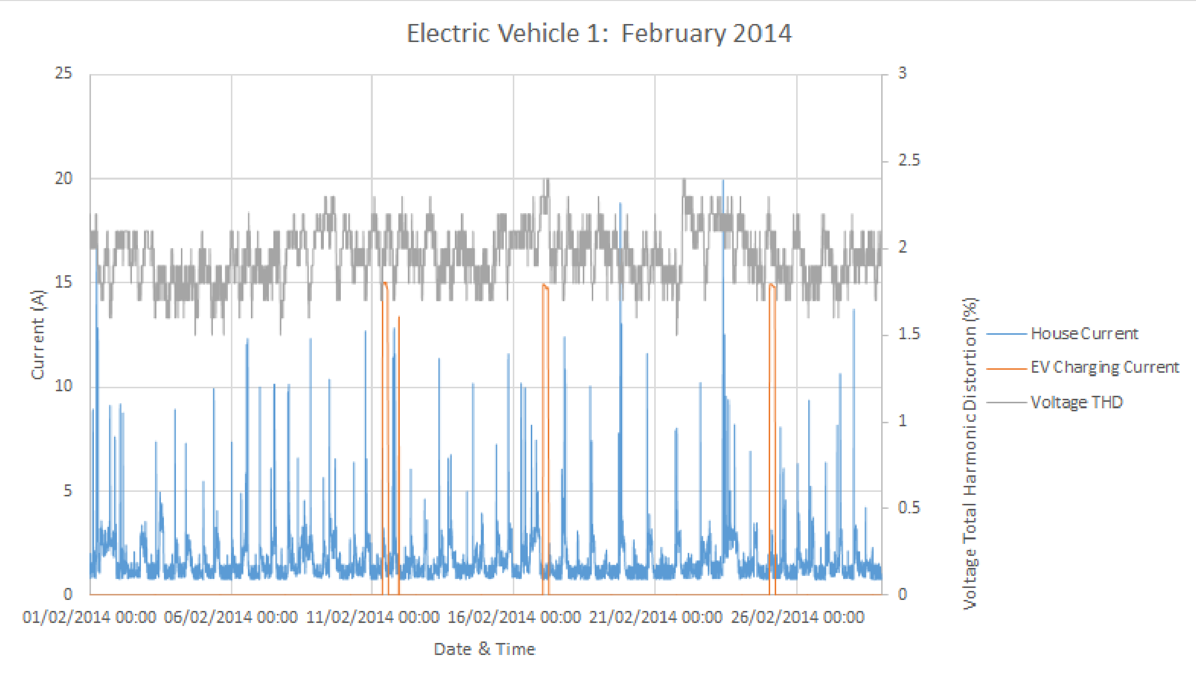

Figure 12 House & EV Charging Current and Voltage THD – February 2014

Figure 13 below illustrates the operation of the charger, the first period of operation is for approximately 5¼ hours with a steady load of 15A for the first 4½ hours reducing as the battery reaches full charge. The second period is both much shorter and at a slightly reduced current suggesting only a top-up charge was required.

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The voltage harmonic distortion is not unduly affected by the operation of the charger, the levels remaining below 2.5% against a planning level of 5%.

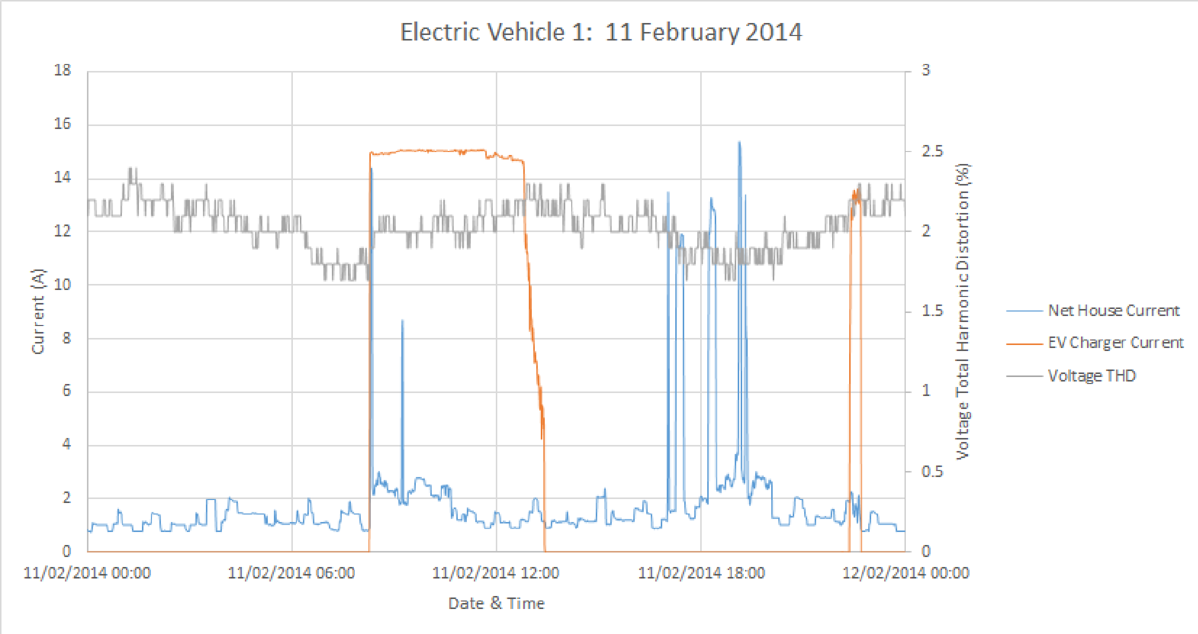

Figure 13 House & EV Charging Current & Voltage THD – 11 February 2014

3.2.2 Electric Vehicle 2

The monitoring for this EV did record the premises load and the EV charger load in the manner described in the introduction, so in this example the premises load is recorded including the charger current. Figure 14 below shows the usage of the EV charger over the course of February 2014.

Figure 15 below shows the demand over the 5 February 2014 which shows three shorter charging periods during the day followed by a sustained 5½ hour charging period during the evening and early night time. The charger draws up to 16A during this charging period for around 5¼ hours before the current reduces as the battery reaches full capacity.

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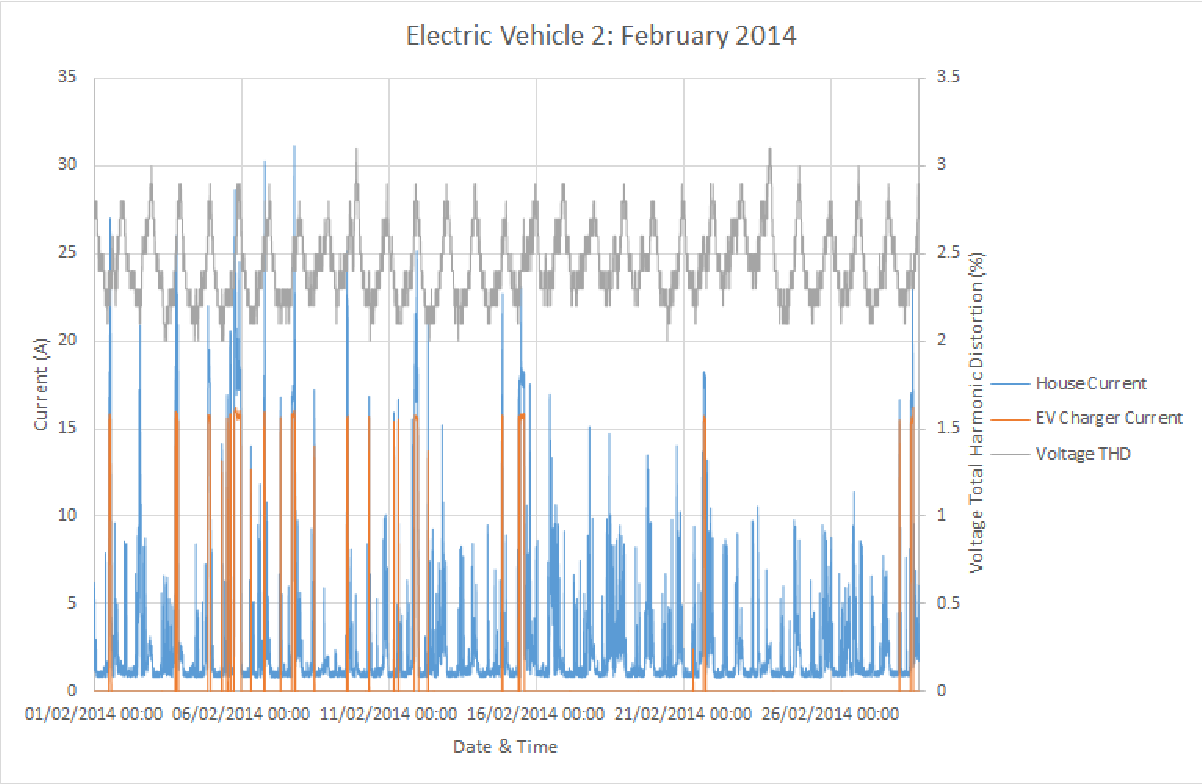

Figure 14 House & EV Charging Current and Voltage THD February 2014

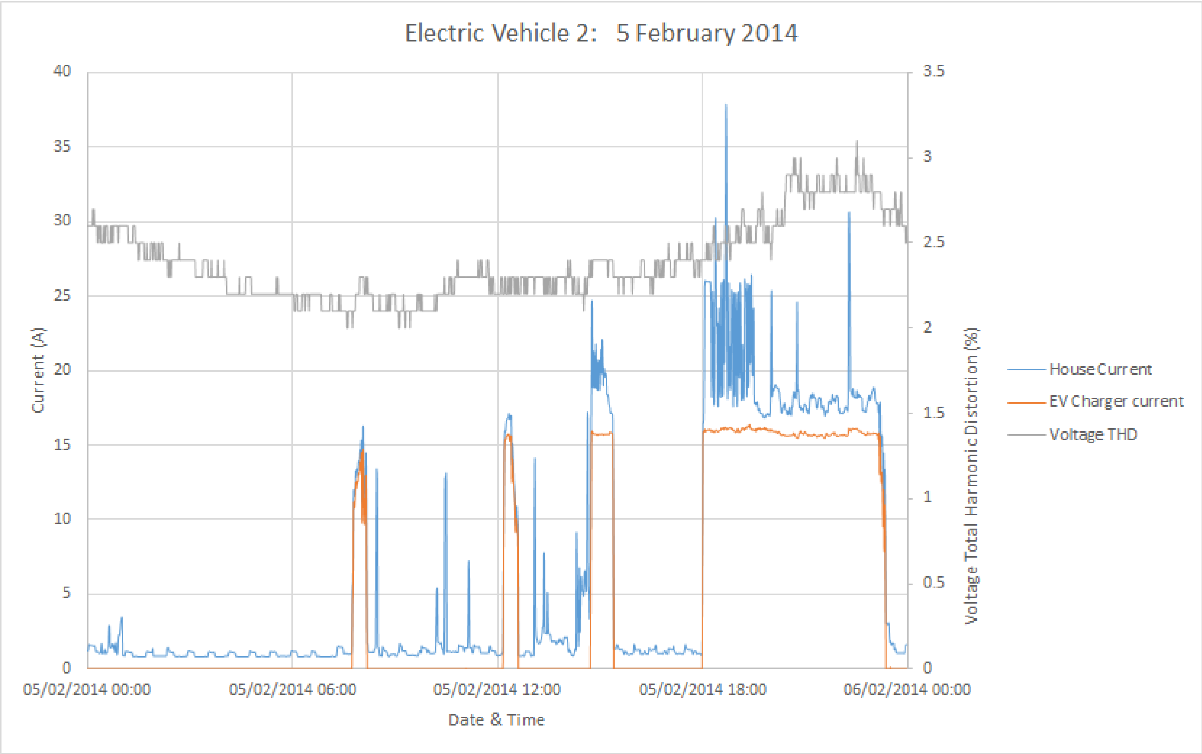

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Figure 15 House & EV Charging Current and Voltage THD – 5 February 2014

3.2.3 Electric Vehicle 3

The operation of the charger for this installation can be seen in Figures 16 & 17 below to be restricted to what appear to almost full charge cycles lasting around 5 hours on each occasion. Although the value of voltage THD does increase during the period of the charger's operation the shape of the change does not follow the shape of the load profile suggesting that the effect is caused more by the summation of other equipment over the network.

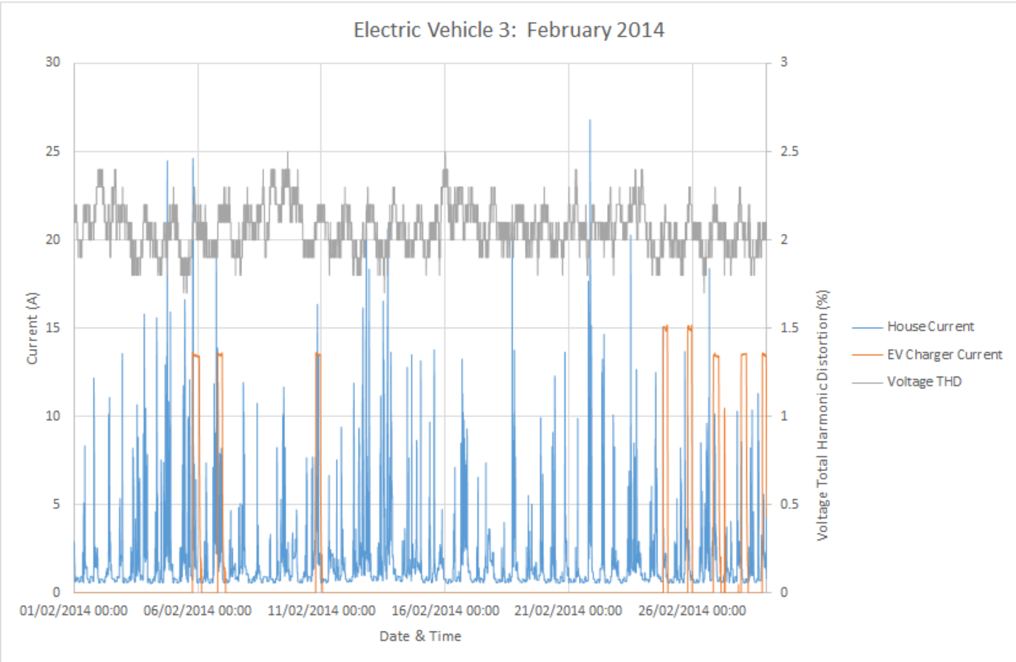

Figure 16 House & EV Charging Current and Voltage THD – February 2014

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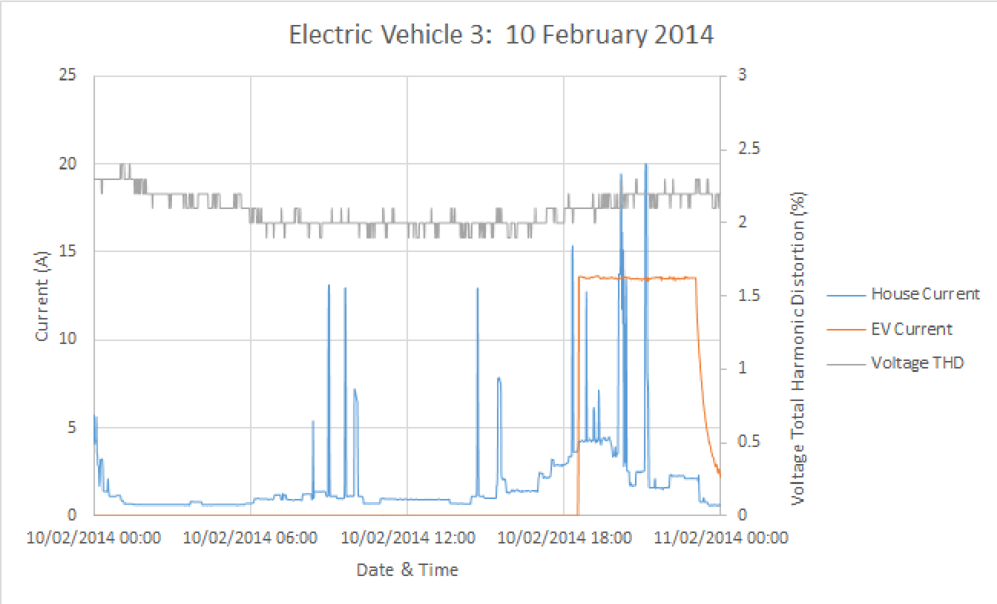

Figure 17 House & EV Charging Current and Voltage THD – 10 February 2014

3.2.4 Electric Vehicle 4

This final example of EV charger monitoring exhibited a very different mode of operation compared to the others which were monitored. The date was not set correctly on the PQube and the bulk of the data was gathered and labelled as being from 1 January 2000 onwards which is the default date when the unit is first energised with no battery backup available. The data was gathered but it is not considered suitable for detailed analysis or comparison.

3.2.5 Current Emissions

Plots have been made to compare the spectrum of harmonic currents measured for each EV charger installation. The plots are based on the maximum values recorded in a day's measurements for each EV charger. It can be seen that the current emissions from the chargers are broadly similar and relatively low magnitude. The levels of emissions suggest that current EV chargers present relatively little concern in terms of their harmonic emissions.

In terms of the application of ENA ER G5/4 there is potentially an issue to be resolved particularly in the case of higher capacity charging connections, although if the percentage emissions measured are typical this may in practice not be an issue. All of the chargers monitored are operating at or below 16A. However there is potential for 32A charging points to be connected, it is however the car which contains the power electronics associated with the charging circuit rather than the charging point. This raises the question of how to ensure compliance with the stage 1 assessment under table 7 of ER G5/4 for loads rated >16A per phase. It is potentially the car rather than the charger for which approval should be obtained, this raises questions about how to manage situation where

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the customer changes their car for another make and what safeguards need to be in place for public charging points to ensure that any limitations on required supply impedance are observed.

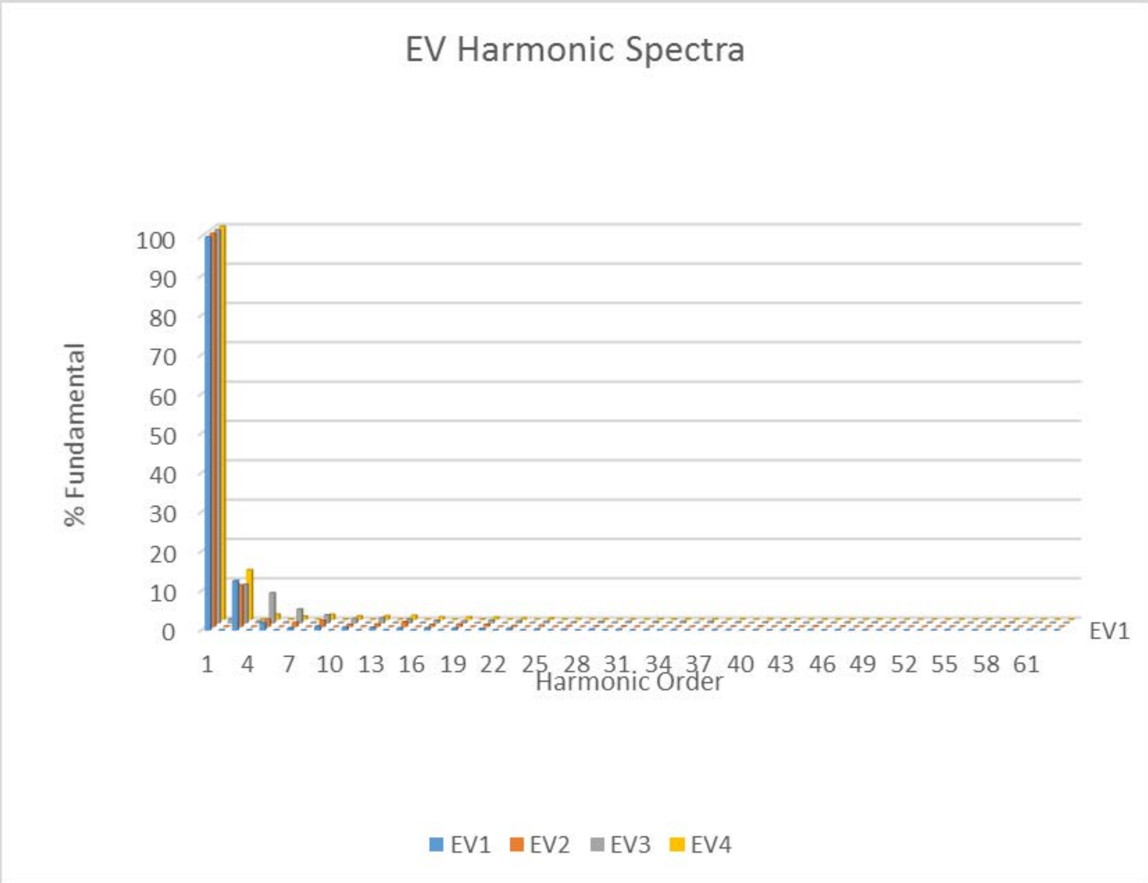

Figure 18 Harmonic Current Spectra

3.3 MicroCHP

Measurements of the effect of MicroCHP generation were only made at a single customer's installation. However, additional information about the Power Quality characteristics of microCHP generation can be drawn from previous studies carried out under the Strategic Technology Programme.

The plot in Figure 19 below shows the power flows, since the PQube does not assign a direction to the values of current, the original data showed that the CT had been installed on the CHP connection so that positive power flow was out of the generator and whilst this might be sensible in many ways it does make comparison with the net load of the premises less obvious. This has been corrected for the graphs and negative power flow is an export from the circuit. It can be seen that there are occasions when the net export from the site exceeds the export from the CHP unit demonstrating that these premises have a second form of micro generation as well.

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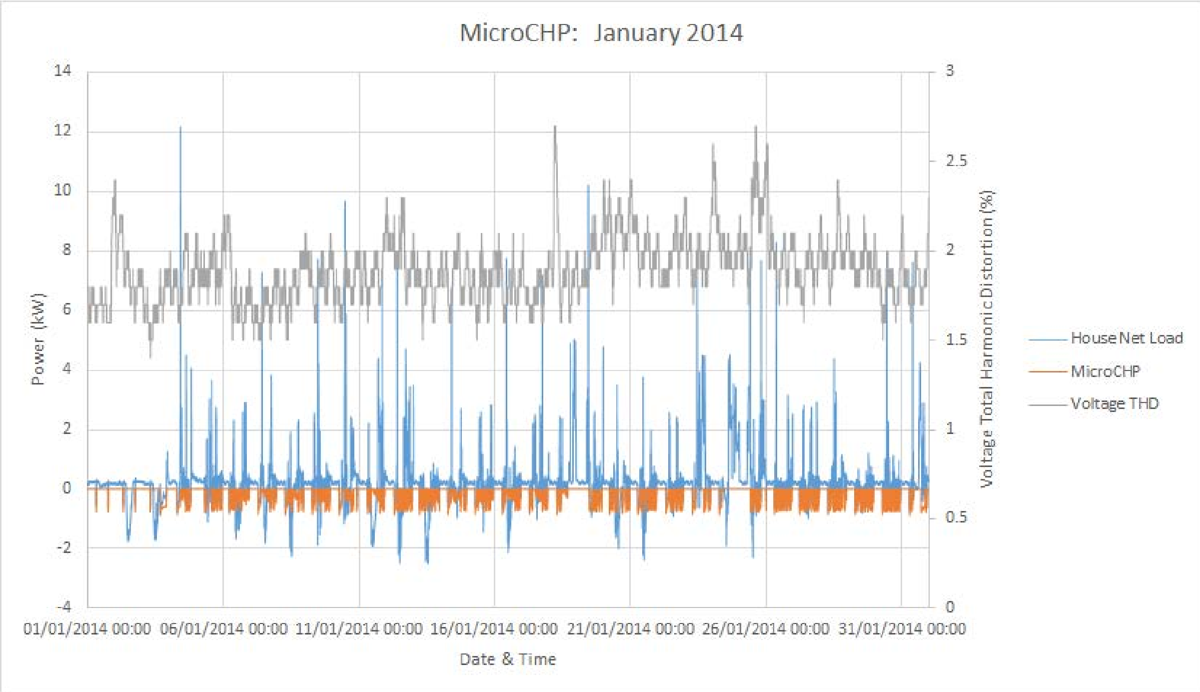

Figure 19 House and MicroCHP Power and Voltage THD January 2014

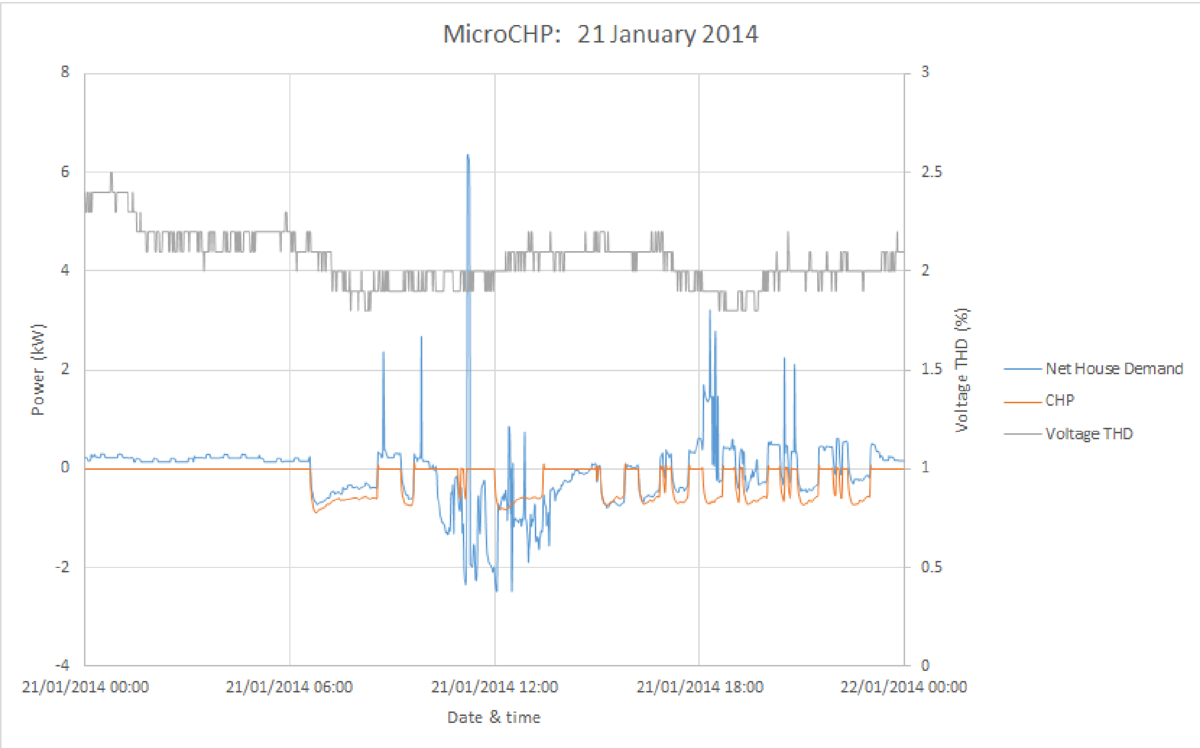

Figure 20 House & microCHP Power and Voltage THD January 2014

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The microCHP unit can be seen to be cycling with heat demand, which is the primary purpose of such a CHP unit, rather than producing a constant electrical output. Since the net export only exceeds the microCHP output during the daytime roughly centred on midday the additional micro generation can be assumed to be a Photovoltaic installation. This is seen more clearly in figure 20 above which focuses on a single day's operation.

3.4 Photovoltaic generation

Measurement of the impact of PV at a customer's installation was made at a single premise. The measurements have been made in line with Figure 2 in section 2, measuring the house load and the generator output separately.

Figure 21 illustrates the readings for September 2013, unfortunately no measurements were made earlier than this and the measurement cycle was concluded in April 2014 so we do not see the peak output from the solar panels which might be expected during the summer months.

Figure 23 illustrates the action of the EMMA coolpower unit to match the load to the generation output, as the output from the PV rises as the sun rises the coolpower unit increases the amount of power it diverts to heat the stored hot water. This action stops sometime after 10.am suggesting that the water was at the required temperature at that point.

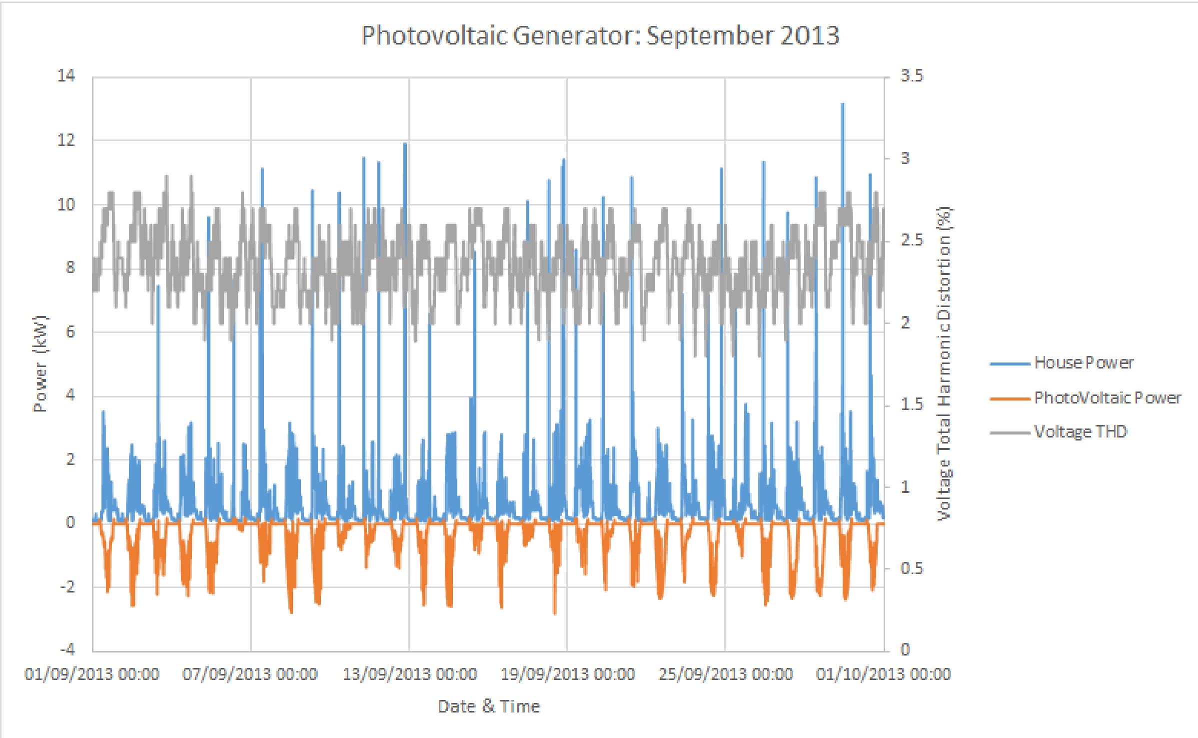

Figure 21 House and Photovoltaic Generator power flow and Voltage THD September 2013

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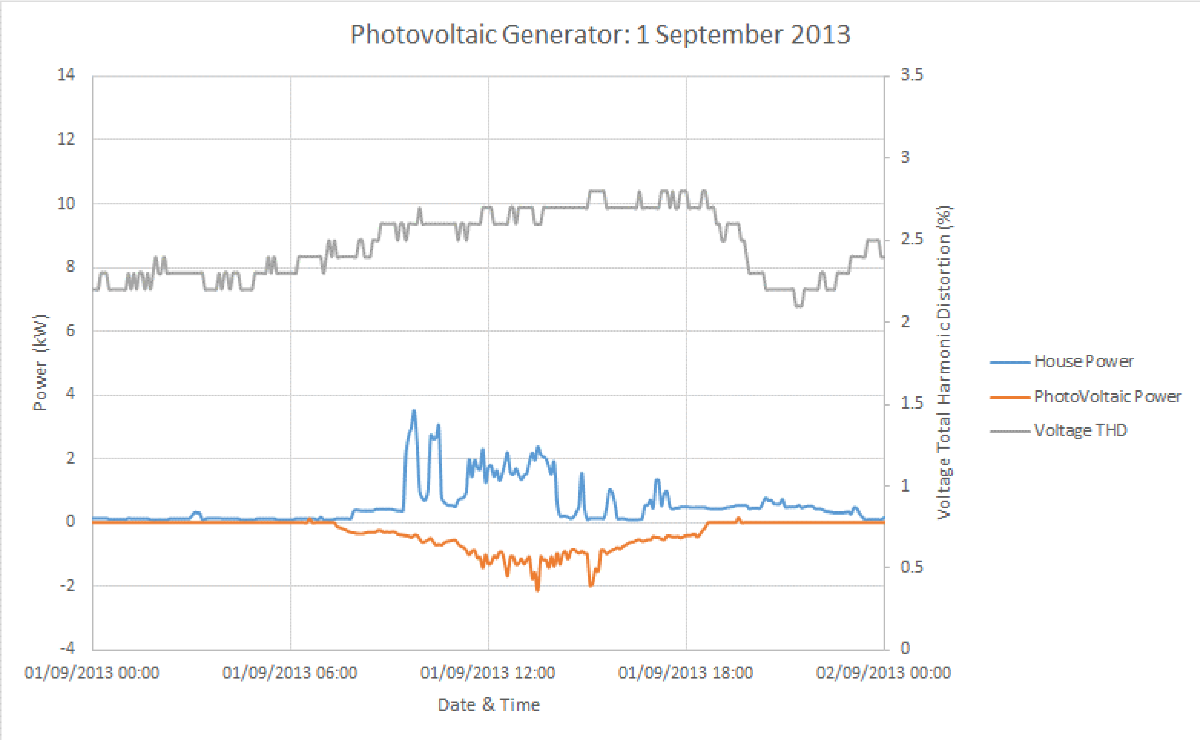

Figure 22 House and Photovoltaic Generator power flow and Voltage THD 1September 2013

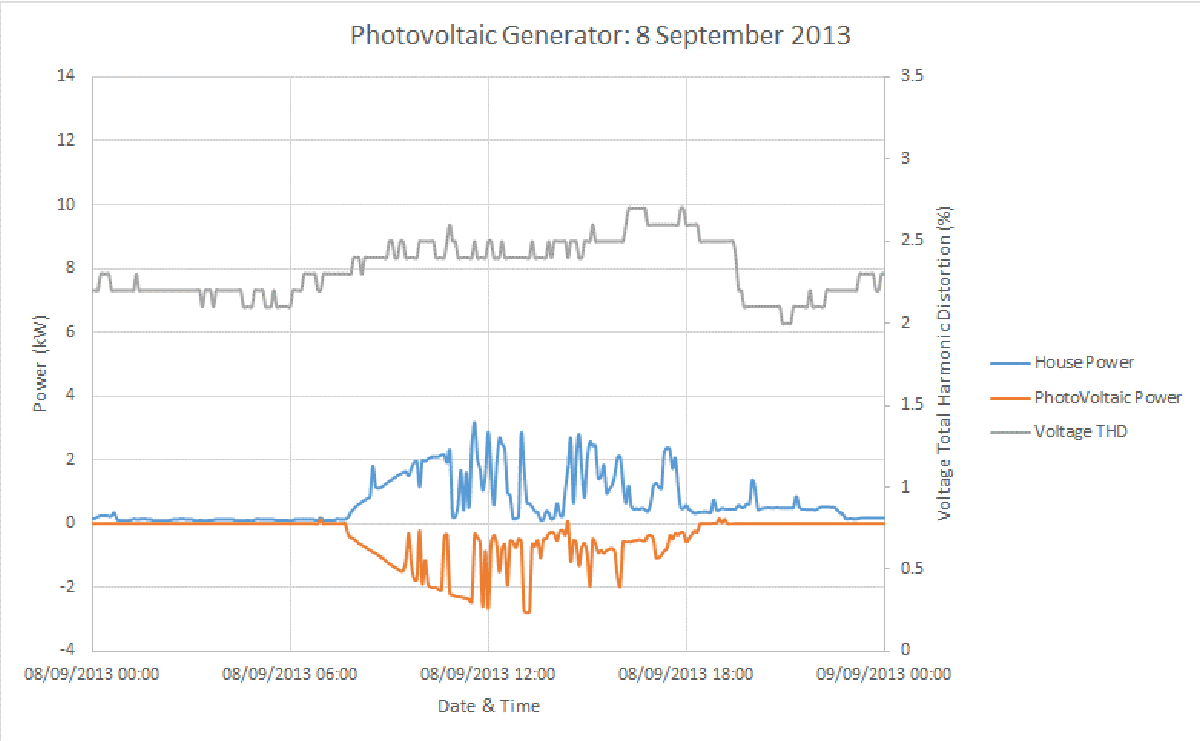

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Figure 23 House and Photovoltaic Generator power flow and Voltage THD 8 September 2013

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3.5 Control Customer Measurements

The control customers were customers where power quality monitoring was installed but no Low Carbon Technologies were present at the premises. The intention is to establish what a typical background condition looks like in the absence of before and after measurements at the customers properties with LCTs installed. Samples of the measurements at both rural and urban customers are shown below in Figures 24 – 33. The general shape of the consumption profile for the base house load is broadly similar between the rural and urban control customers. Similarly the control customers exhibit similar usage profiles to the base profile of the LCT equipped customers when the effects of the LCT on consumption are ignored.

The levels of harmonic distortion and the variation witnessed are broadly similar to those seen with the various LCTs under test. The control customer Voltage THD levels have varied between around 1.5% and 2.5% which is consistent with the values seen for customers equipped with one or more LCT.

3.5.1 Rural Control Customers

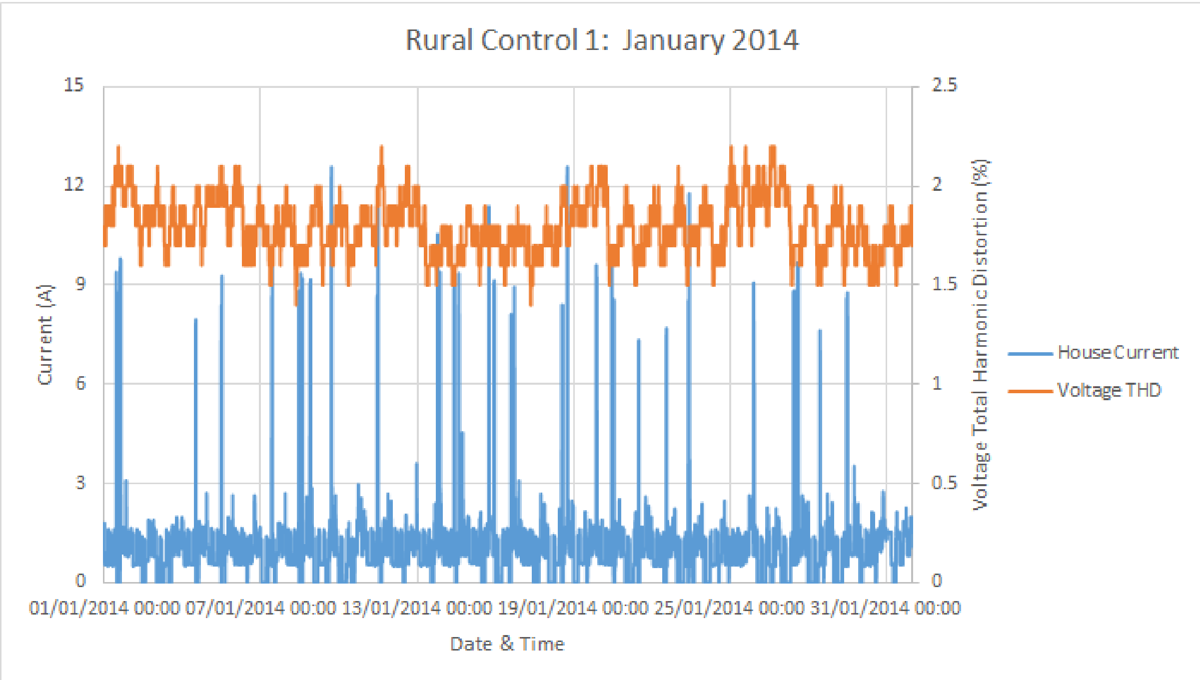

Figure 24 Rural Control Customer 1 House current and Voltage THD: January 2014

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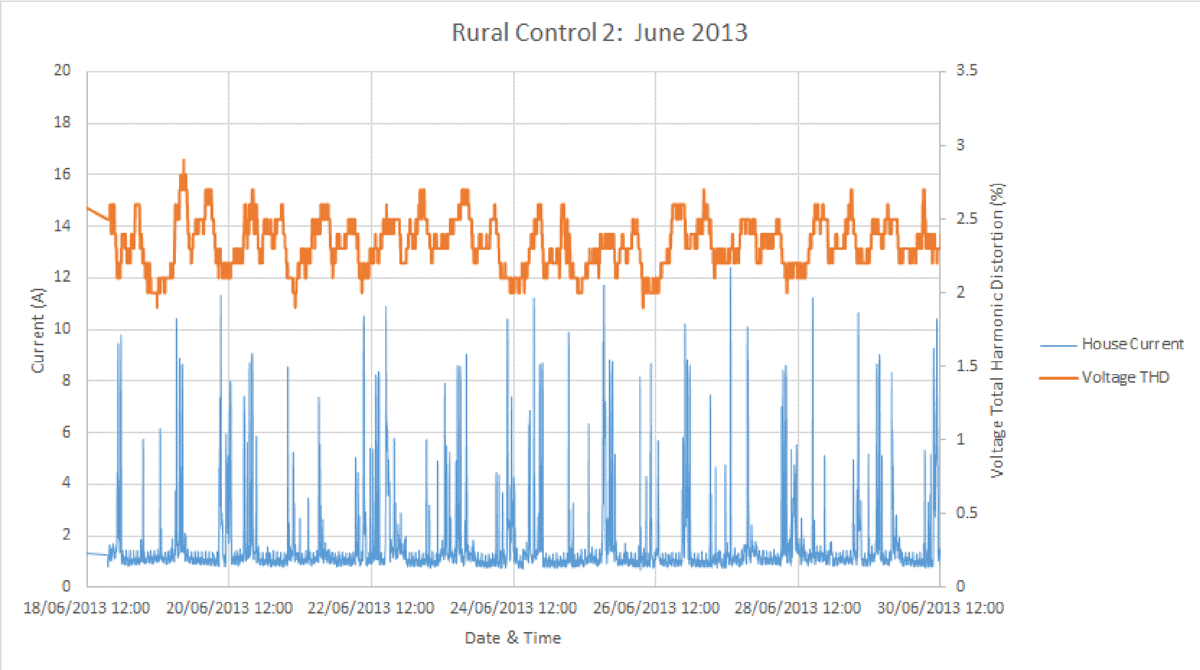

Figure 25 Rural Control Customer 2 House current and Voltage THD: June 2013

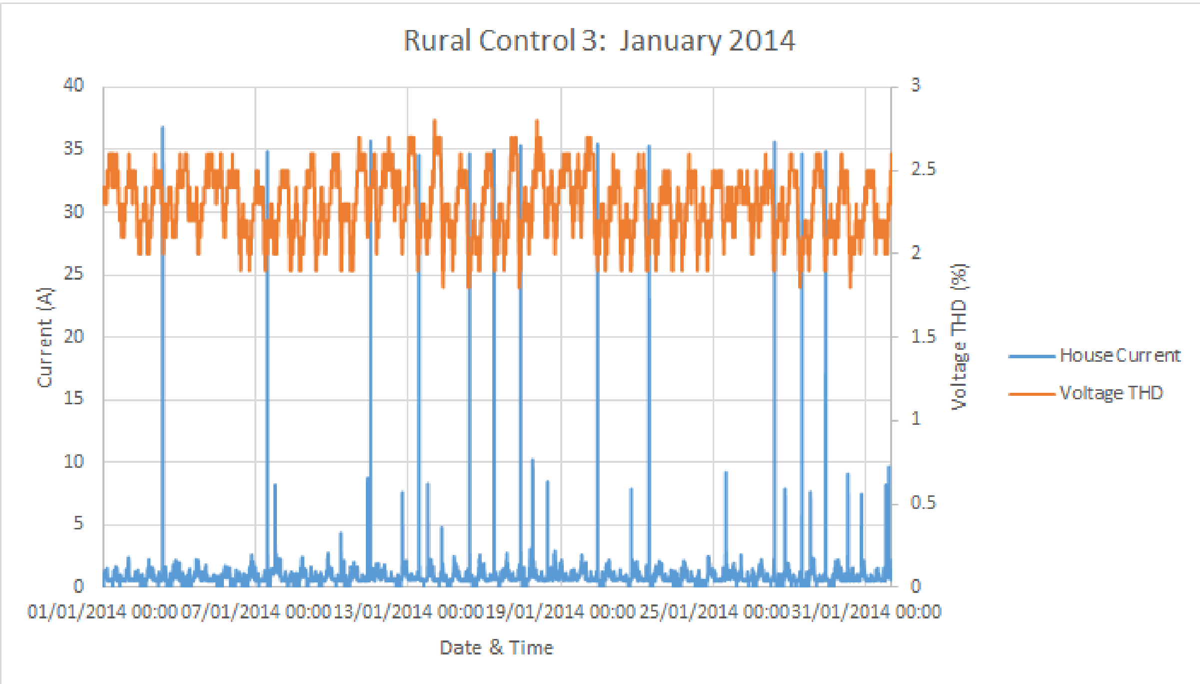

Figure 26 Rural Control Customer 3 House current and Voltage THD: January 2014

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3.5.2 Urban Control Customers

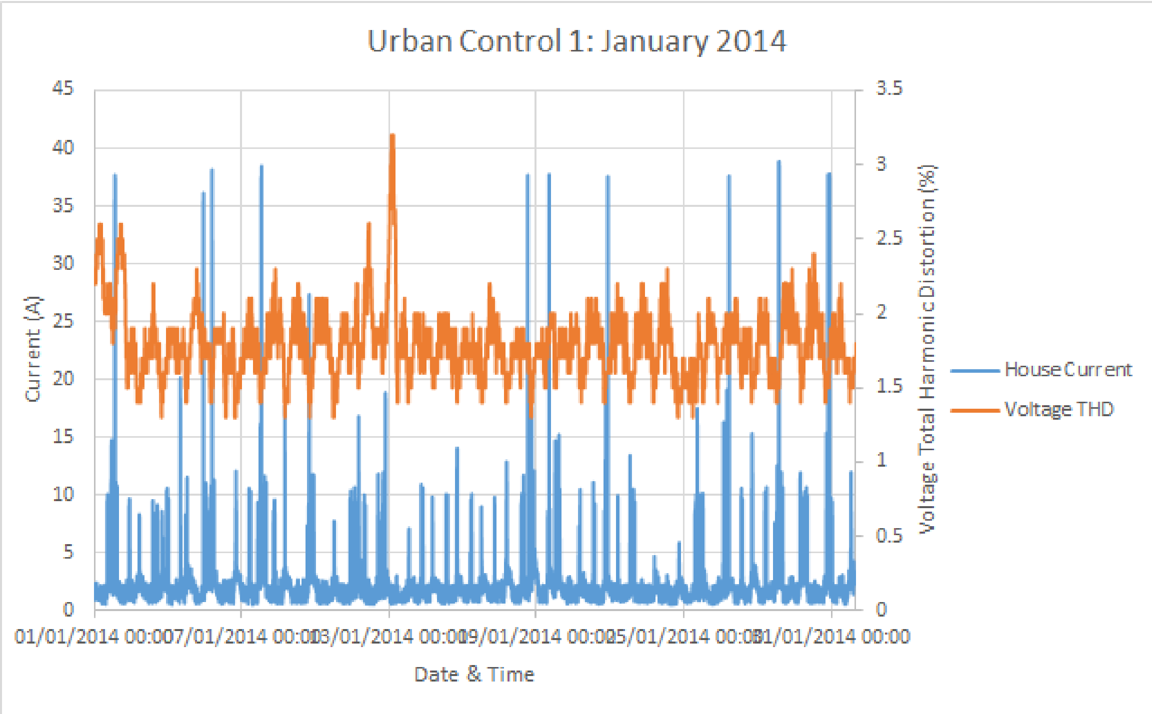

Figure 27 Urban Control Customer 1 House current and Voltage THD: January 2014

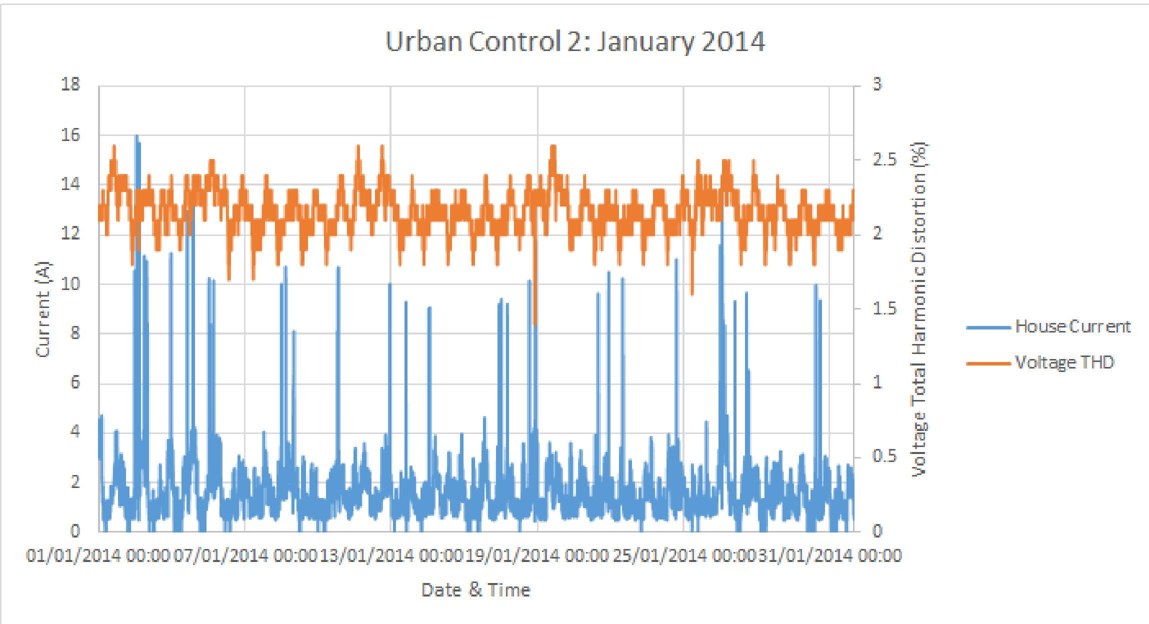

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Figure 28 Urban Control Customer 2 House Current and Voltage THD: January 2014

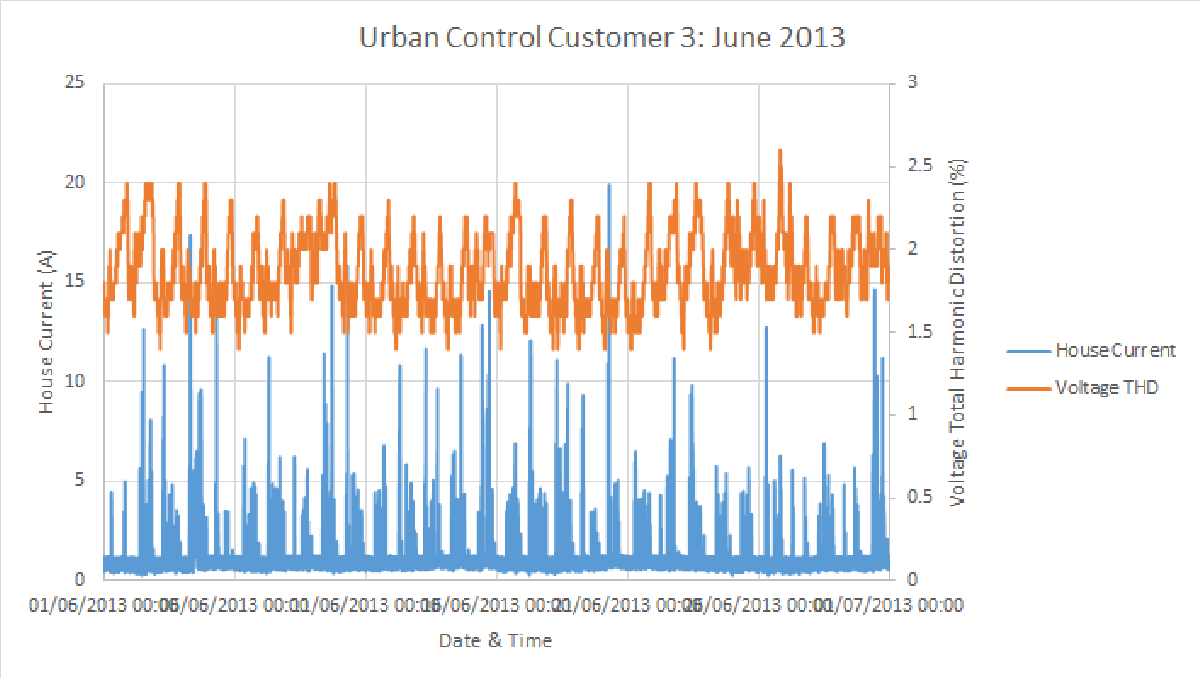

Figure 29 Urban Control Customer 3 – House Current and Voltage THD June 2013

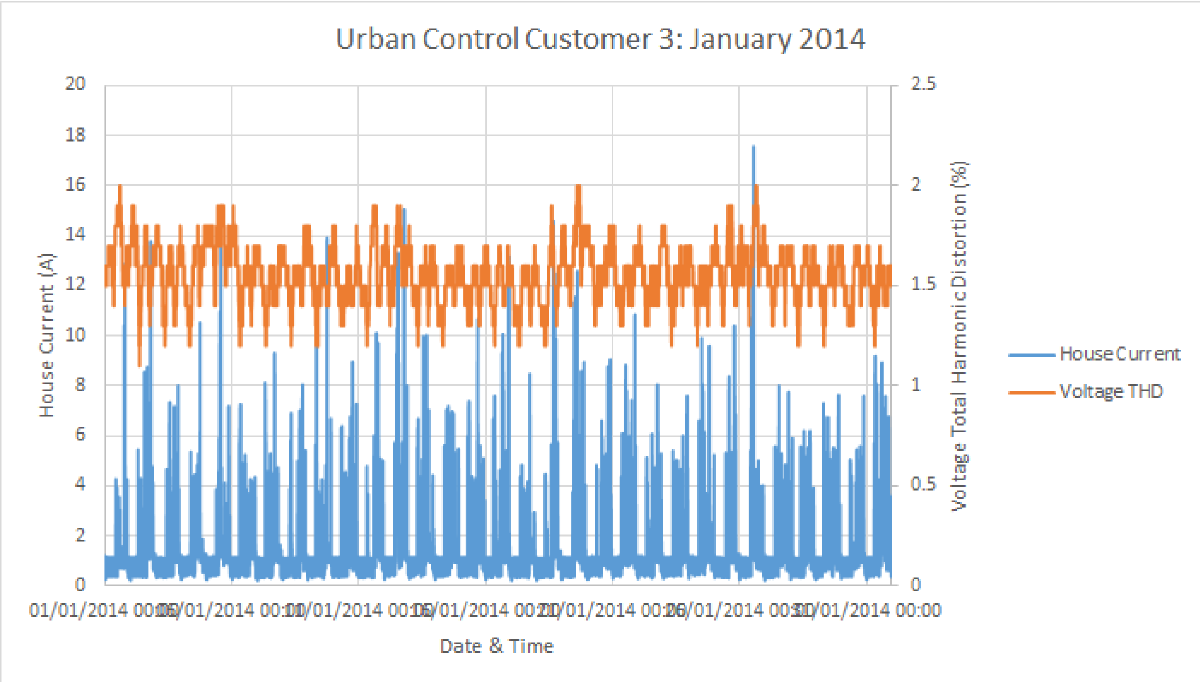

Figure 30 Urban Control Customer 3 – House Current and Voltage THD January 2014

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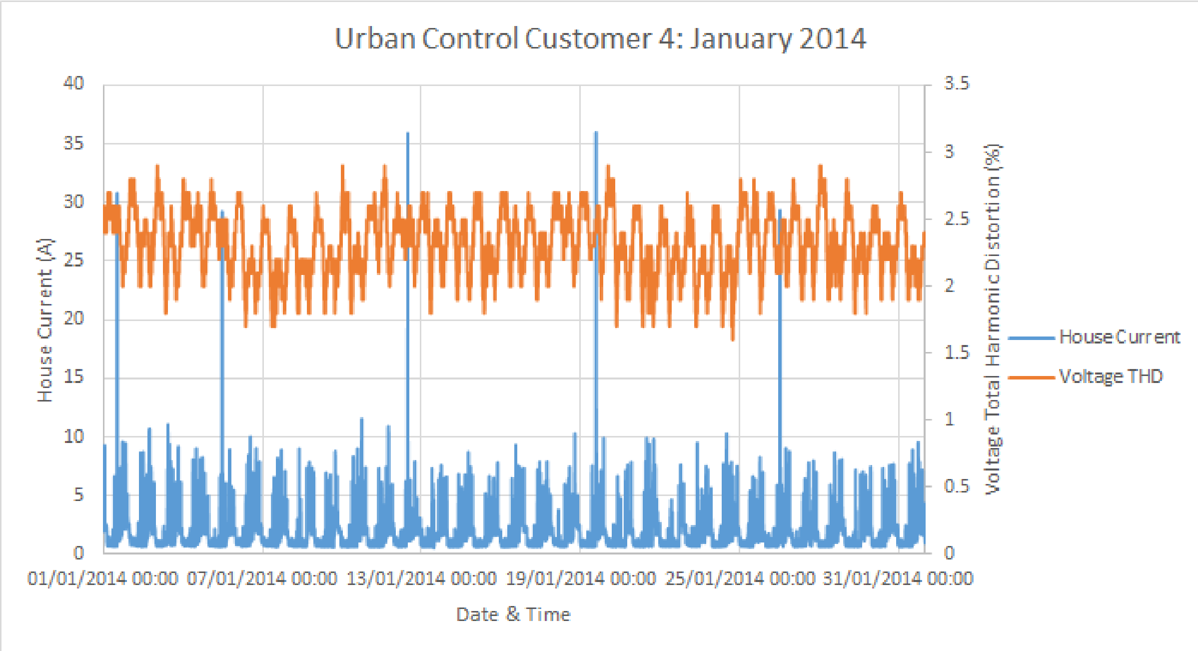

Figure 31 Urban Control Customer 4 – House Current and Voltage THD January 2014

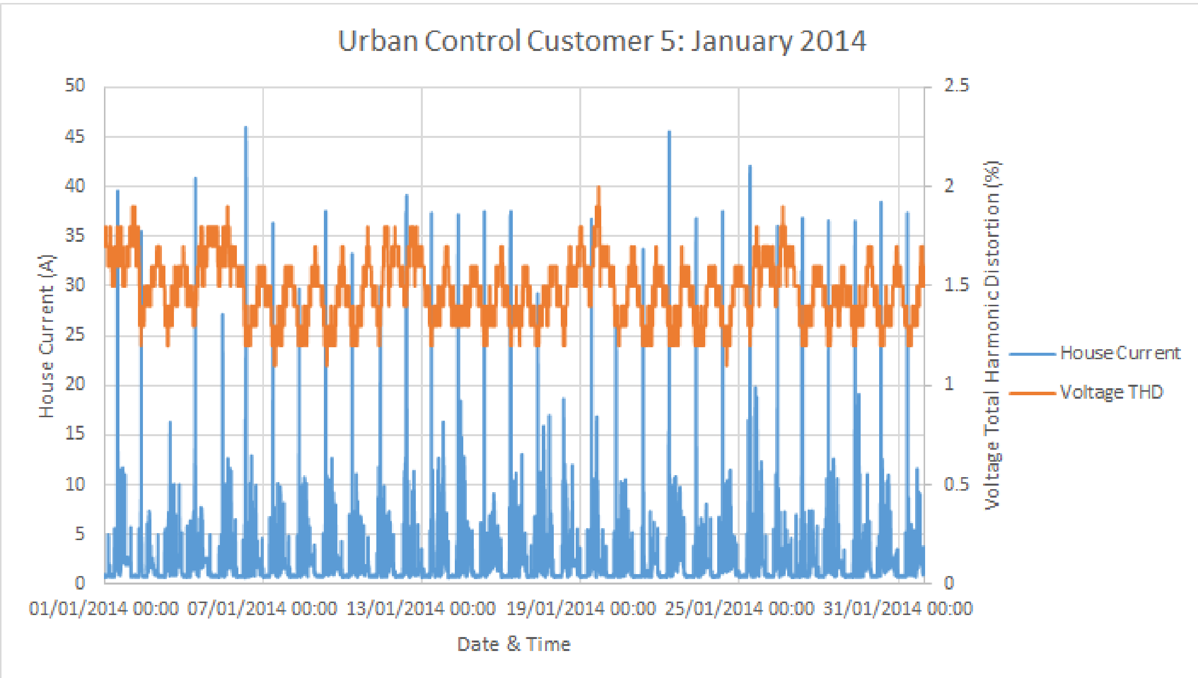

Figure 32 Urban Control Customer5 – House Current and Voltage THD January 2014

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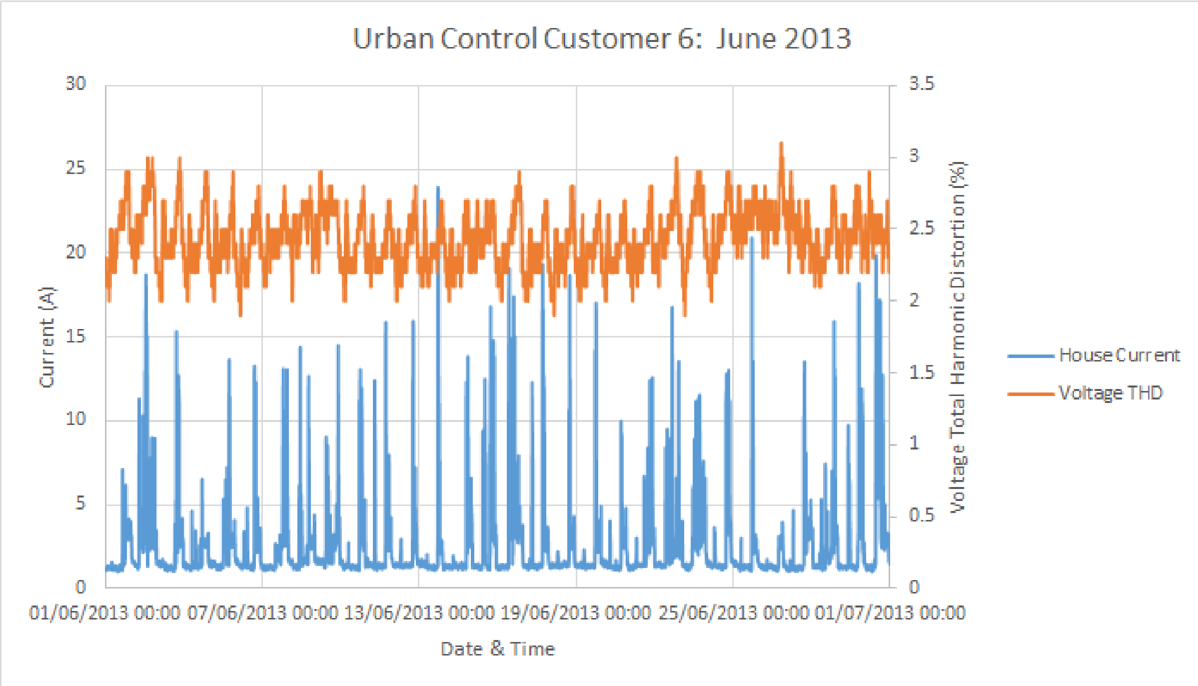

Figure 33 Urban Control Customer 6 – House Current and Voltage THD June 2013

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4 Monitoring Results for Clusters of LCTs

4.1 Heat Pumps

Two heat pump clusters were monitored at Towhouse Green in Redburn and Sidgate Lane in Newbrough, both in Northumberland. The heat pumps a 6kW output device from Heat King were installed by the Landlord and developer of the properties concerned.

4.1.1 Townhouse Green- Redburn

The Redburn cluster has 4 feeders, 3 without any heat pumps and one with 13 out of 15 customers having a heat pump installed. This circuit forms a T within the cul-de-sac where the cluster of Heat Pump installations is located. There is a PQube monitor installed at the end of each arm of the T. At the source substation there was no PQube installed. However measurements were made of the busbar voltage and the transformer current using Northern Design Rail 350 meters, data for these meters was obtained from the ihost system.

Voltage Variation

Plots of the voltages at the ends of the heat pump cluster suggest that the cluster has not had an unduly negative impact upon the voltage seen at the end of the feeder. These are shown in Figure 34 below for January 2014. It can be seen that the minimum 10 minute average voltage value is around 238V which taking account of the substation loading at the time and the transformer voltage drop is well within the normal design parameters for LV network voltage drop described in Northern Powergrid's LV design policy document.

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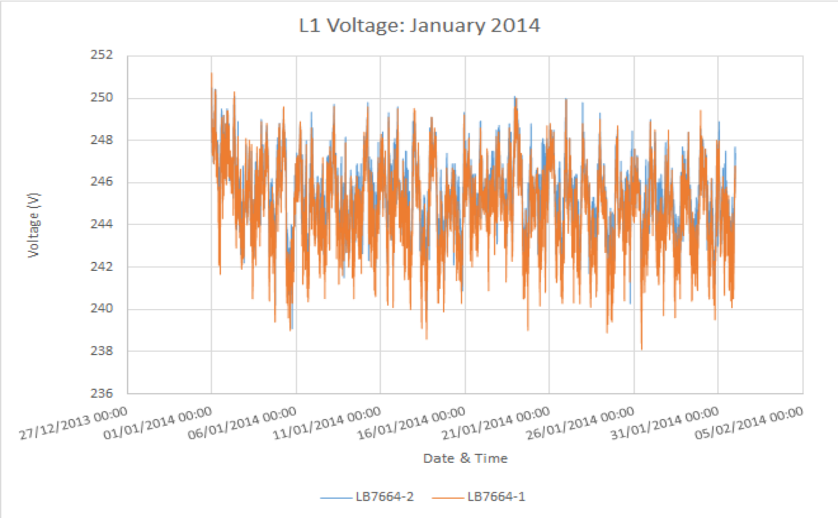

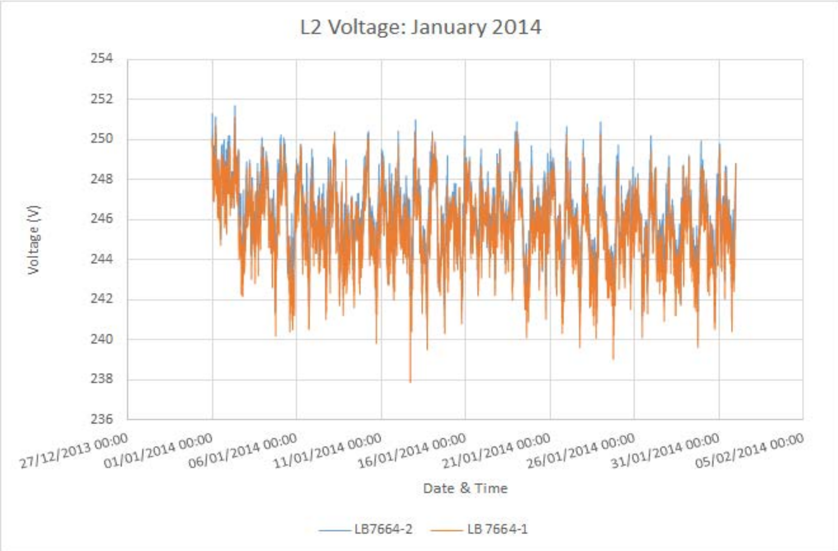

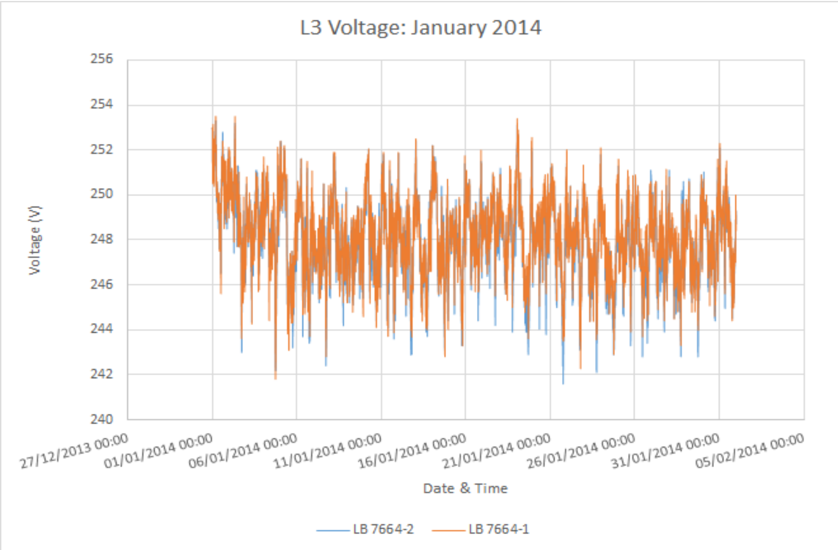

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Figure 34 L1, L2 & L3 Voltage at Linkboxes 7664-1 and 7664-2

Flicker Levels

The levels of flicker seen on each phase at the ends of the feeder are shown in Figure 35 for the same period. These values are within limits described in ENA ER P28 and BS EN 50160. It can be seen that the flicker levels are constantly fluctuating but generally not exceeding 0.4. It is not clear why the flicker level reduced markedly around the 10 January on phase L1 and around 14 January on Phase L2.

The dominant peak value of Pst approaching 0.8 on the 8 January can be seen on all three phases and at both linkboxes which indicates that this as a result of an upstream event affecting all three phases. As a consequence this value can be ignored from the point of view of considering the effects of the operation of heat pumps on the network.

Based on the measured values of flicker it appears that the heat pumps have led to an increase in flicker levels but in this case they are still well within acceptable limits. The effect of their operation on the flicker levels is doubtless reduced to a degree by the size of the main distributor cable to which they are connected a 300sqmm Waveform CNE cable since this will have resulted in a supply impedance even at the most remote customer below the (0.25+0.25j) Ω reference impedance which is used to determine the acceptability of disturbances caused by equipment designed to be connected to the network without need for reference to the DNO.

It can be seen from the graphs below that rather than a relatively steady level of flicker there are significant variations between the typical minimum and maximum levels. The nature of these changes and the cause are further explored in Figure 36 and 37 below.

An expansion of the plot to show a single day (8 January 2014) for each phase and for each link box measurement more readily illustrates the variation in flicker levels being experienced and helps to illustrate the cause of the peaks of flicker by providing comparison between the minimum, average and maximum values of voltage and also shows the relatively localised effects which are seen in this case.

The first thing that is most noticeable is that the general flicker levels are lower at Linkbox 7664-2 than are seen at Linkbox 7664-1. This is to be expected as LB7664-2 is electrically closer to the source substation than LB7664-1.

In the second set of three graphs which show the Pst Flicker measurements for each individual phase at LB7664-1 there are more instances of short term peaks of Pst at around 0.38 – 0.4. In each case it can be seen that the minimum voltage exhibits a greater deviation from the average value. The average value typically remains closer to the maximum value indicating that the duration of the minimum voltage during the averaging period was of a relatively short duration. Such a situation is consistent with a voltage drop being caused by the higher starting current of a motor. This is precisely the sort of behaviour which would be expected from a heat pump, the extent of the problem being determined by a combination of the magnitude of the starting current and the supply impedance at the point of connection, in this case with the main distribution cable being a 300sqmm

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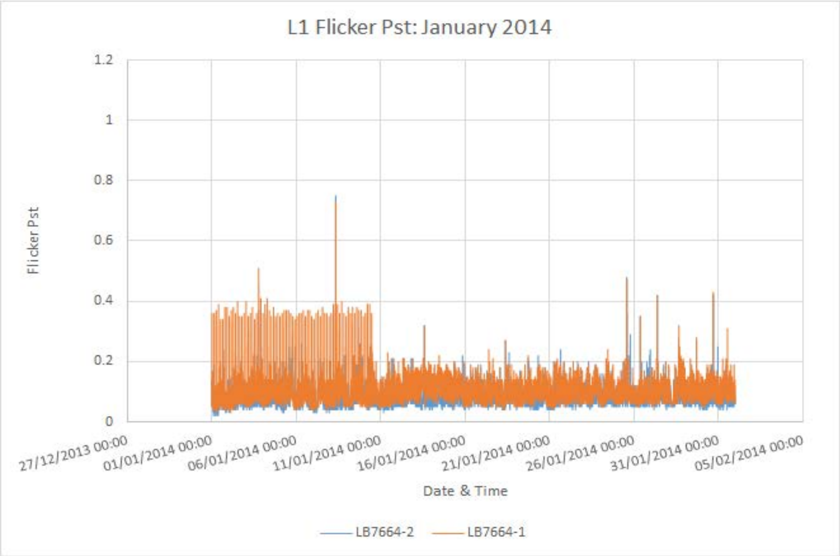
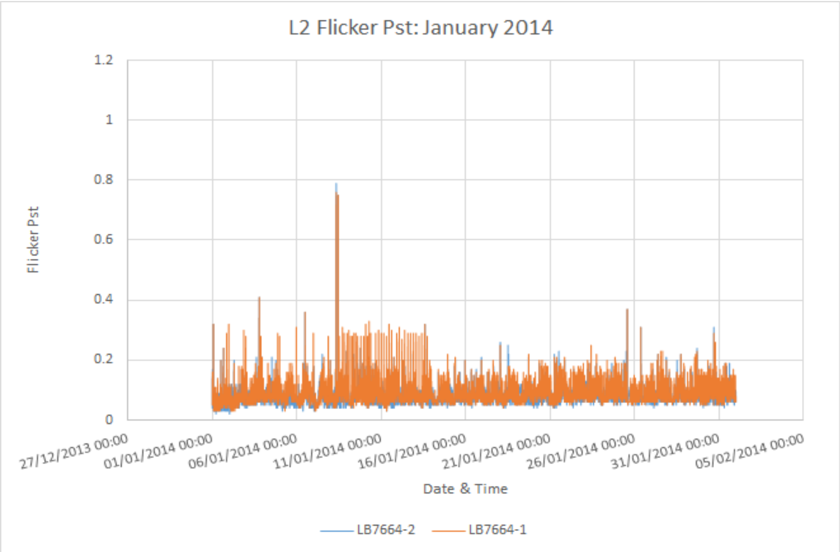
waveform cable the supply impedance is likely to be relatively low even at the feeder end points where the measurements were taken.





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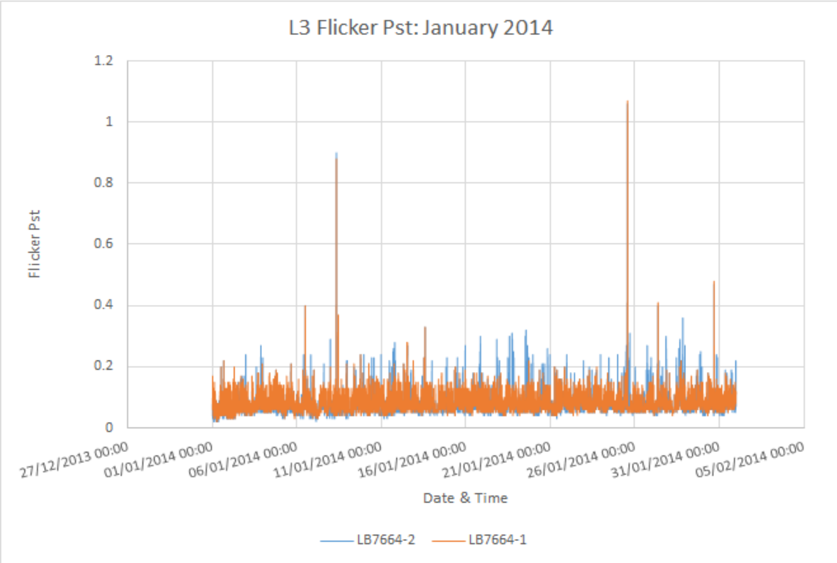
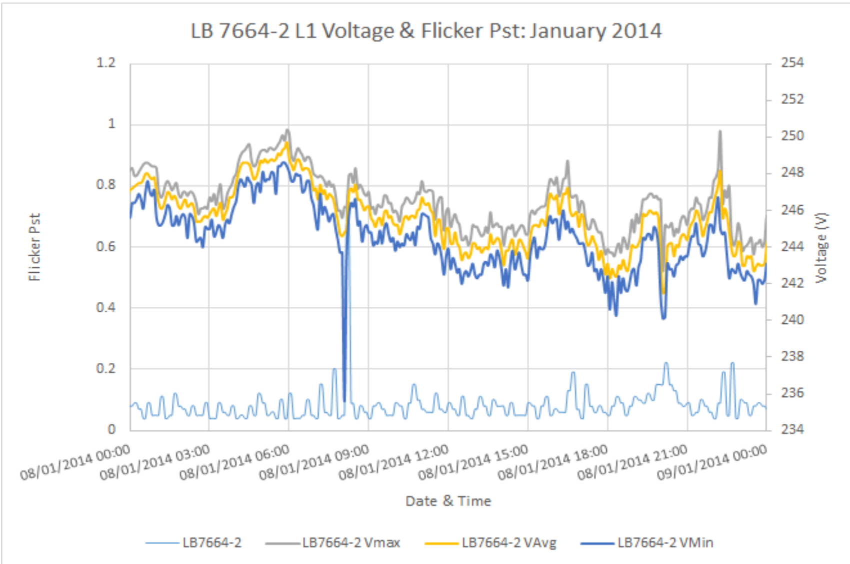


Figure 35 L1, L2 &L3 Flicker Pst at LB 7664-1 & LB7664-2



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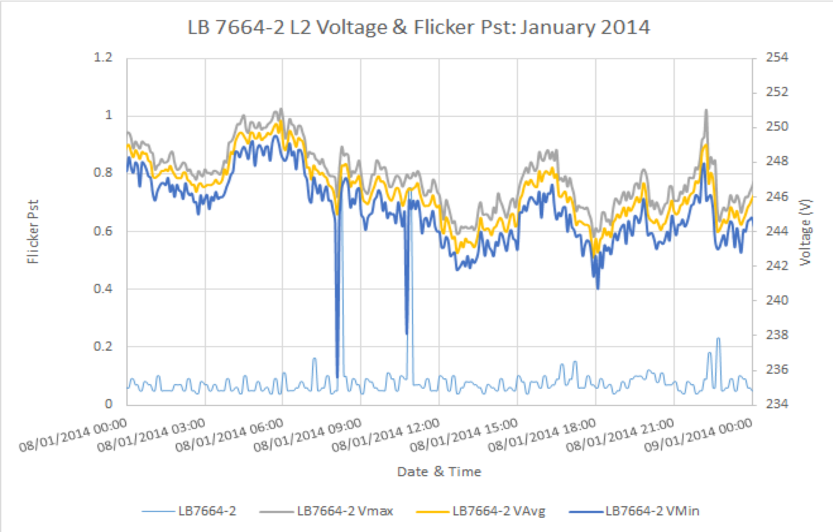

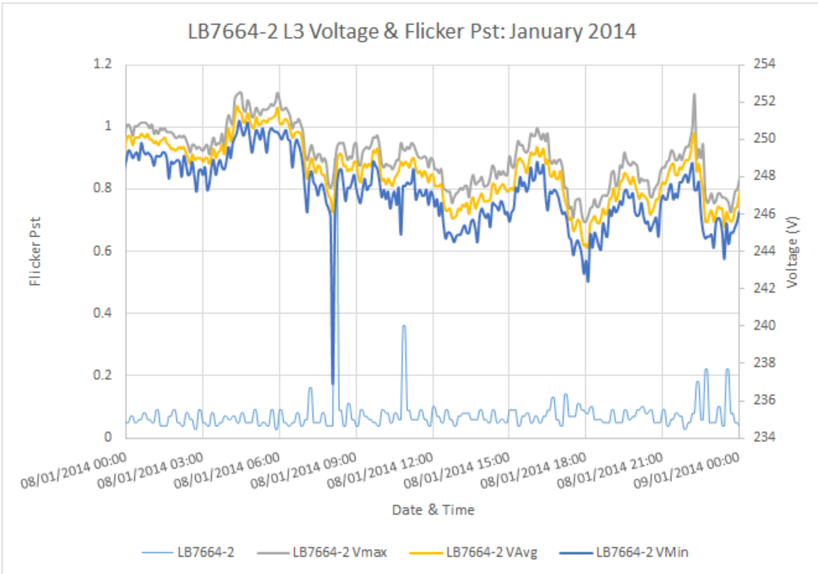

Figure 36: LB7664-2 L1 L2 & L3 Phase Voltage and Flicker levels: 8 January 2014

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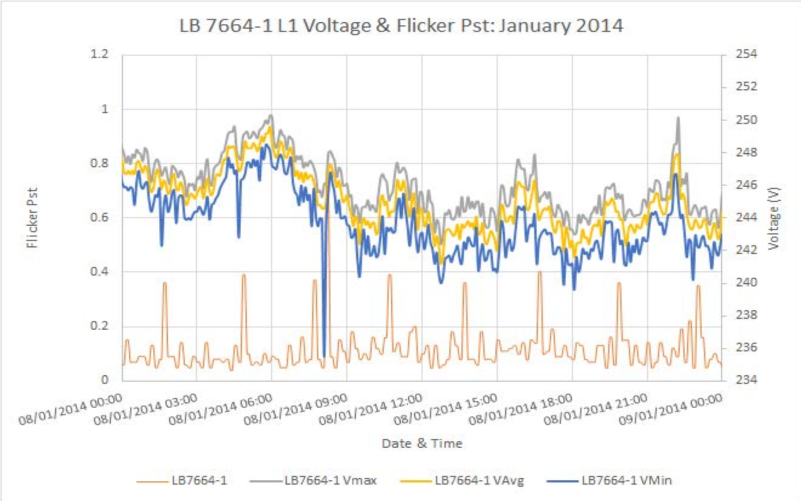

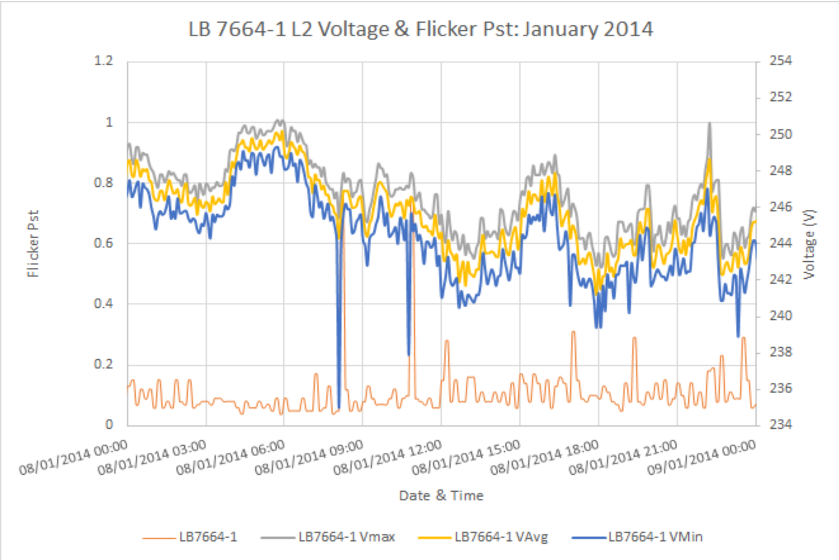

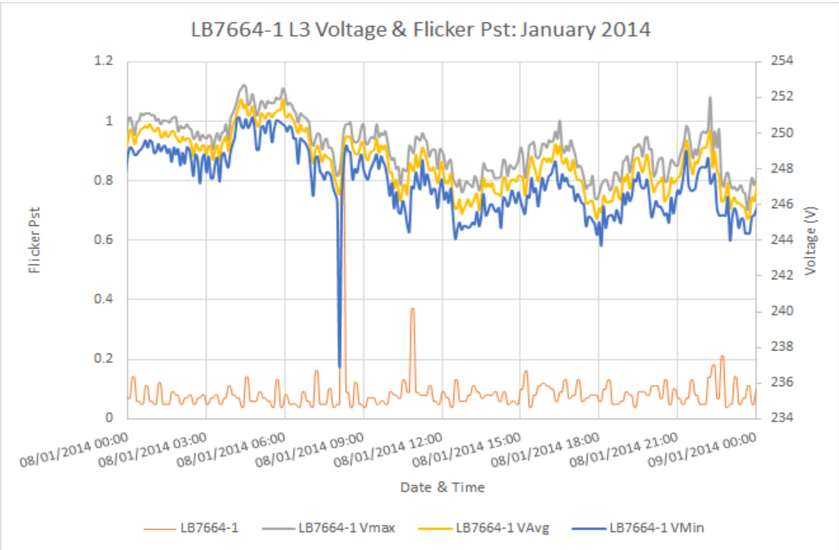

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Figure 37: LB7664-1 - L1, L2 &L3 Phase Voltage and Flicker levels: 8 January 2014

The magnitude of the voltage change seen due to the starting current of the heat pump is greater than was witnessed in the case of the individual British Gas customers monitored as part of this project, which suggests that the heat pumps employed on this cluster have a higher starting current than was observed for the individual customers particularly when account is taken of the fact that these measurements were made on the main distributing cable whereas the individual customers' measurements were of course made at the end of a service cable where the same magnitude of starting current would be expected to give rise to a greater voltage drop.

Harmonic Distortion

The Voltage Total Harmonic Distortion levels are shown in Figure 38 below. It can be seen that the levels are well within the planning limits of G5/4-1 peaking at 3.5% on the 8th January compared to a planning limit of 5% at Low Voltage. Heat Pumps equipped with induction motors should be expected to have little in the way of significant harmonic emissions.

Unbalance

The levels of voltage unbalance seen at the ends of the feeder are illustrated in Figure 39 below. During the course of the measurements there is a fair degree of variation in the levels of unbalance from a minimum of around 0.2% peaking at around 1.4%. A degree of variation and unbalance is to be expected on any system with a number of distributed single phase loads. As the main distributing cable is a 300sqmm cable the level of voltage drop experienced along the main cable is reduced for a given load and were the same load to have been applied to a smaller cross-section cable then the effect may have been expected to be greater as the individual variation per phase would be increased.

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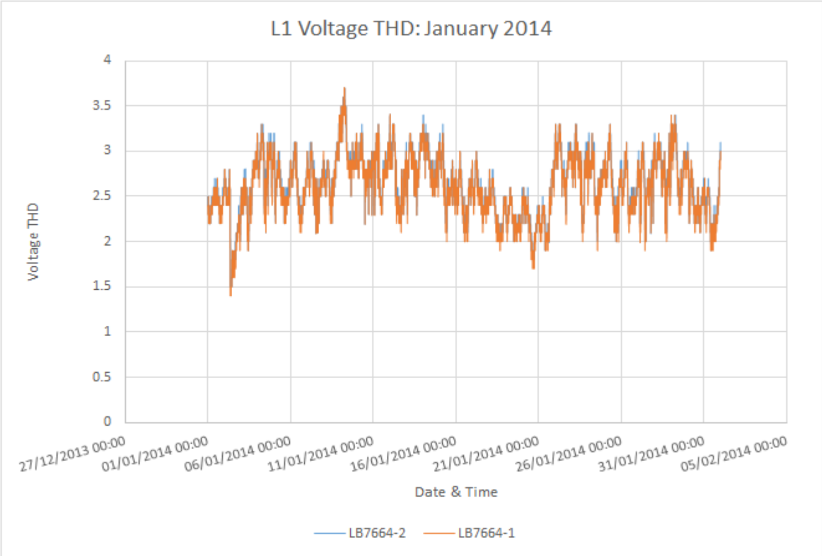

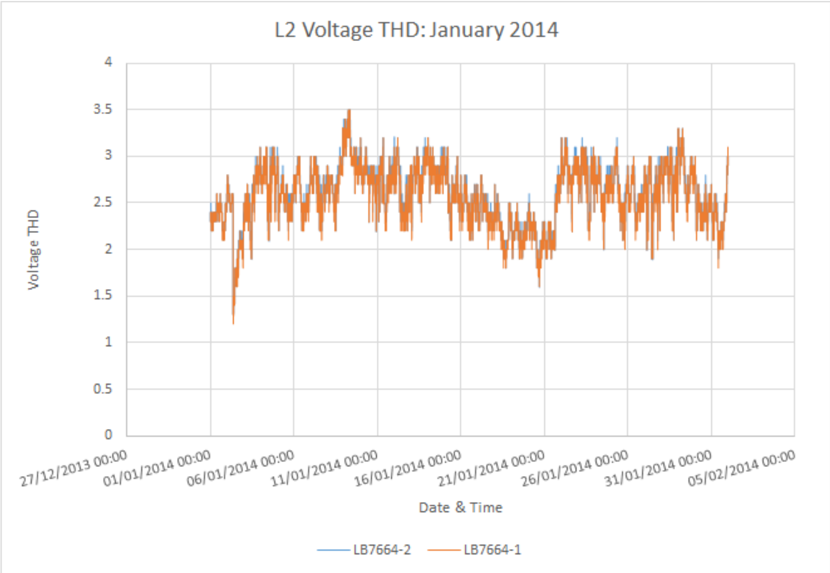

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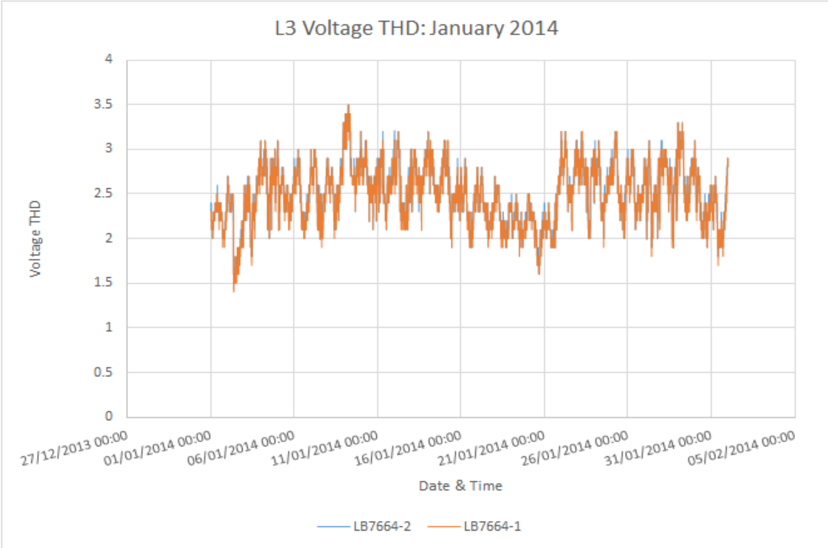
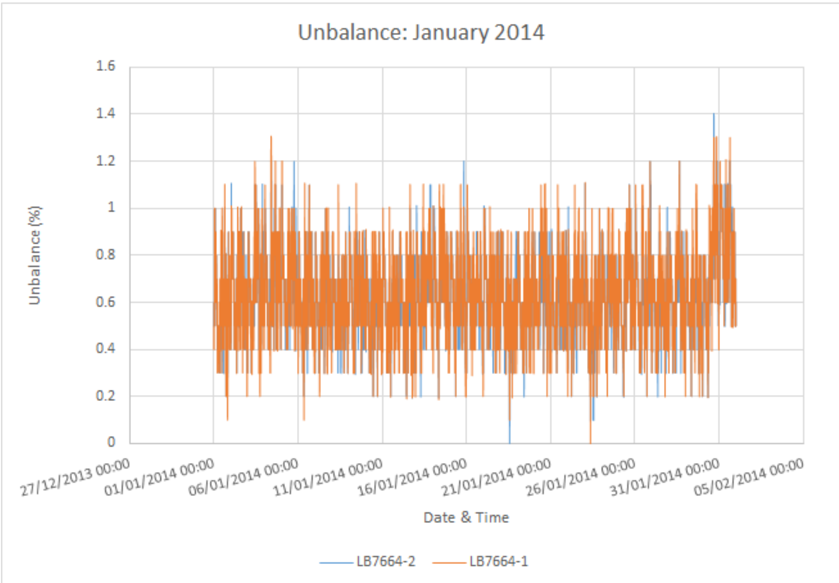


Figure 38 L1, L2 & L3 Voltage Total Harmonic Distortion LB7664-1 & LB7664-2



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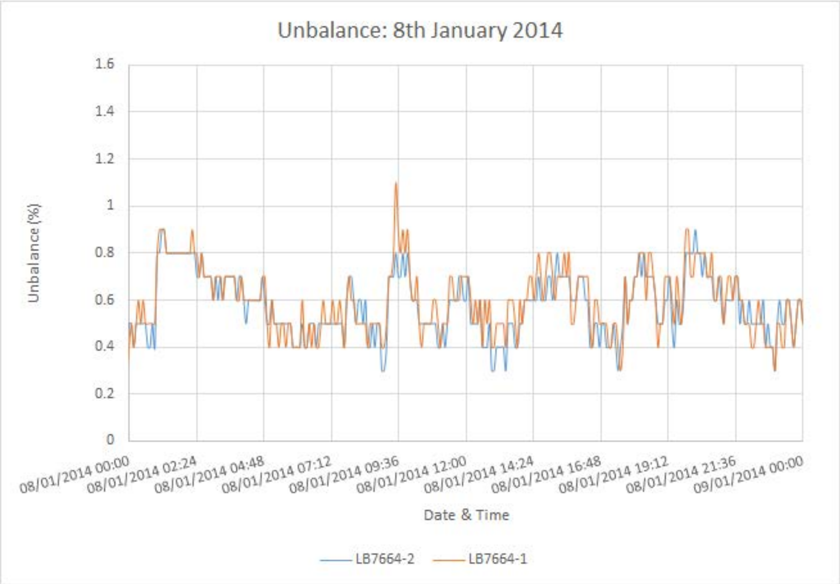

Figure 39 – Unbalance at LB7664-1 & LB 7664-2

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4.1.2 Sidgate Lane - Newborough

Sidgate Lane substation has two LV feeders, one with 10 customers all equipped with a heat pump whilst the second has 12 customers with no heat pumps installed. A PQ monitor is installed at the source substation LV Board and at the end of the feeder equipped with the heat pumps. This is the relatively short 185 sqmm waveform cable shown at the bottom of Figure 40 below.

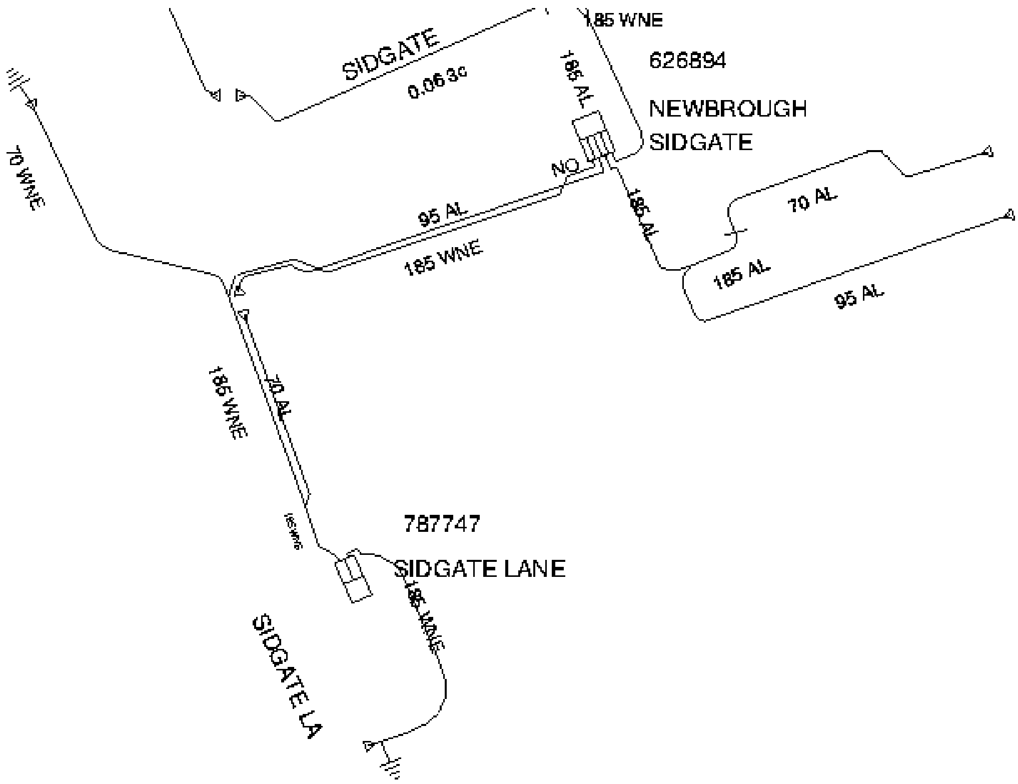

Figure 40 – LV Network skeleton for Sidgate Lane Substation

Voltage Variation

The graphs of voltage variation illustrated in Figure 41 below show two distinctly different aspects to the trace, one where the linkbox voltage measurements closely mirror those of the source substation LV board and one where there is a noticeable difference between the two traces. These differences arise due to the operation of the voltage regulator installed at Sidgate Lane between the source substation and the first customer on the feeder equipped with the heat pumps. The relatively short length of the main distribution cable and the small number of customers connected to it mean that the voltage drop along the main cable would always be expected to be relatively small even if all of the heat pumps are operating at the same time.

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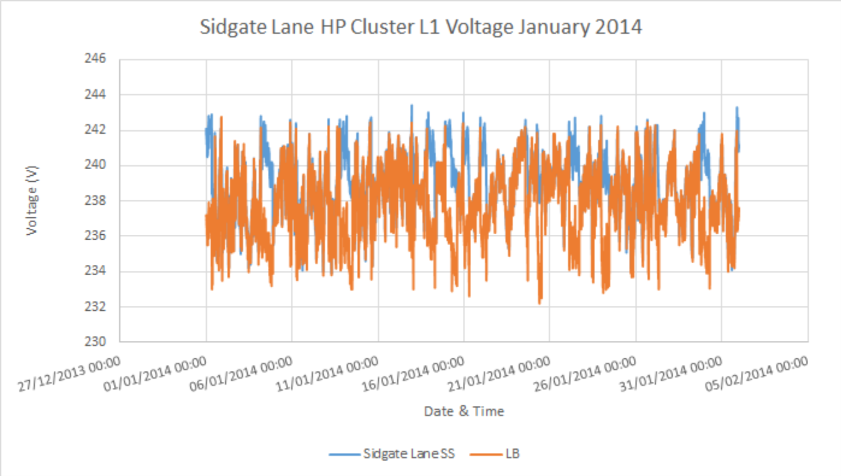

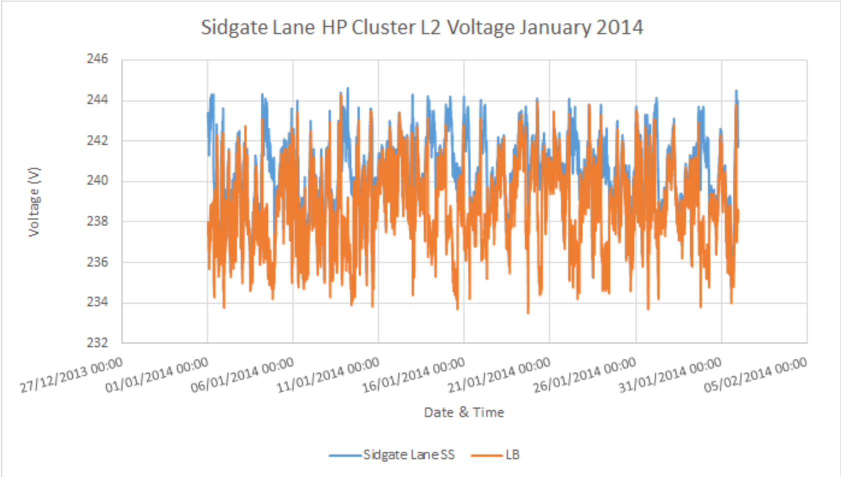

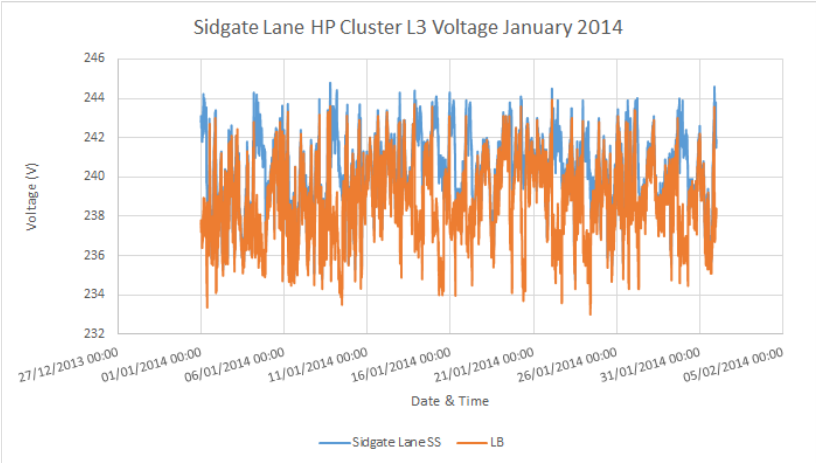

Figure 41 Voltage Variation at LB 7664-1 and LB 7664-2

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Flicker Level

The flicker levels for each phase are illustrated in figure 42 below

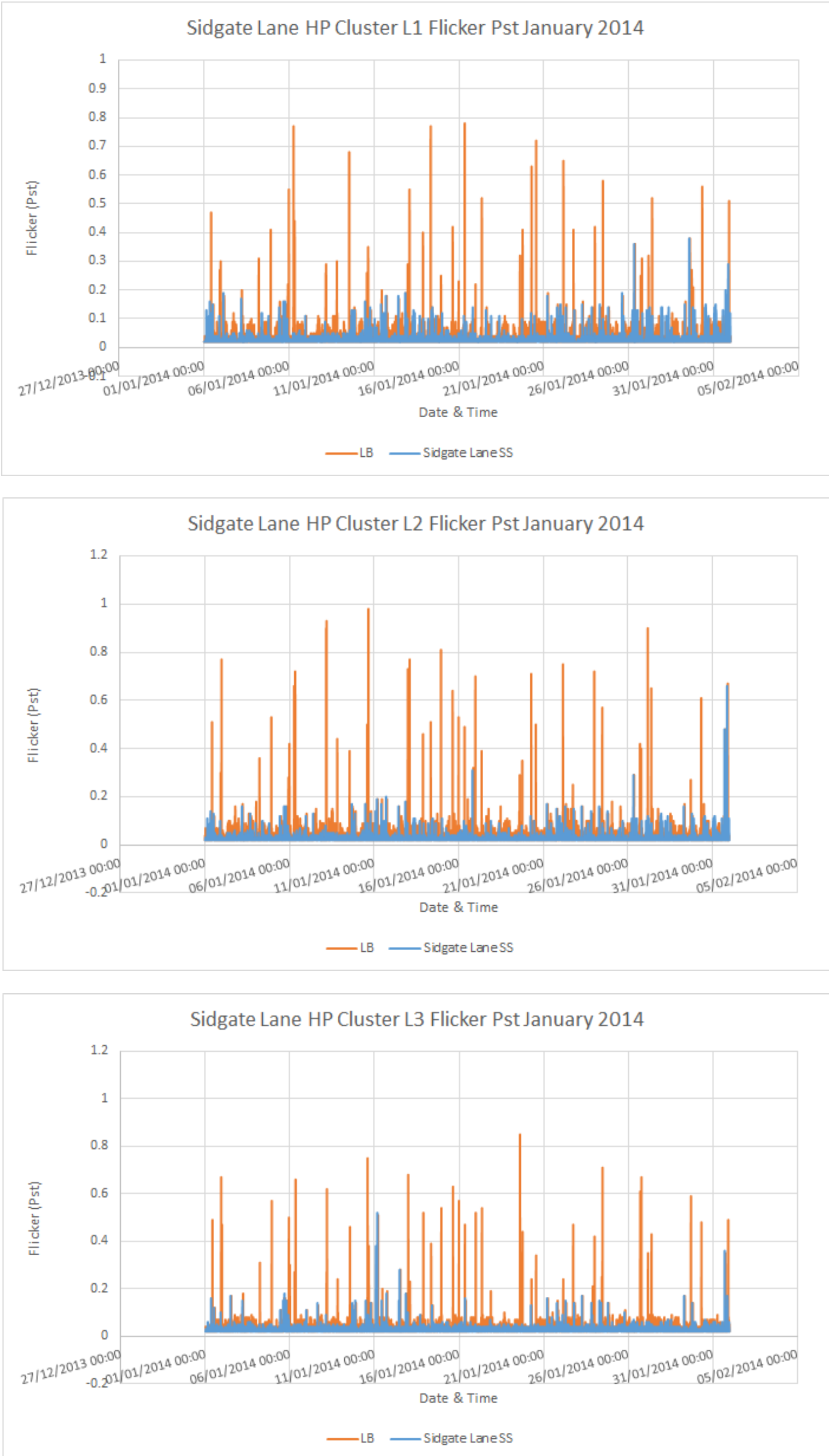

Figure 42 Flicker Levels for L1, L2 and L3

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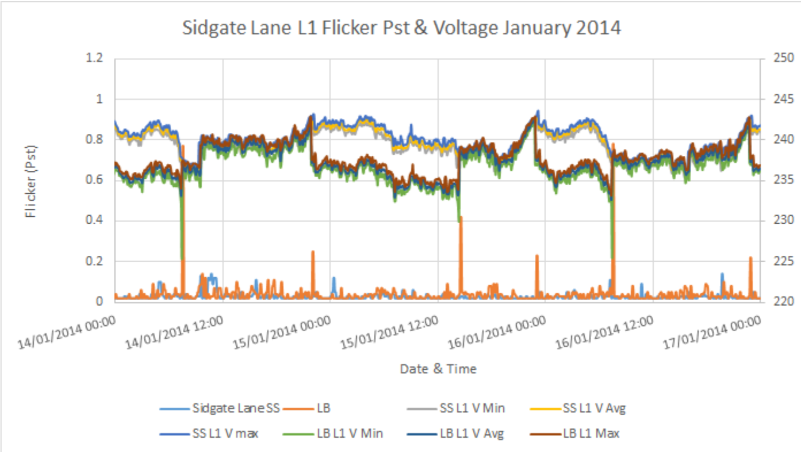
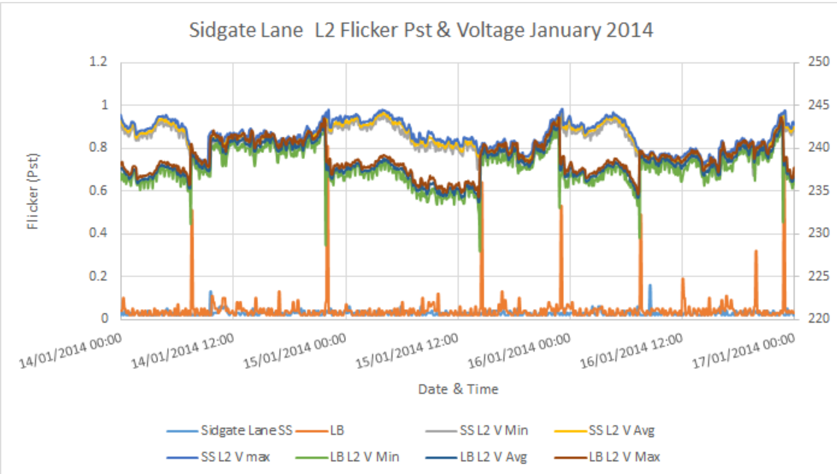
Flicker levels at the source substation busbar are much lower than those seen at the remote end of the feeder. This is a result of the action of the voltage regulator. The majority of the peak values of flicker seen at the remote end of the feeder are as a result of step changes in voltage brought about by the action of the voltage regulator rather than the operation of the heat pumps. This can be seen more clearly in figure 43 below.





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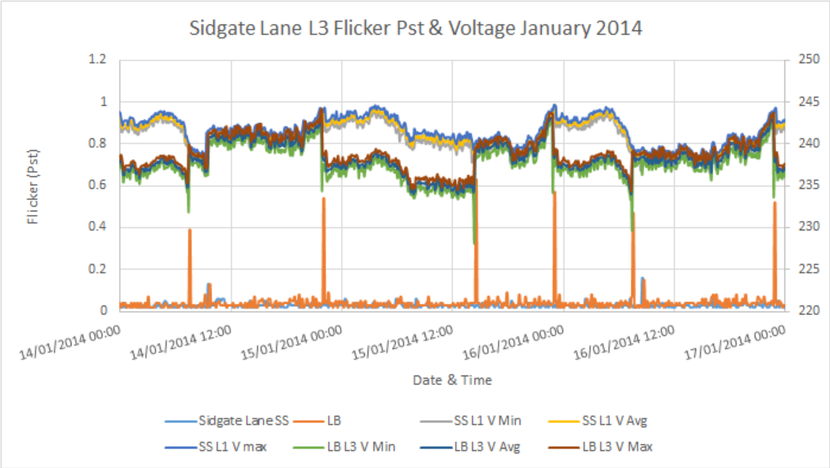
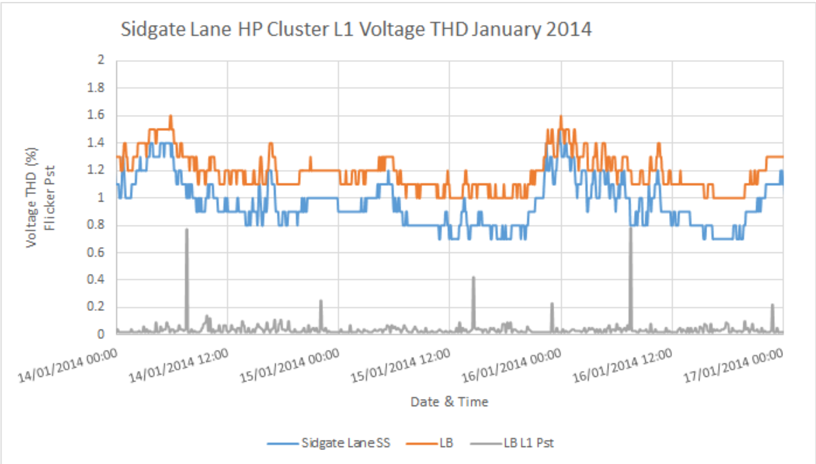
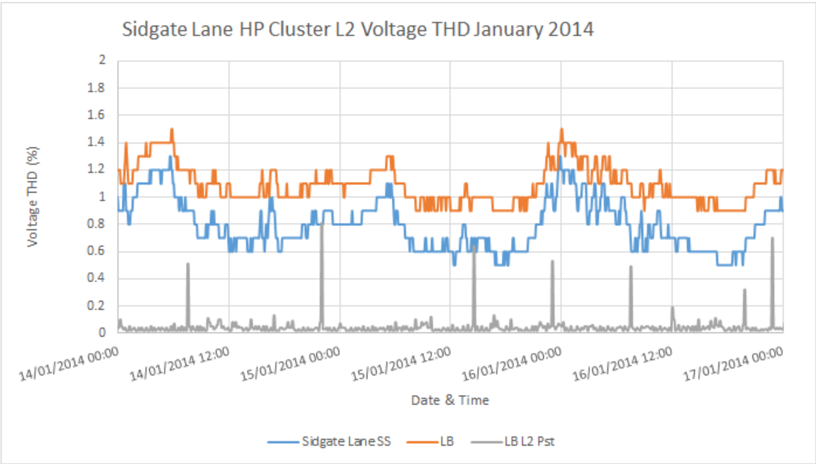


Figure 43 – Flicker Pst & Voltage Profiles: 14-17 January 2014

Voltage Total Harmonic Distortion

Figure 44 below illustrates the Voltage Total Harmonic Distortion levels at Sidgate Lane substation and the linkbox which are well within the G5/4 planning levels





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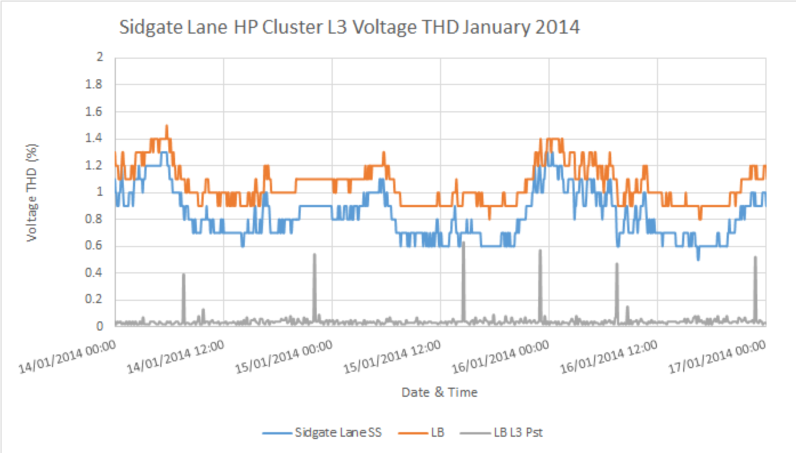

Figure 44 Voltage THD Sidgate Lane 14 -17 January 2014

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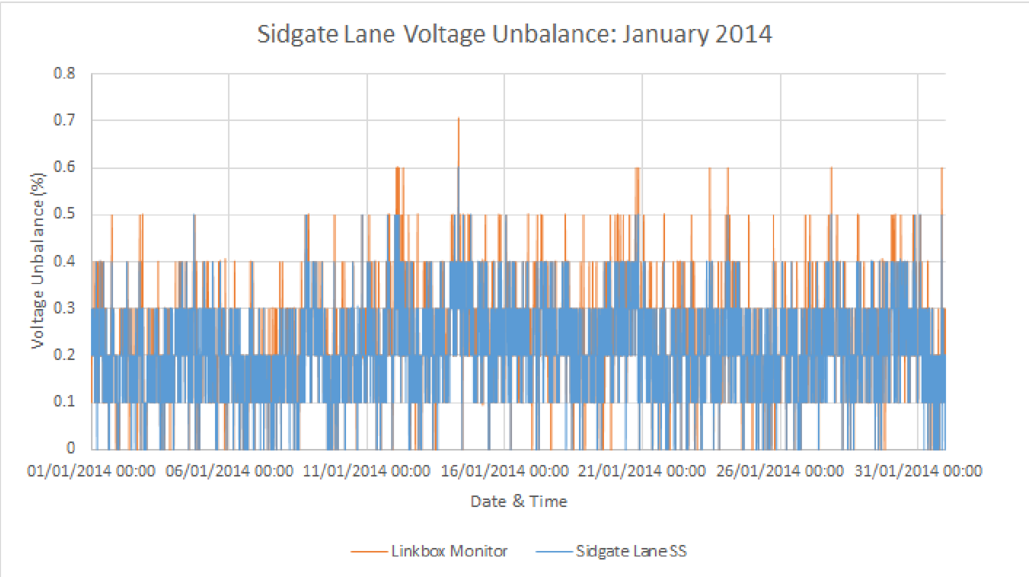
Unbalance

The levels of unbalance fluctuate between 0 and 0.7%. There is as would be expected some variation between the source and the remote end of the feeder but in general they show quite close alignment with one another. The feeder being monitored is relatively short and with only 10 customers connected so there is perhaps limited scope for significant variation in the levels of unbalance.



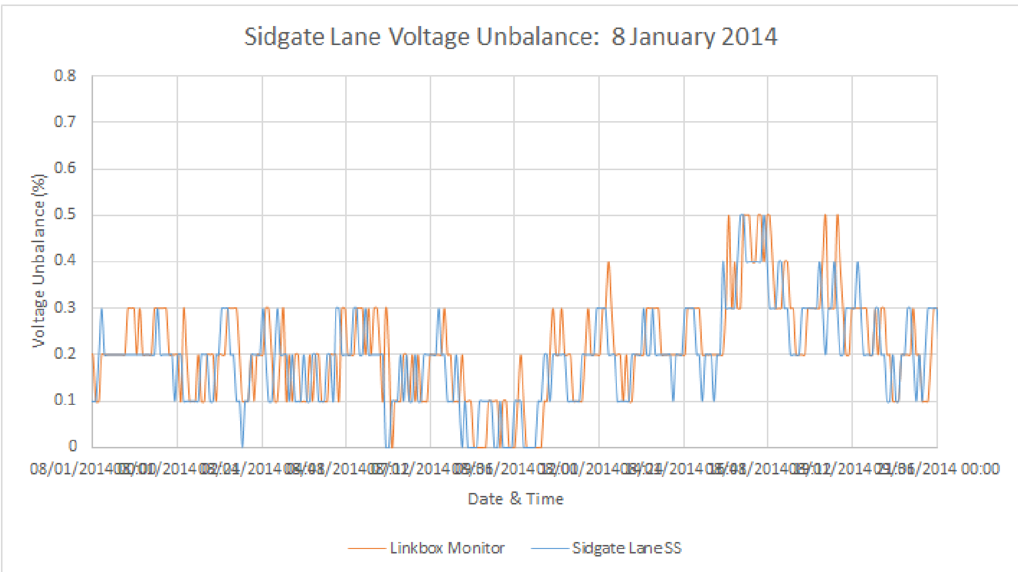


Figure 45 Voltage Unbalance at Sidgate Lane Substation and Feeder End Linkbox

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4.1.3 Conclusions

The clusters of heat pumps have not resulted in any problematic changes to the network power quality. Although the voltage depression which might be associated with motor starting and the resulting flicker values have been visible on the Redburn cluster the values are within tolerable levels. Similar situations on a network with higher supply impedance (smaller cross-section cables may have seen a greater effect.

The Sidgate Lane cluster did exhibit some raised flicker levels, however these were attributable to the operation of the voltage regulator switching into and out of circuit rather than the operation of the heat pumps, whose operation was actually very difficult to detect.

Harmonic distortion levels at the remote end of the cluster feeders have remained within the planning levels contained in Engineering Recommendation G5/4-1.

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4.2 Photovoltaic Generators

A cluster of photovoltaic generators were monitored at Mortimer Road substation in Maltby, the substation transformer is equipped with an on-load tap changer. There are 5 LV feeders from the substation. There are no measurements available from the end of Feeder 3 so this is not discussed further in the following commentary. Feeder 4 from this substation which has the most PV installations was also equipped with an Electrical Energy Storage system mid-way along the feeder. The following sections are grouped by the power quality feature being examined and then by each feeder for which there are measurements available. The features have been examined for the month of June 2014, which includes the Summer Solstice, the longest day of the year, and potentially therefore the time of greatest output from the solar panels as the sun is at its highest in the sky.

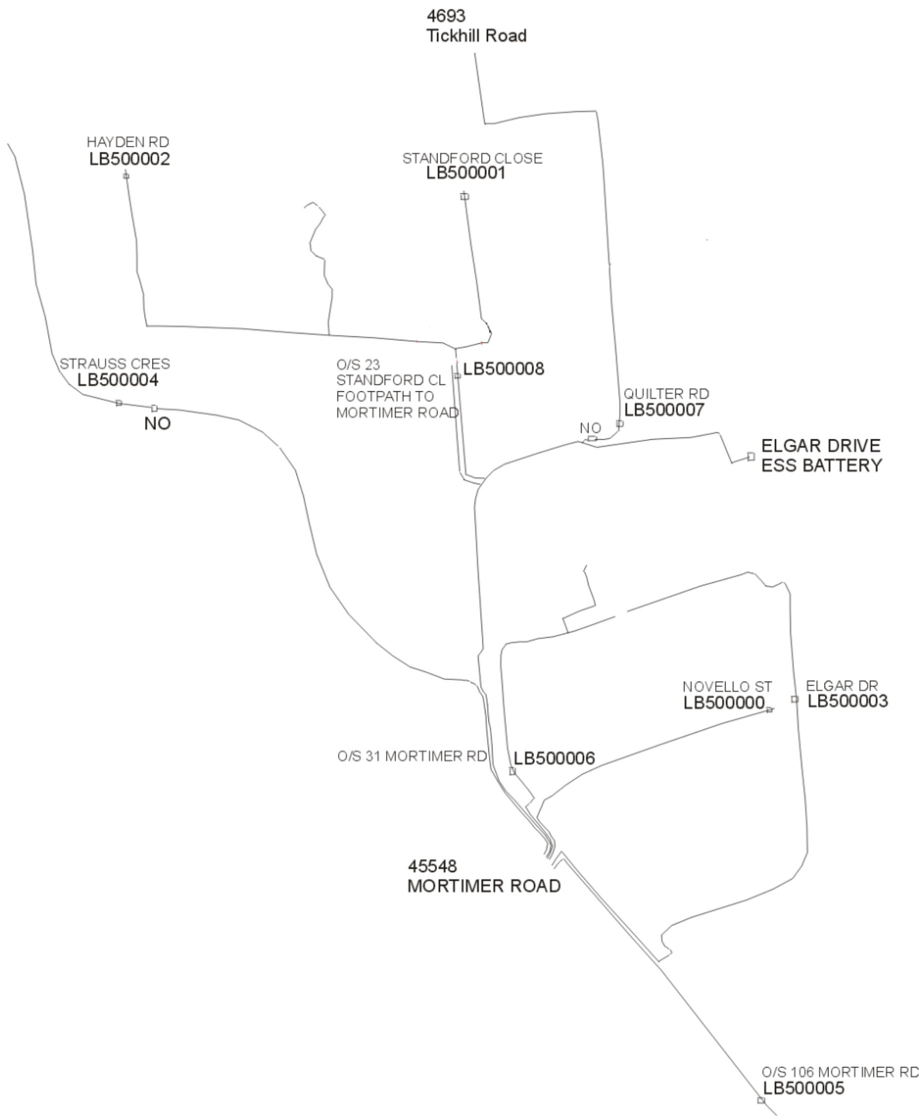

Figure 46 – LV network skeleton diagram for Mortimer Road Substation

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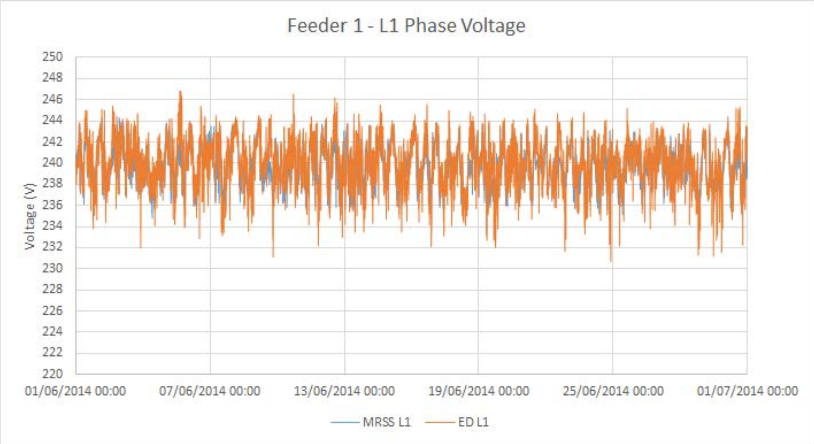
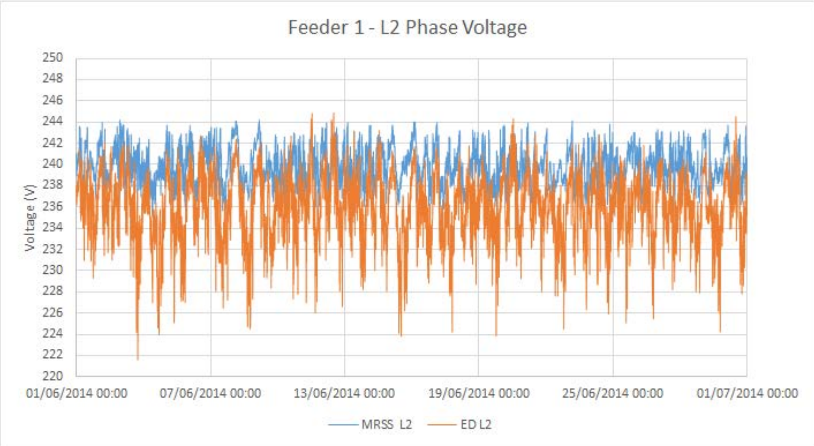
4.2.1 Voltage Variation

Feeder 1

Feeder 1 phase L2 exhibits a greater degree of voltage difference between the source substation and the monitoring linkbox than either phase L1 or L3. This is consistent with increased net loading on phase L2 compared to L1 & L3.





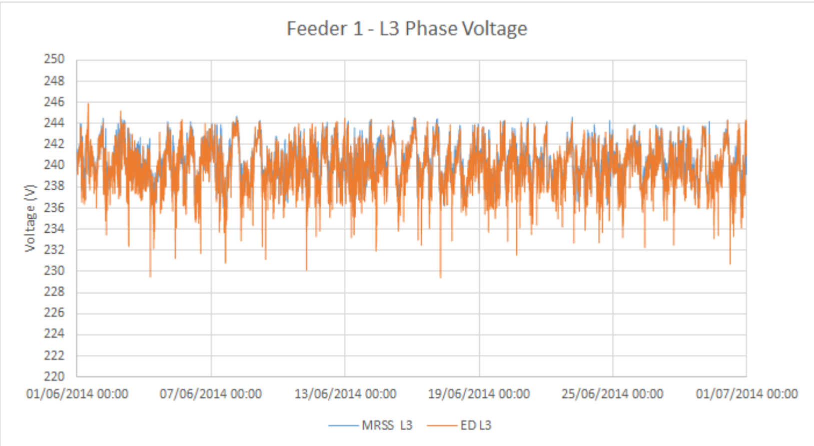


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Figure 47 Mortimer Road feeder 1 voltage profiles.

Phase L1 and Phase L3 exhibit voltage profiles between the source substation and LB500003 which suggest frequent occurrences of export from the feeder towards the substation. Phase L2 does exhibit some evidence of export from the feeder towards the substation but much less frequently and at a lower magnitude. This is demonstrated in Figure 48 below which shows the voltage traces for 12 June for Phase L1 and L2.

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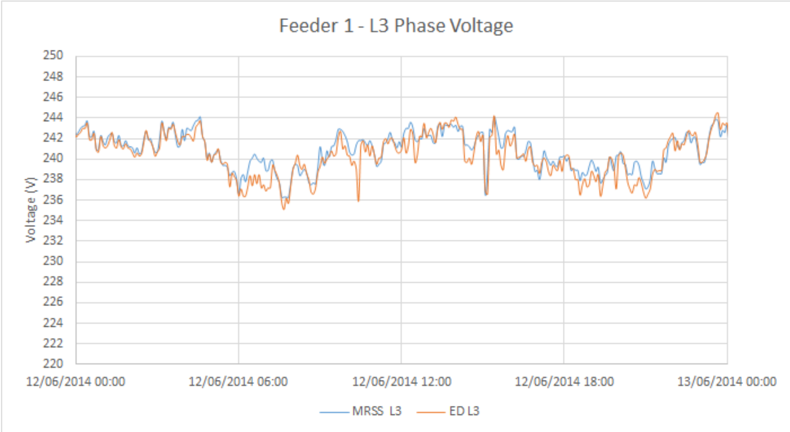
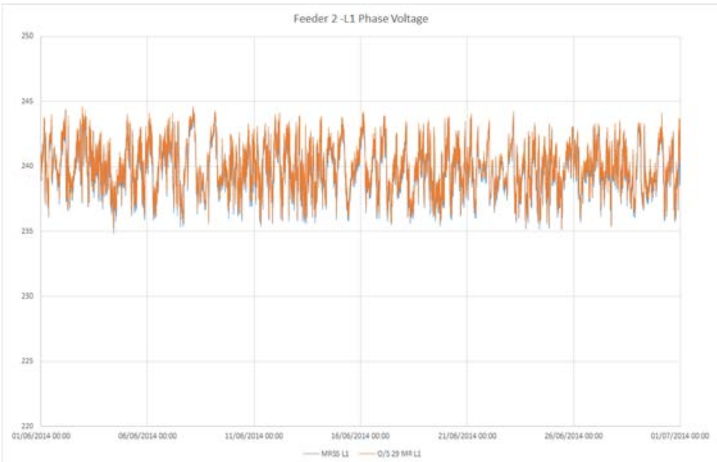


Figure 48 Voltage Variation Phase L1 L2 and L3

Feeder 2

Feeder 2 exhibits voltage traces with very close alignment between the source substation measurements and the measurements at LB500006. LB 500006 is physically and electrically close to the source substation meaning that except under higher load or export conditions a close conformity between the two sets of measurements is to be expected.



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Customer-Led Network Revolution

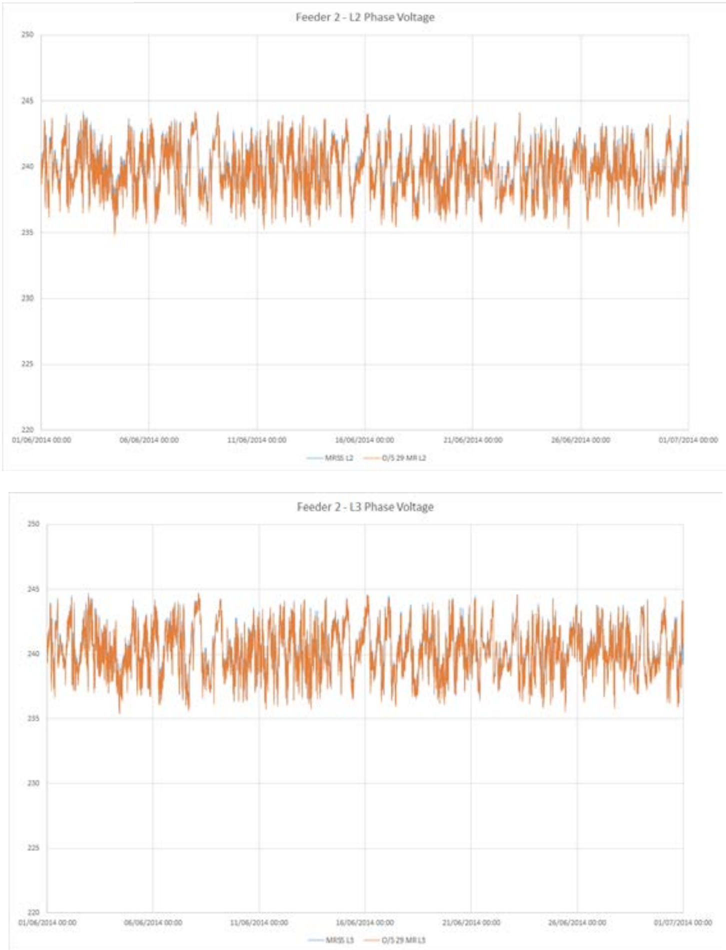

Figure 49 – Feeder 2 voltage profiles

Feeder 4

Feeder 4 does exhibit some occasions where the remote feeder voltages exceed the source substation voltage levels although these are relatively short lived and the magnitude of the voltage rise is only approximately between 1% and 2% of nominal.

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Figure 50 – Feeder 4 voltage profiles

Feeder 5

Feeder 5 has no PV installations connected to it, the feeder is relatively short and as a consequence the remote linkbox measurements are electrically close to the Mortimer Road substation.

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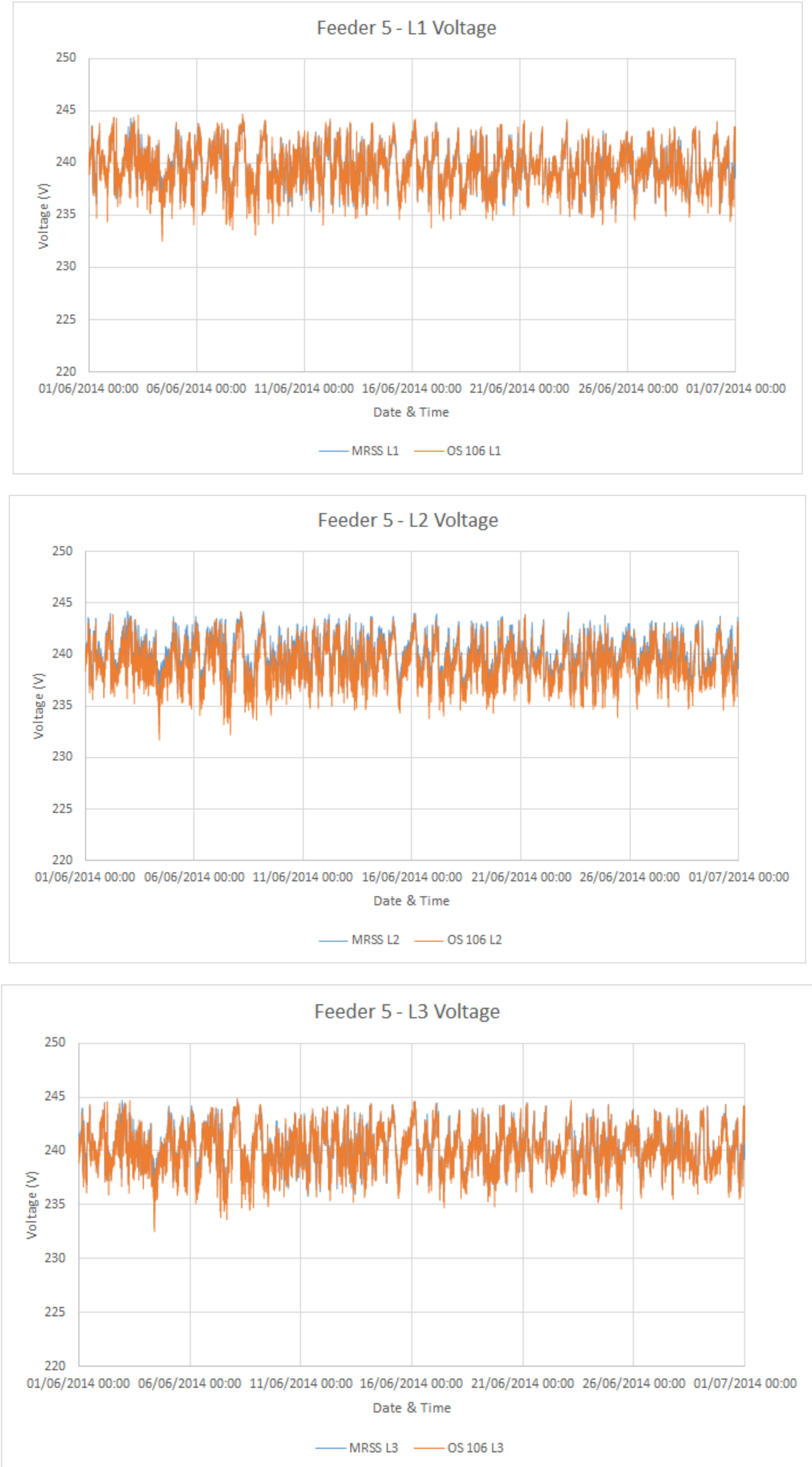

Figure 51 – Feeder 5 Voltage Profiles

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4.2.2 Flicker Levels

The flicker levels experienced along each feeder are illustrated in the following sets of figures. It can be seen that there was one event which dominates above all others. This event is seen at an equal magnitude on all of the individual feeders and affects all three phases; it can therefore be deduced that this was an upstream 3 phase event at a higher voltage level, there is therefore no need to consider it further from the point of view of the impact of PV generation or Electrical Energy Storage on the network. It does however produce a convenient point against which to reference all of the traces to ensure that they are aligned in time.

The following sections illustrate the whole month and a single day to provide greater detail of the variation in flicker levels.

Feeder 1

The flicker levels for feeder 1 exhibit a fluctuating level between levels of around 0.1 and 0.7 for most of the period with some examples of values around 1.0. There are some noticeable reductions in the typical upper levels of flicker which occur from around midday on a Saturday until around 6pm on a Monday. During these periods there is an increased difference between the levels measured at the Mortimer Road substation busbars and those measured at the remote feeder linkbox.

Feeder 1. This is suggestive that for the most part the flicker levels on Feeder 1 are dominated by upstream sources of disturbance. Figure 52 below shows the flicker measurements for feeder 1 in June 2014, whilst Figure 53 offers a more detailed look at 21 June. The 21 June was a Saturday and also the longest period of daylight. Up until around mid-day it can be seen that the flicker levels measured at the linkbox broadly align with the source substation measurements i.e. that upstream disturbances are dominating any downstream disturbances, whereas after midday the flicker levels at the remote end of the feeder exceed those seen at the substation busbars which are markedly reduced.

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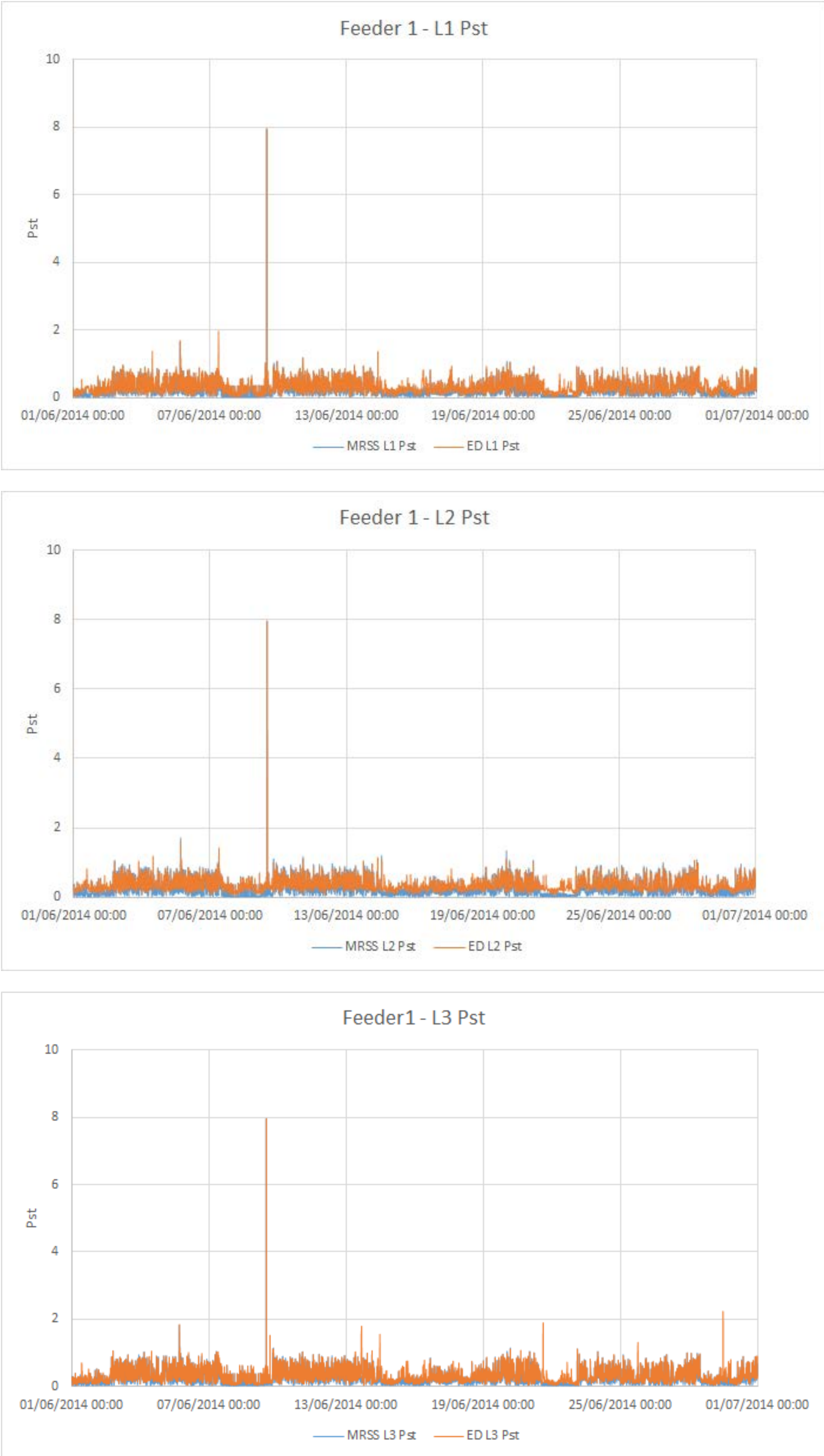

Figure 52 – Feeder 1 Pst June 2014

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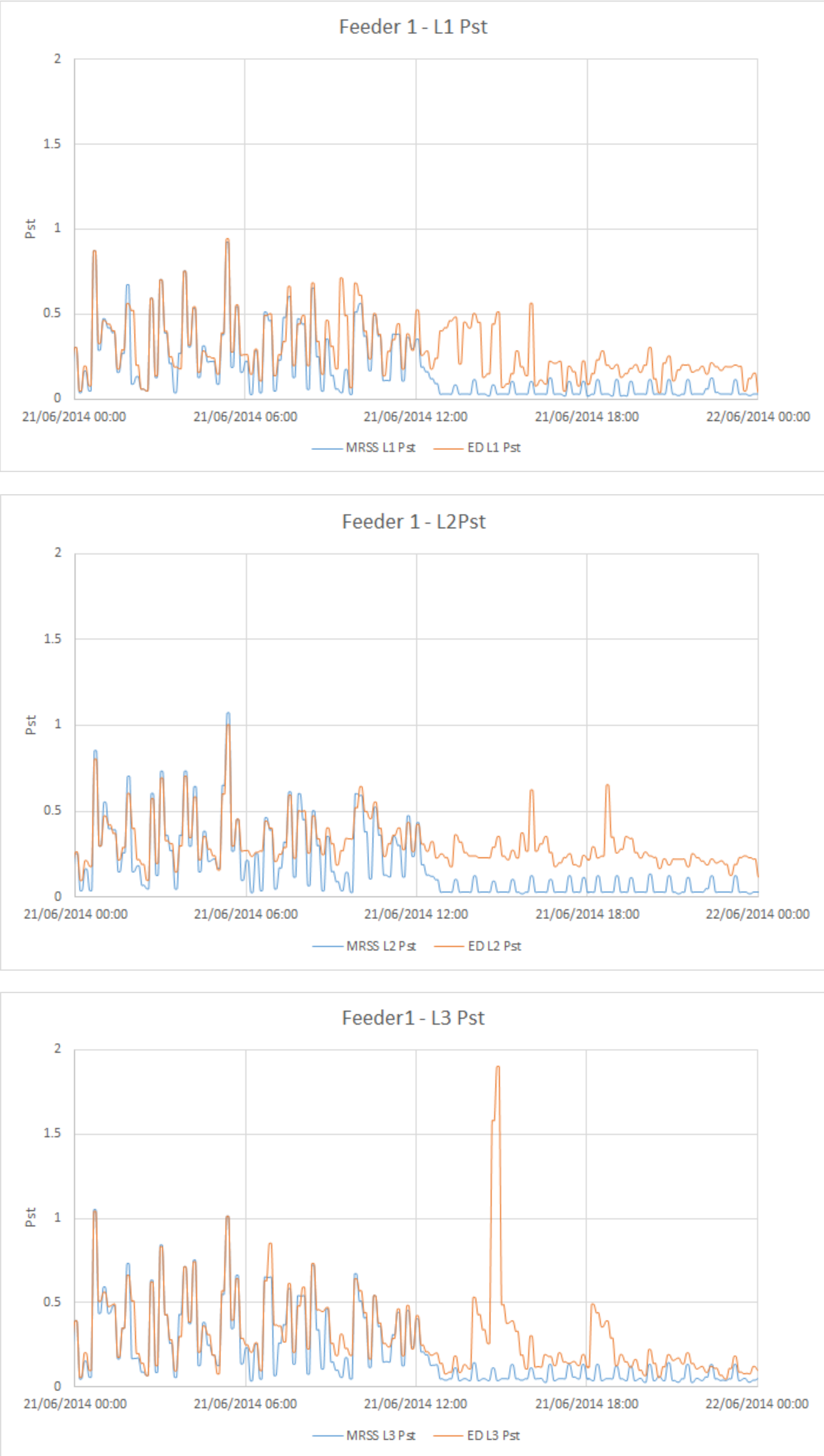

Figure 53 – Feeder 1 Pst 21 June 2014

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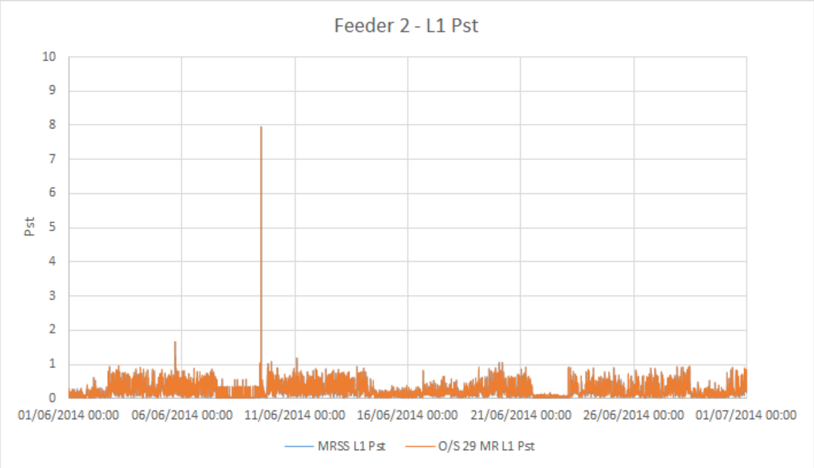
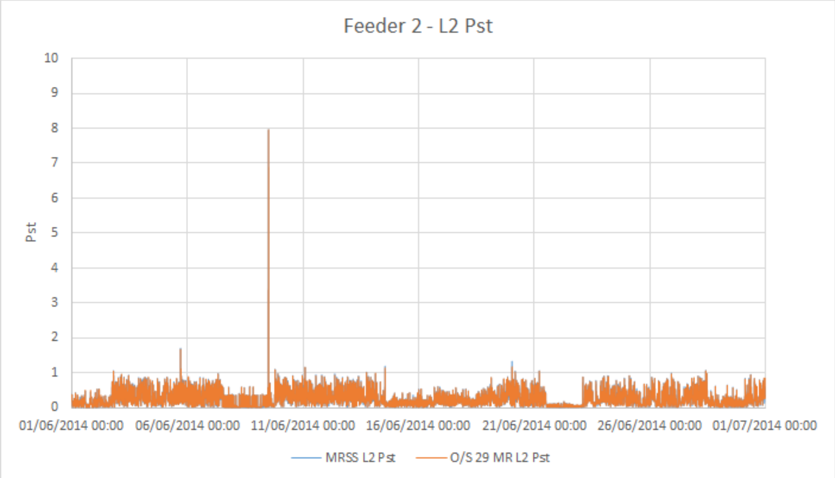
Feeder 2

Feeder 2 exhibits a close alignment between the source station Pst measurements and those at the linkbox although as observed in the voltage traces this is to be expected as the linkbox measurement point is physically and electrically relatively close to the source.





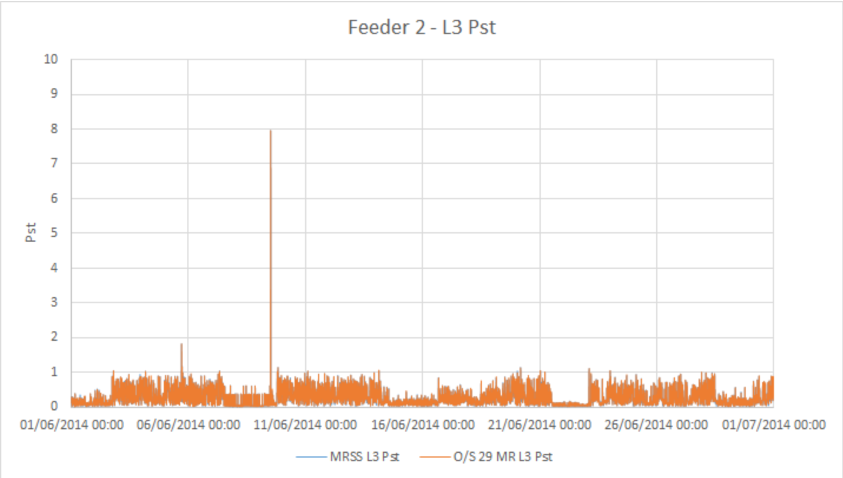


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Figure 54 – Feeder 2 Pst June 2014

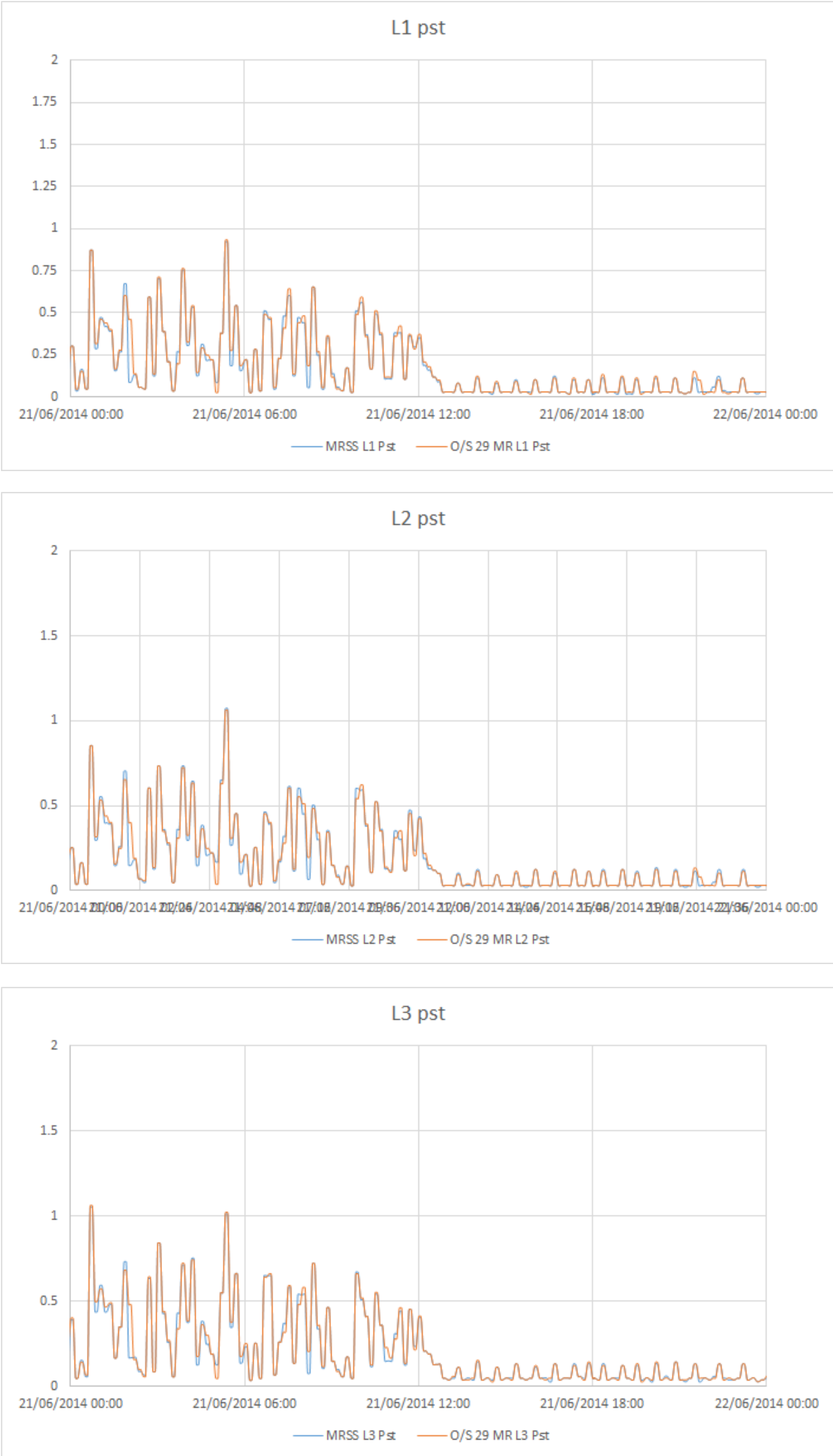

Figure 55 – Feeder 2 Pst 21 June 2014

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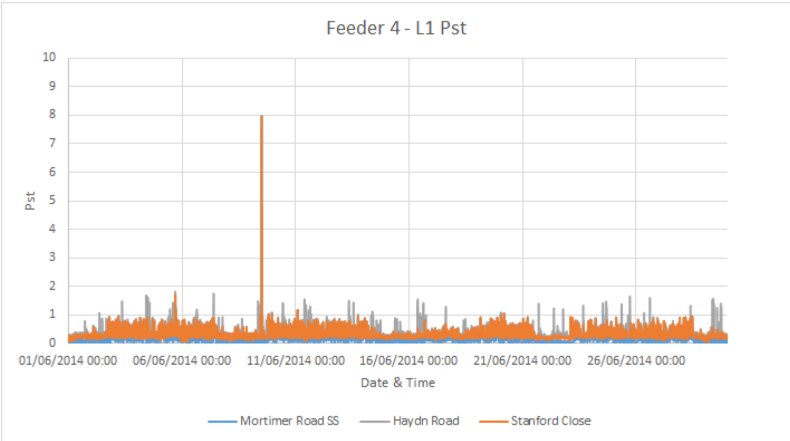
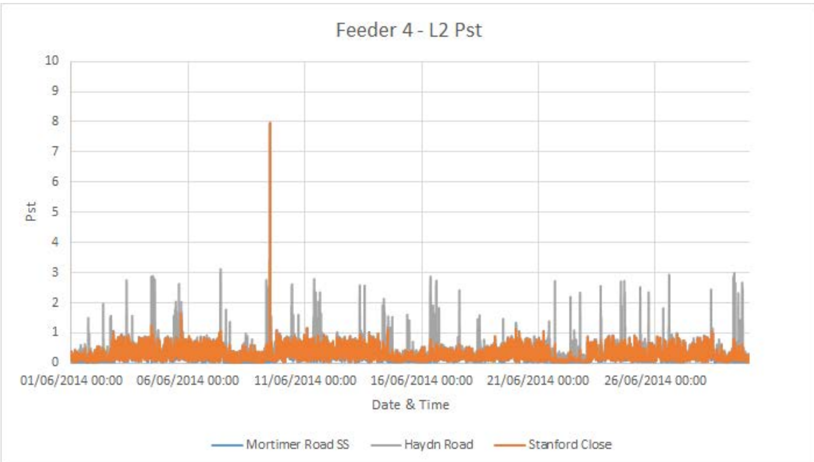
Feeder 4

Feeder 4 exhibits broadly the same flicker characteristics as have been seen on Feeders 1 & 2 already, there are however, some significant differences. Phase L1 exhibits an almost constant base level of flicker around 0.25 at the remote ends of the feeder whilst Phase L3 exhibits a higher base level of flicker at 0.5 at the same points. All three phases exhibit some significant peaks of Pst flicker values at Haydn Road exceeding 1.5 on phase L1 & L3 and approaching 3 on phase L2.





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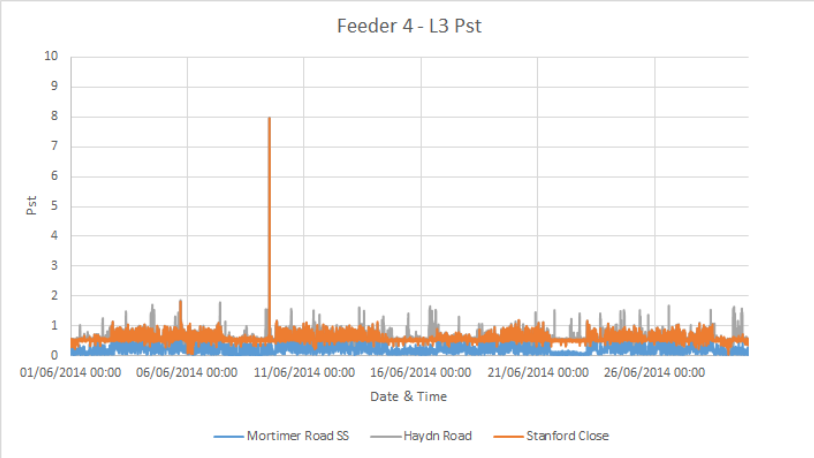
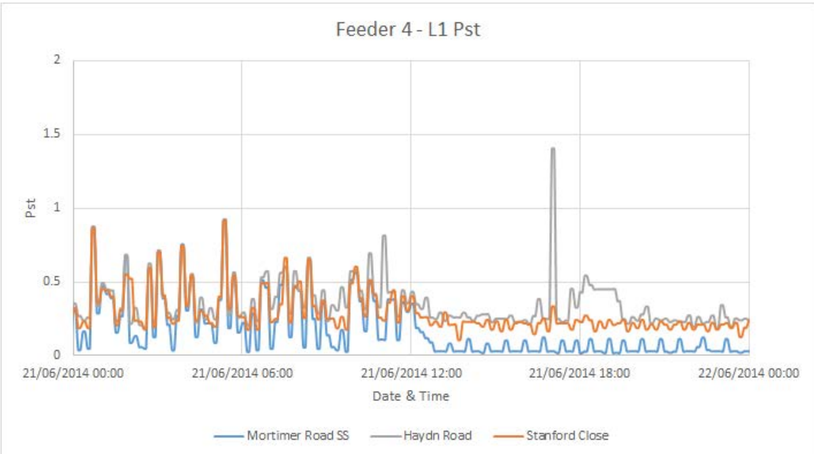


Figure 56 – Feeder 4 Pst June 2014

It can be seen that although the values of Pst measured at Haydn Road are potentially of concern they are a fairly localised effect not being reflected at either Stanford close or Mortimer Road measurement points. This suggests that the cause of this disturbance is close to the monitoring point at Haydn Road and whilst giving rise to significant voltage disturbances at that point the fact these are not reflected further back into the network indicates that the magnitude of the load change is relatively small compared to the overall network capacity.



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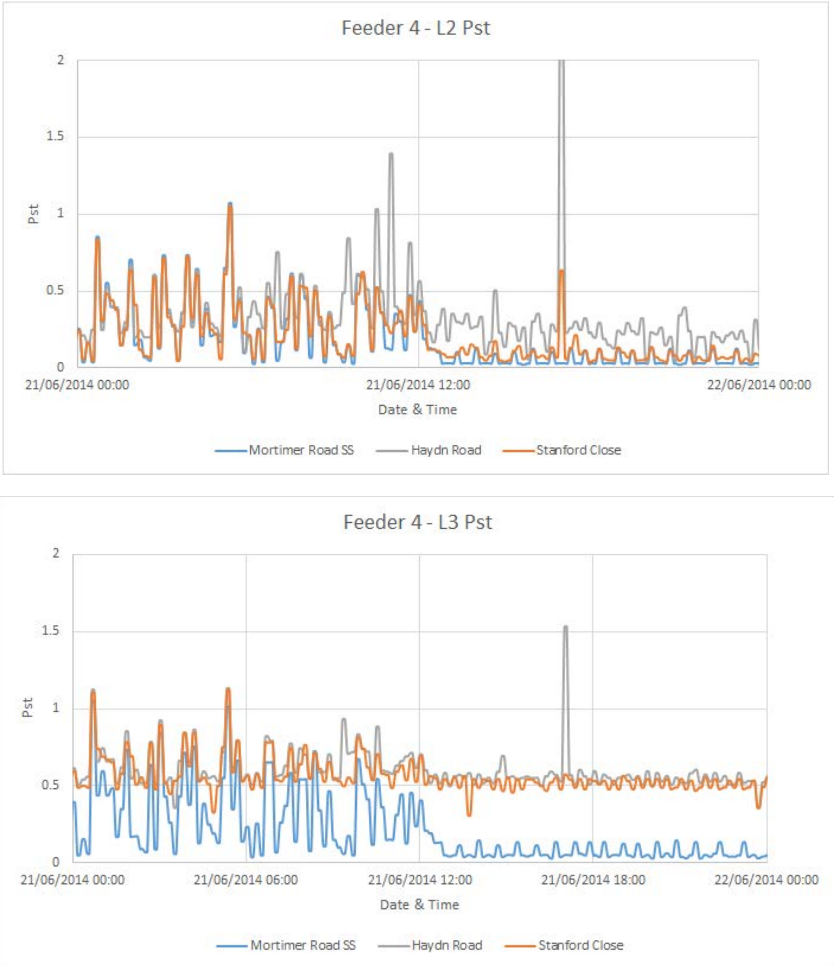

Figure 57 – Feeder 4 Pst 21 June 2014

Feeder 5

Feeder 5 does not exhibit the same reduction in flicker levels between mid-day Saturday and Monday evening seen on the other feeders

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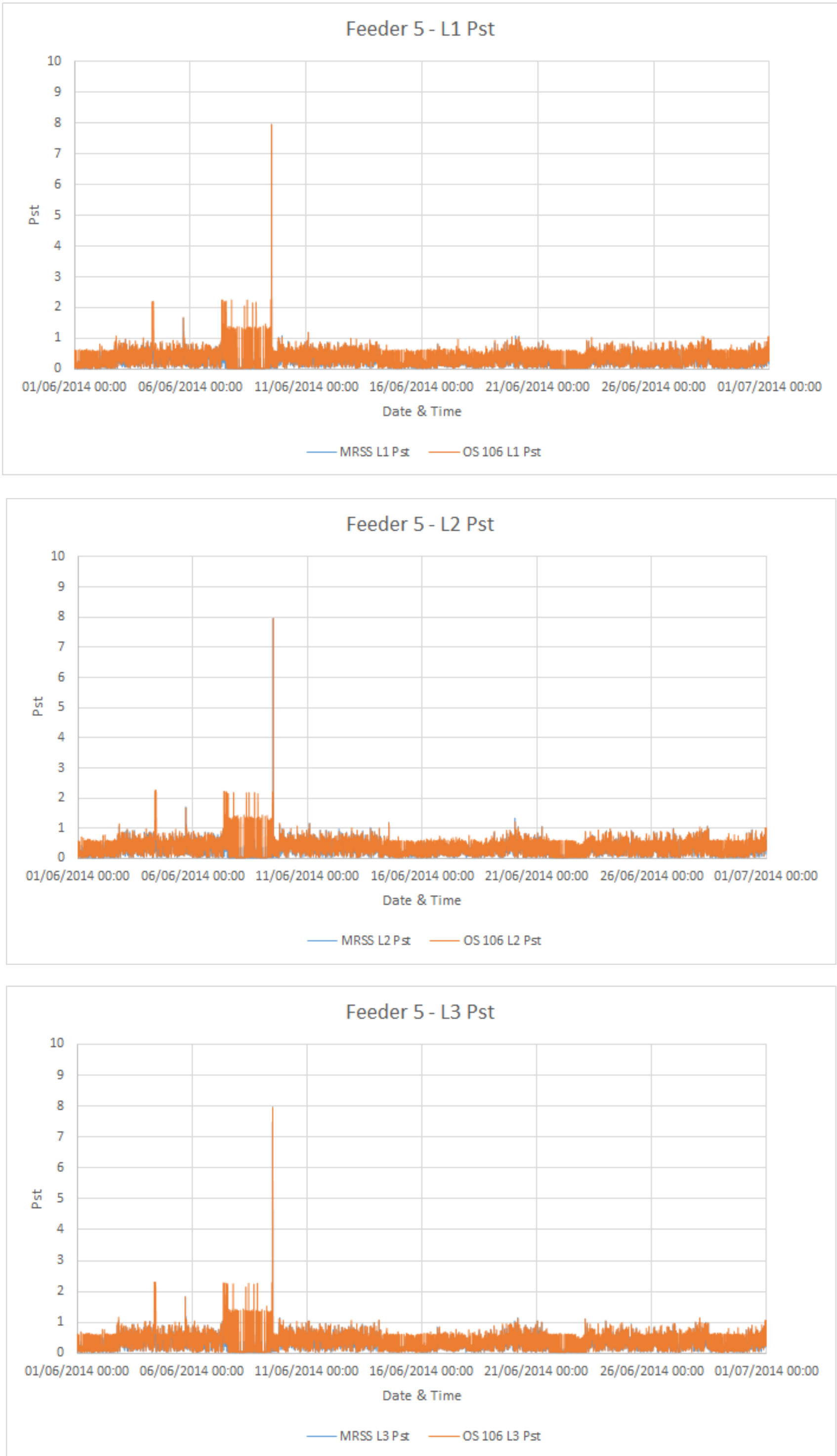

Figure 58 – Feeder 5 Pst June 2014

It can be seen that prior to mid-day on the Saturday there is a mixture of conditions with the flicker level at the remote end of the circuit exhibiting both alignment with the source levels and local peaks of flicker driving a small increase in levels at the source substation. After mid-day it can be

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seen that the disturbances on Feeder 5 which are giving rise to the peaks of flicker level at the remote end of the feeder are driving the source substation busbar flicker levels.

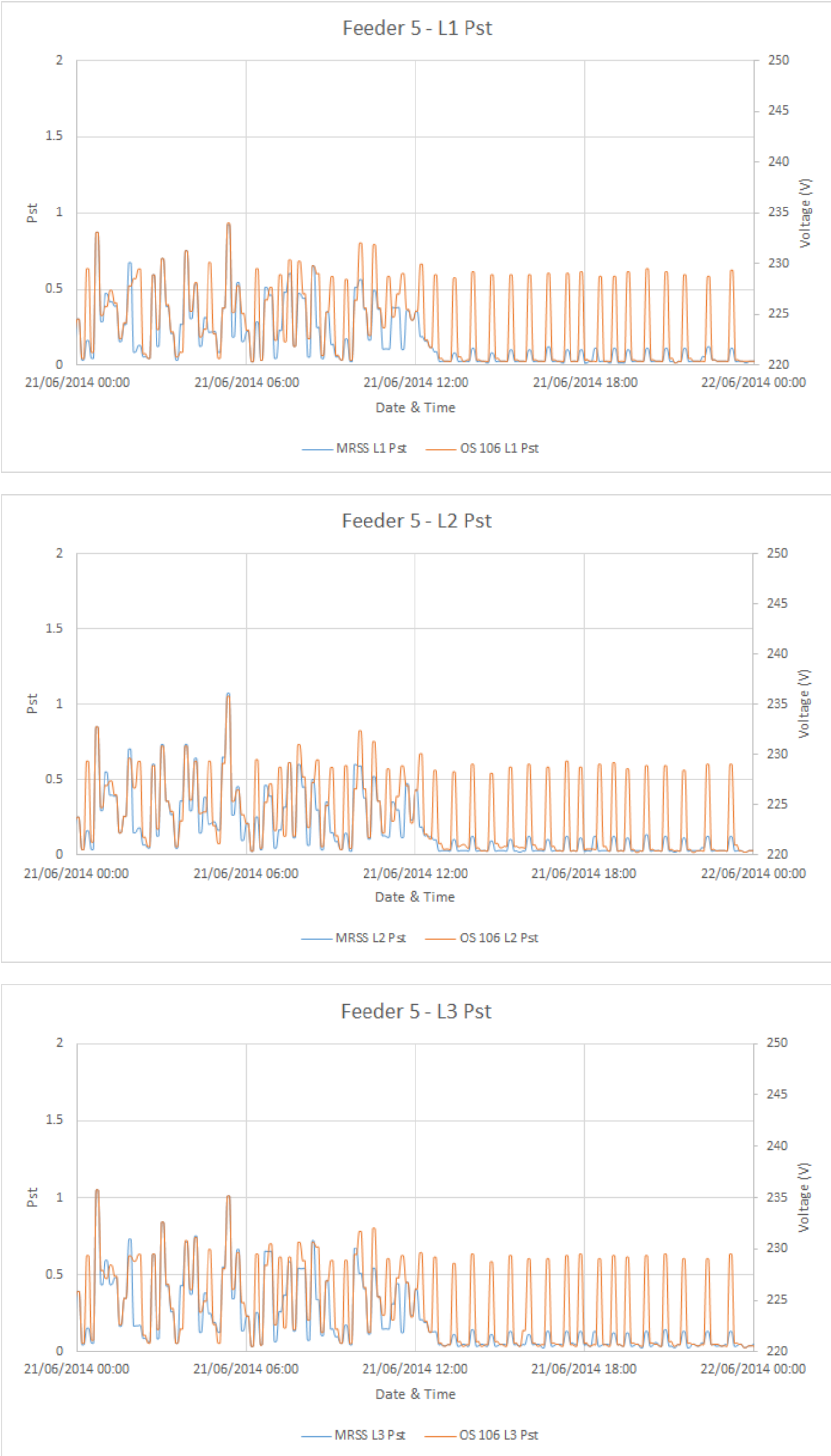

Figure 59 – Feeder 5 Pst 21 June 2014

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If we overlay the minimum, average and maximum voltage on the flicker graph we can see that a voltage depression of around 4% is occurring cyclically after mid-day giving rise to the Pst values of around 0.6. Similar depressions are seen before mid-day which is also generating additional increases in flicker although these are less obvious, although still discernible, when mixed in with the background disturbances.

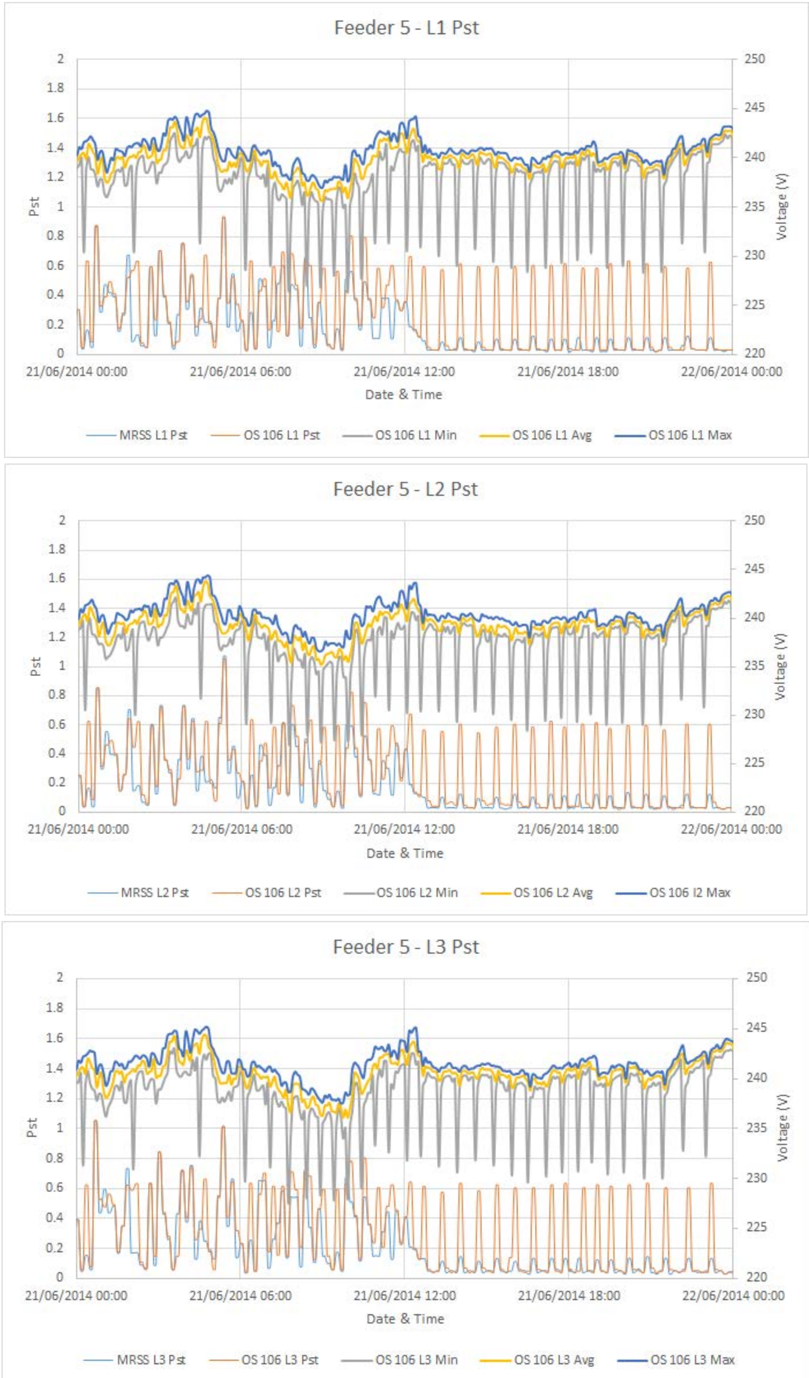

Figure 60 – Feeder 5 Pst and Voltage variation at LB 500005

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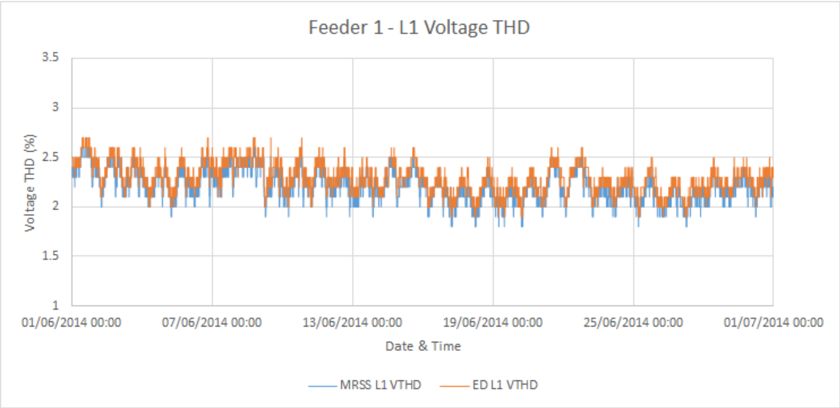
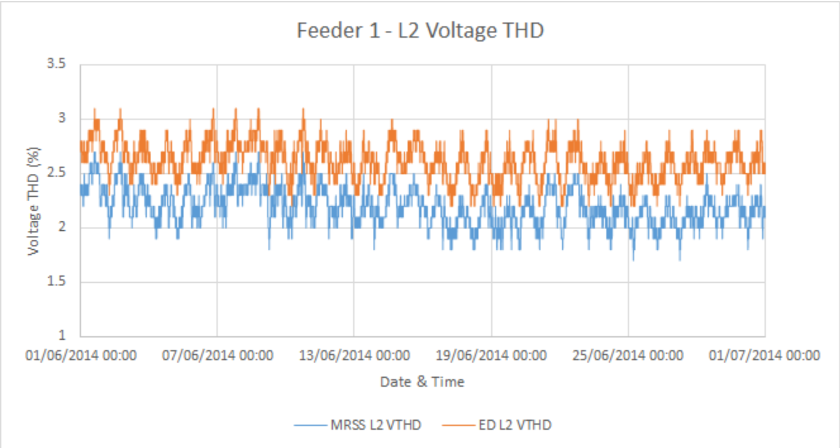
4.2.3 Harmonic Distortion

The results of measurements of Voltage Total Harmonic Distortion seen across the Mortimer Road LV network are illustrated in Figure 61 – 64. The feeders all exhibit the same characteristic that the Total harmonic Distortion increases to some degree at the remote measurement point compared to the source substation busbar measurements.

Feeder 1





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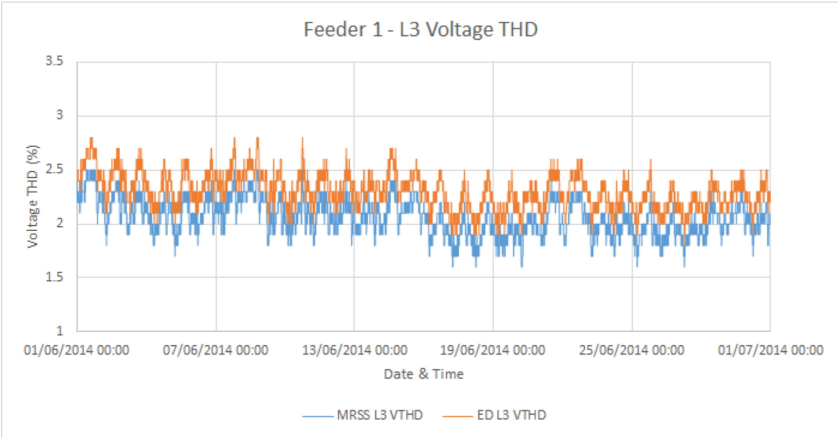
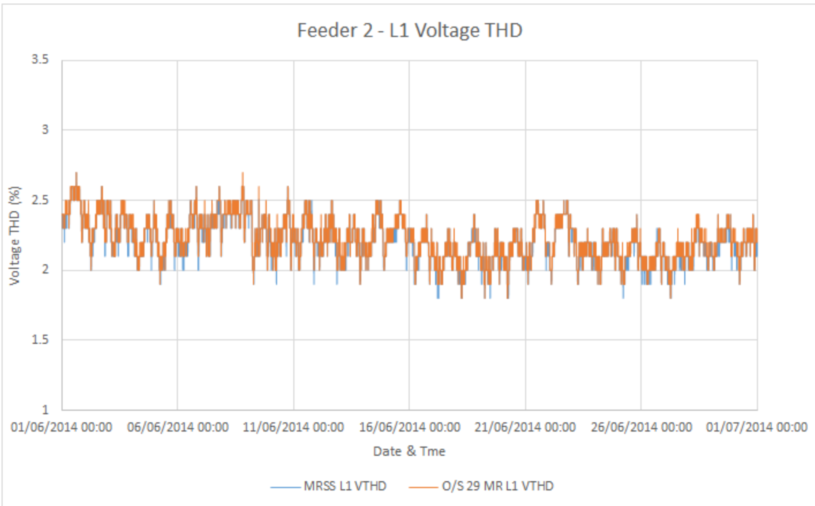
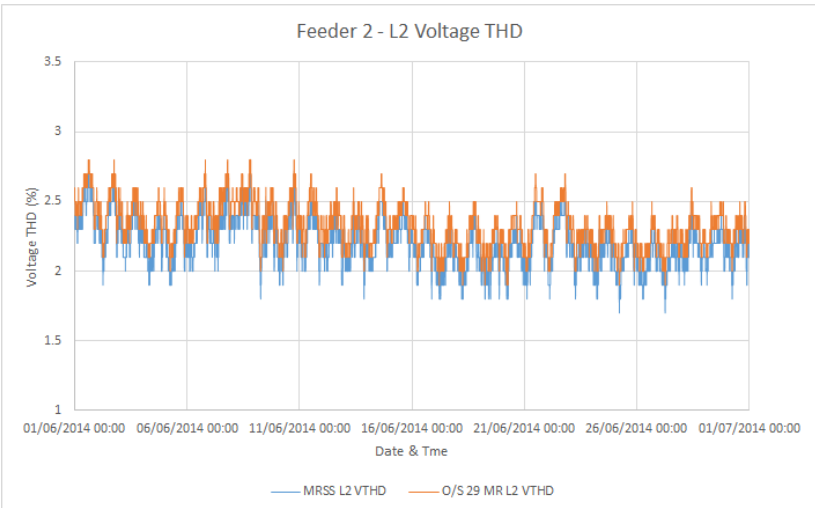


Figure 61 Voltage Total Harmonic Distortions at Mortimer Road and LB 500003

Feeder 2





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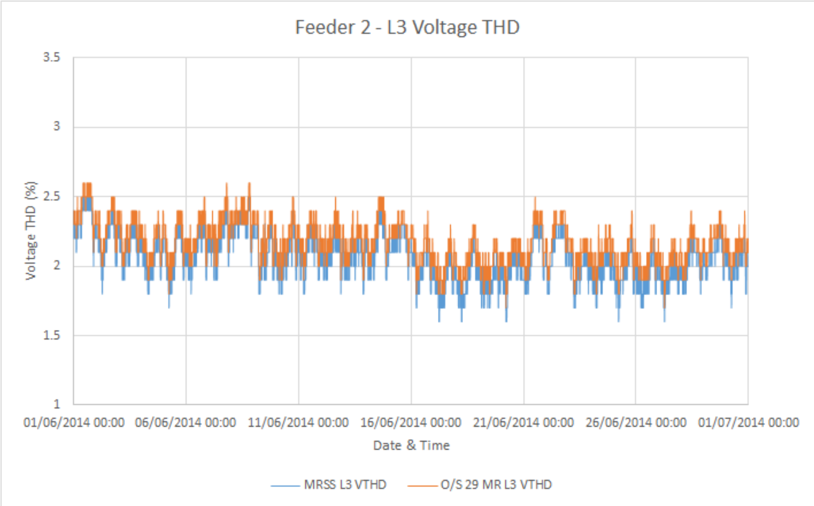
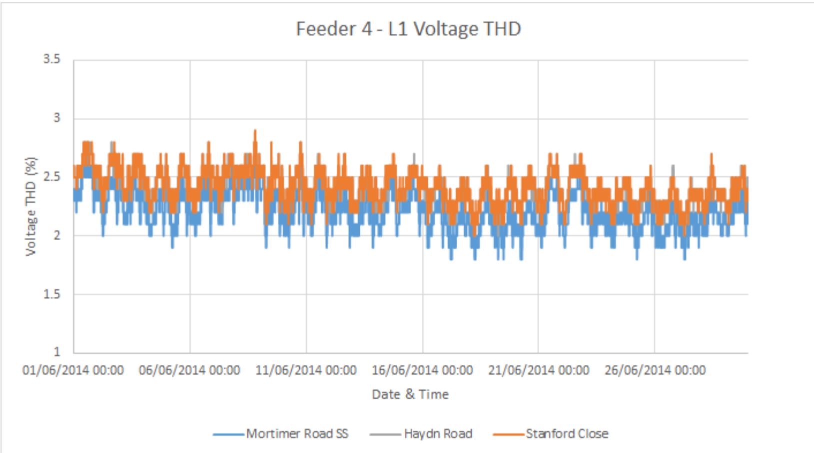
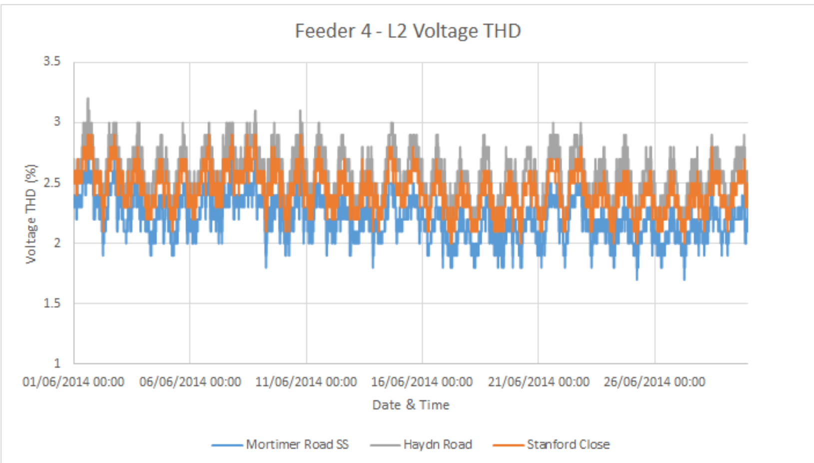


Figure 62 Voltage Total Harmonic Distortions at Mortimer Road and LB 500006

Feeder 4





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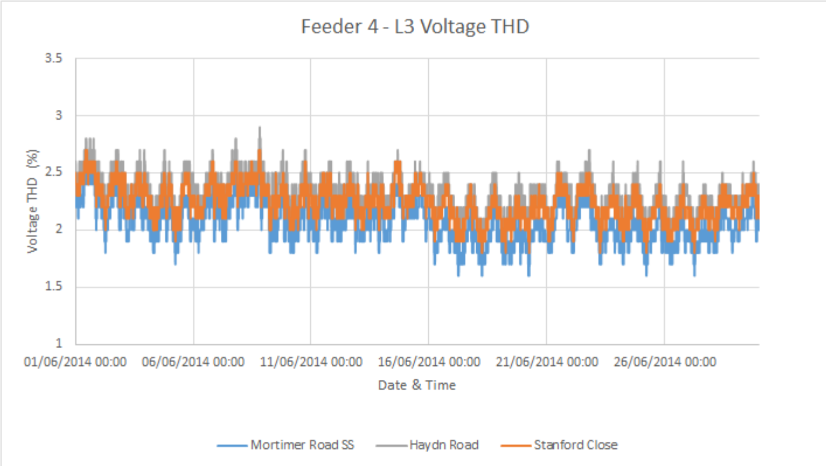
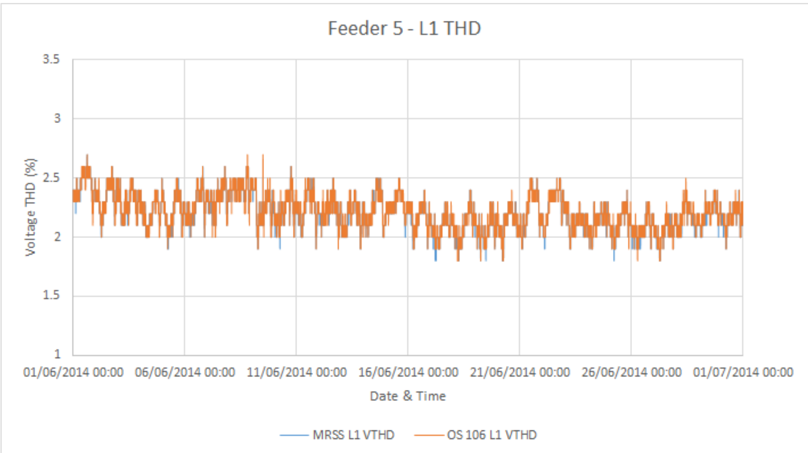


Figure 63 Voltage Total Harmonic Distortions at Mortimer Road and LB 500001 & LB 500002

Feeder 5



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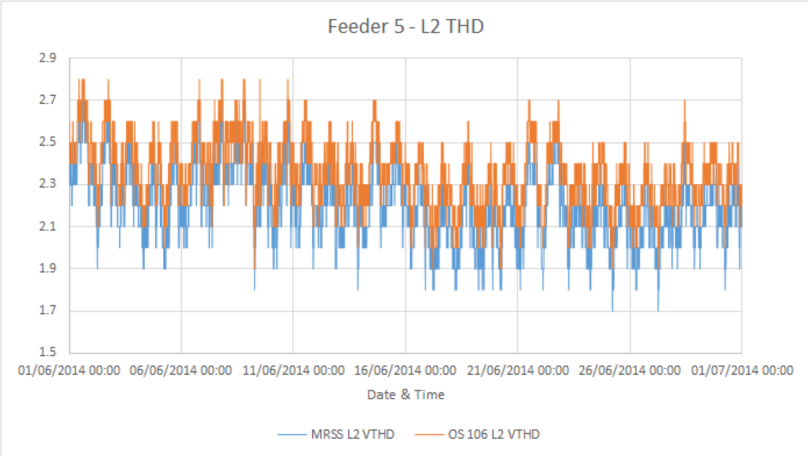

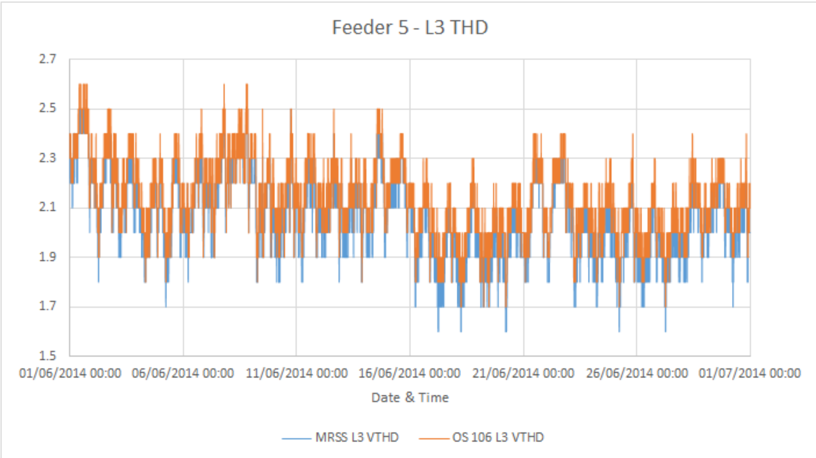

Figure 64 Voltage Total Harmonic Distortions at Mortimer Road and LB 500005

4.2.4 Conclusions

There is evidence of export from the feeders which are equipped with PV generation but whilst the voltage at the remote end of the feeder is elevated above that of the source substation it does not exceed the statutory limits and the elevation is typically less than 1%. Clearly the magnitude of any voltage rise is affected by the installed capacity of PV generation and where the tariff structure incentivises installation of the maximum capacity available on a roof particularly for private investors then the effect may in some cases be greater. However another factor which affects the voltage profile along a feeder is the power factor of the generator output and the power factor of the load. A report carried out in STP module 5, S5245-2, to look at the implications of designing networks with lower supply impedances to accommodate some of the higher capacity Low Carbon Technologies seeking connections shows that if, as is usually the case, the generator output is at unity power

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factor the remaining reactive power flow of the network load can act to counter the voltage rise which would otherwise occur.

The presence of a cluster of photovoltaic generators has not driven any particular increase in flicker levels, the dominating factors in the flicker levels seen at Mortimer Road substation are the background flicker levels driven from the 11kV network and the action of the load on Feeder 5 which also demonstrably affects the level of background flicker at Mortimer Road substation.

The harmonic distortion levels seen on the network remain within the planning levels of Engineering Recommendation G5/4-1. All of the feeders exhibit the same typical pattern that the Harmonic distortion levels increase with distance from the source busbar.

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4.3 Electric Vehicles

The results of Power Quality Monitoring applied to two electric vehicle clusters, located in Wylam, and South Shields are discussed in this section.

4.3.1 Wylam

For the Wylam cluster there are 9 vehicles in total, there are three legs to the circuit with 3, 1 and 5 cars supplied from each leg. The PQube monitor was installed at the end of the leg with 3 cars connected, 1 on red phase and 2 on blue phase. The traces for flicker & Voltage Total Harmonic Distortion are shown below. Analysis of this data is further complicated by the fact that the time and date have not been set correctly leading the monitor to default to 1 January 2000 on start-up. The graphs are therefore less readily considered against time of day.

The flicker values shown in Figure 65 exhibit a number of distinct peaks of short term flicker Pst which correspond to significant voltage depressions as evidenced by the maximum minimum and average voltage traces. The fact that the average and maximum voltage traces remain close together when the minimum voltage trace has dipped as low as 150V clearly indicates that this is a short duration voltage depression associated with a higher voltage fault the effects of which are being reflected into the LV system. Even the smaller peaks of Pst can be seen to be associated with a voltage change which is of relatively short duration there being no sustained step change in the voltage level. It can therefore be concluded that any effect on Flicker levels as a result of the installation of the cluster of Electric Vehicles in Wylam is only marginal.

The Voltage Total Harmonic distortion values seen at the monitoring point in Figure 66 are broadly in line with the values seen at other monitoring points for this project. Since we are unable to identify with any certainty from the voltage traces when the Electric Vehicle Chargers are operating it is not possible to identify what effect their operation may be having in the levels of distortion. It should be remembered that the measurements made at individual customer premises also exhibited little if any evidence of any effect which could clearly be attributed to the EV charging current. Taking account of the additional impedance of the service cable for the individual customer measurements compared to these measurements made directly from the main distribution cable there was greater potential to see an effect at an individual customer.

The Voltage Unbalance in Figure 67 fluctuates for the most part between approximately 0,2% and 0.8%, there are however several examples where the unbalance briefly peaks above this to values up to 1.4%. The spike right at the beginning is an artefact of the monitor being energised and can be ignored. The measurements for this cluster were made at one of the remote ends of the feeder where the values would be expected to be at their highest.

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Figure 65 Voltage and Short term flicker values for Wylam EV Cluster

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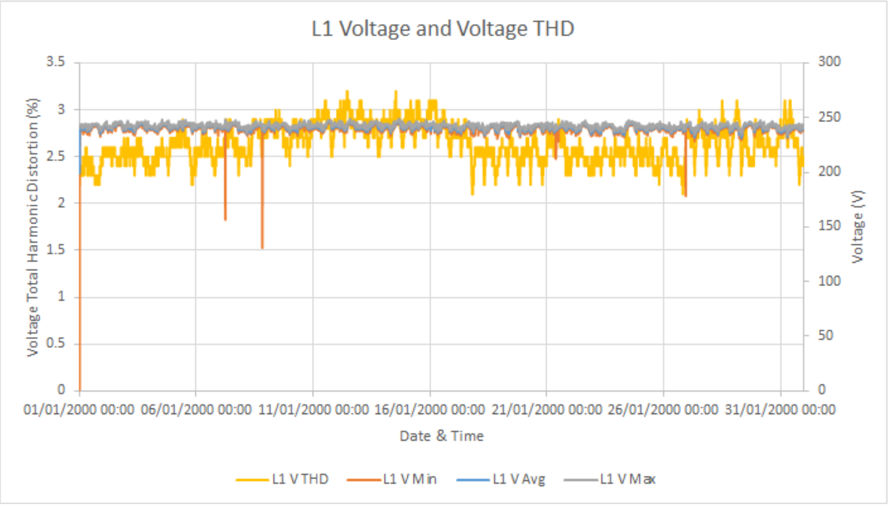

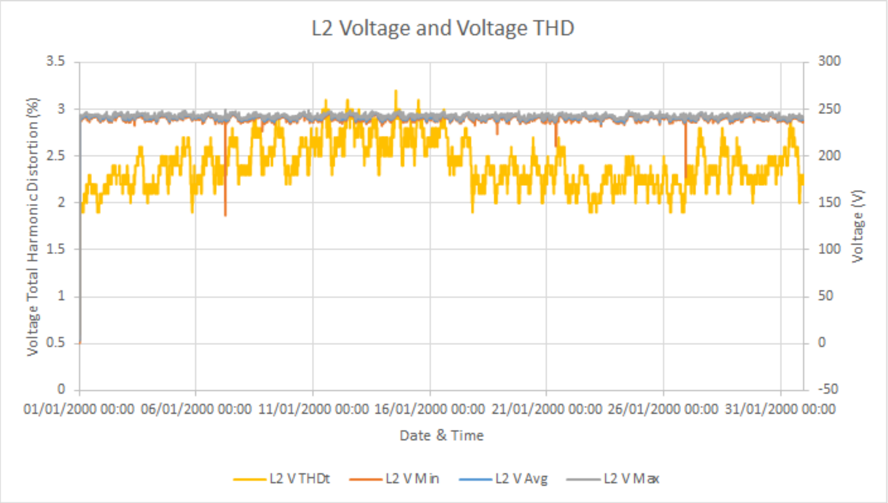

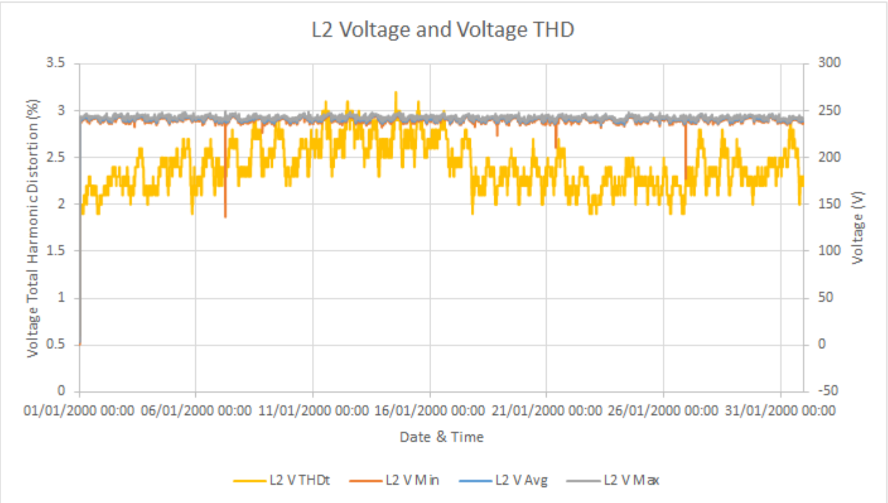

Figure 66 Voltage and Voltage Total Harmonic Distortion values for Wylam EV Cluster

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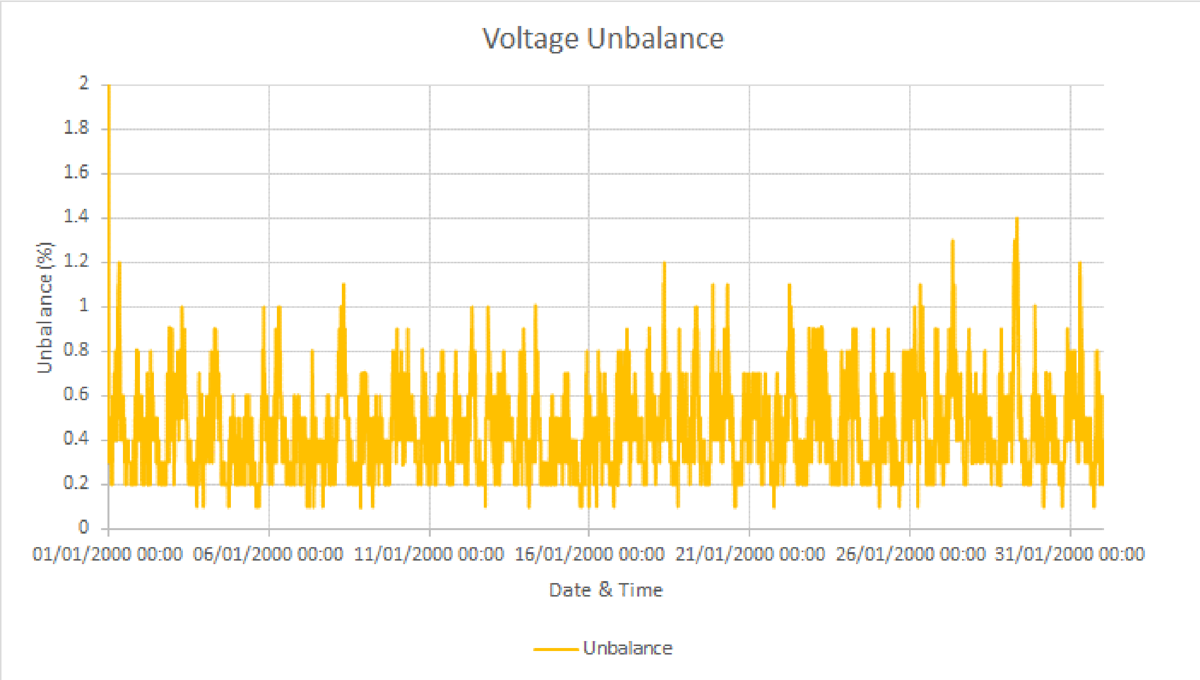

Figure 67 Voltage Unbalance for Wylam EV Cluster

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4.3.2 South Shields

The South Shields EV Cluster consists of 11 cars in total with one on red phase seven on yellow phase and three on blue phase. The monitoring is installed mid feeder with all of the cars located downstream of the monitoring point.

The Flicker and Voltage Total Harmonic Distortion levels are shown in Figures 68 and 69 below, the levels are more in line with those seen at other monitoring points, though of course with there being significant number of customers located beyond this monitoring point there is scope for both values to increase further along the feeder as the network impedance increases.

The levels of Total Harmonic Distortion and flicker are broadly the same across the three phases with if anything red phase exhibiting the highest level of voltage harmonic distortion. Since the red phase has only one Electric Vehicle connected to it, it can be seen that this effect is not as a result of the Electric Vehicle emissions.

Figure 70 illustrates the Voltage Unbalance measurements made for this cluster, the values fluctuate for the most part between zero and 0.3%, peaking occasionally at 0.4% and 0.5%. In this case the measurements have been made mid feeder where the levels would be expected to be lower than might be found at the remote end of the feeder.

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Figure 68 Voltage Variation and Flicker Values for South Shields EV Cluster

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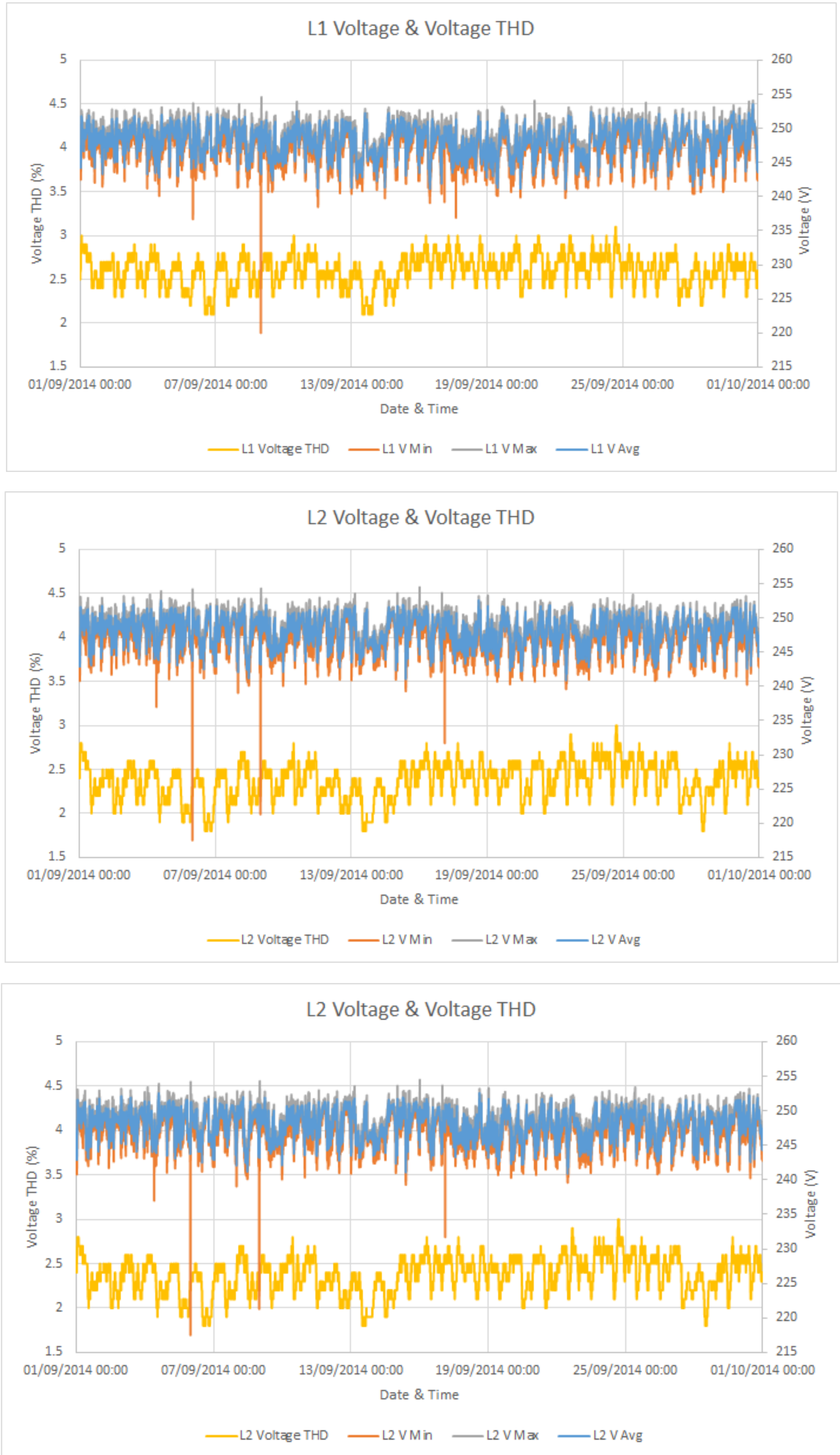

Figure 69 Voltage Variation and Voltage Total Harmonic Distortion for South Shields EV Cluster

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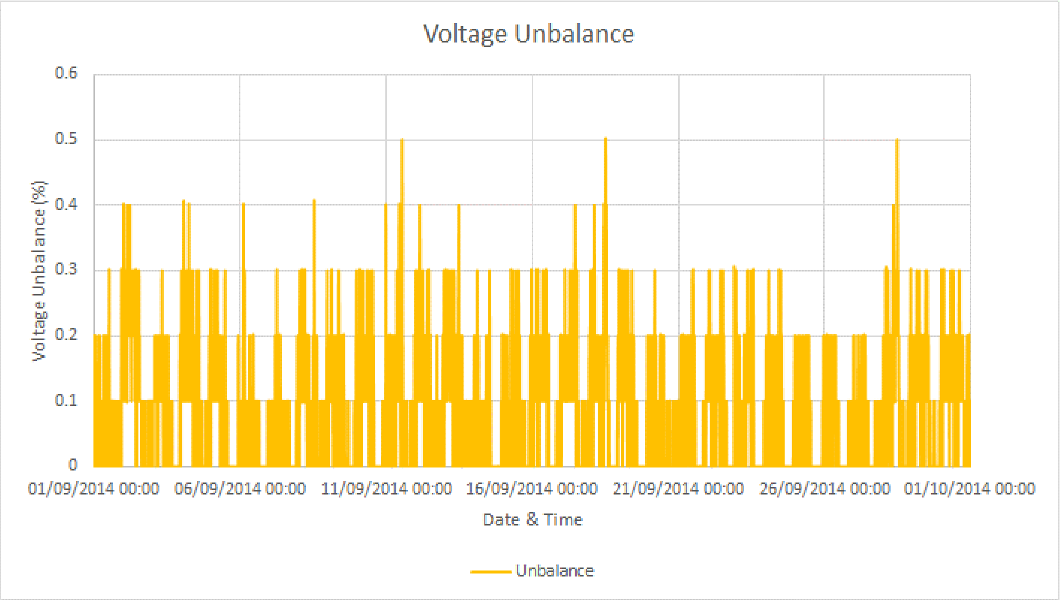

Figure 70 Voltage Unbalance for South Shields EV Cluster

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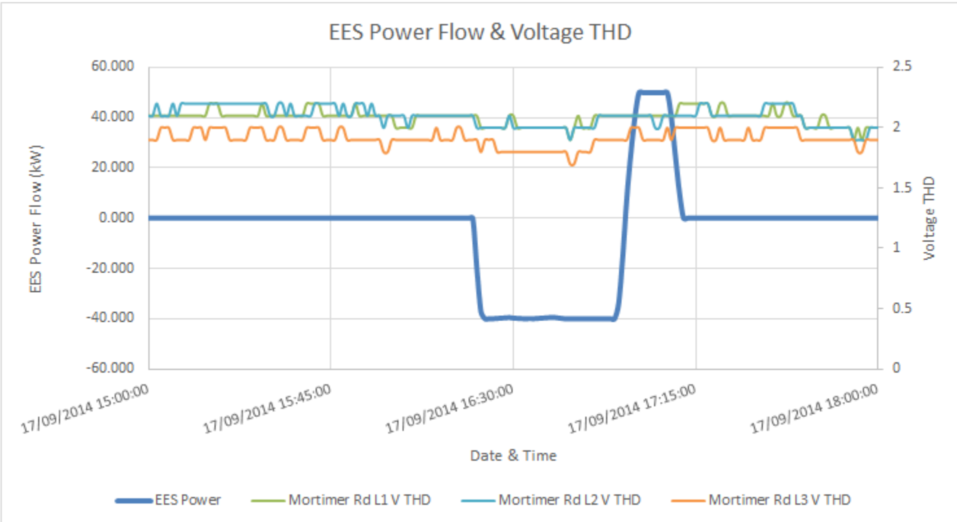
5 Monitoring Results for Electrical Energy Storage Equipment

5.1 Mortimer Road

The records of the operation of the Electrical Energy Storage (EES) system show when it has been charged and discharged. The traces of the source busbar and the feeder linkbox monitors for the periods of the operation the storage system show that the Total Harmonic Distortion hardly varies during the cycle of operation of the EES, and what variation there is does not align with the change in operating states suggesting that it is most likely driven by other elements on the network. A negative power flow is seen when the battery is discharged whilst a positive power flow indicates that the battery is charging



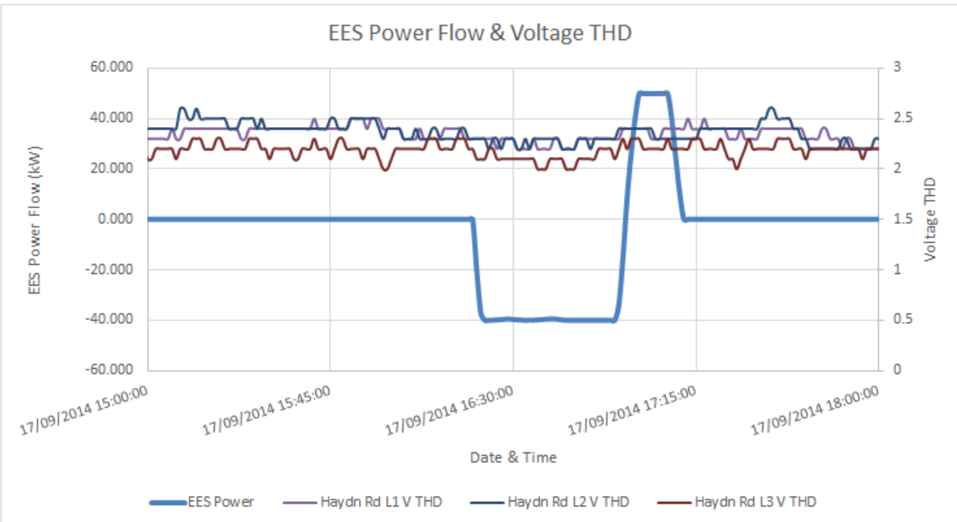


Figure 71 Network Harmonic Distortion and EES Power Flow

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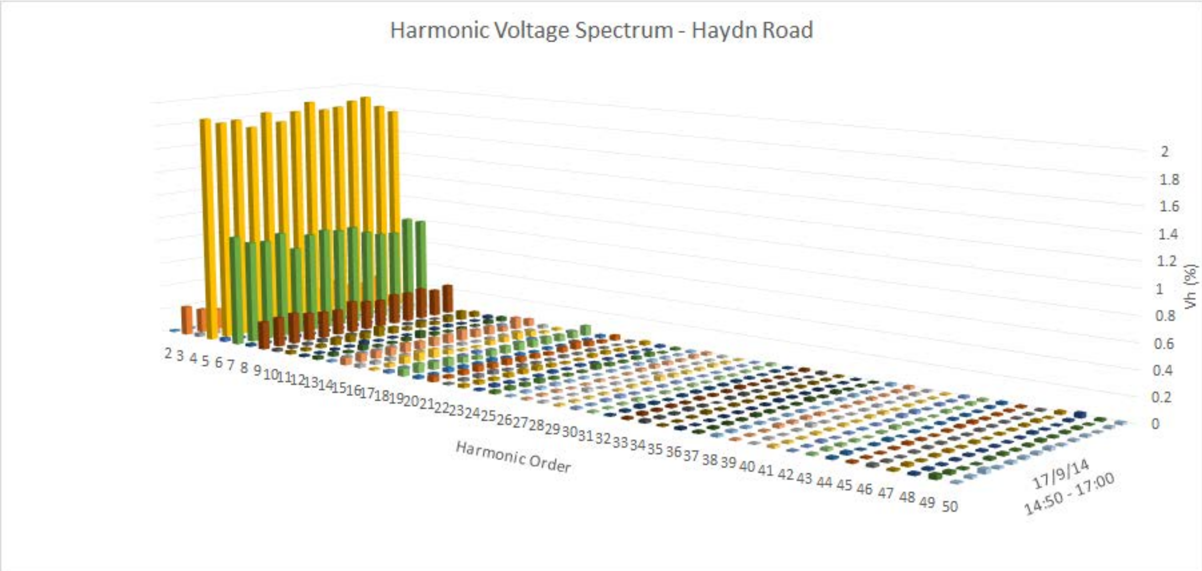

Figure 72 Voltage Harmonic Emission spectra during charge and discharge operation

The spectrum of harmonic voltage emissions illustrated in Figure 72 shows that the levels are well with in the planning limits for ER G5/4 and also shows very little change through the charge and discharge cycle.

The flicker levels, Pst, illustrated in Figure 73 below do show some fluctuation during the operation of the EES system, however levels of flicker seen are no higher or lower than those seen at times when the battery is neither charging or discharging. If there was to be an effect one might imagine that the flicker levels might reduce during discharge due to increased infeed capacity and rise during charging or at least as the battery changes from one mode to the other, however the evidence of the measurement plots shows the opposite effect suggesting that the change in flicker levels is not driven by the operation of the EES system.

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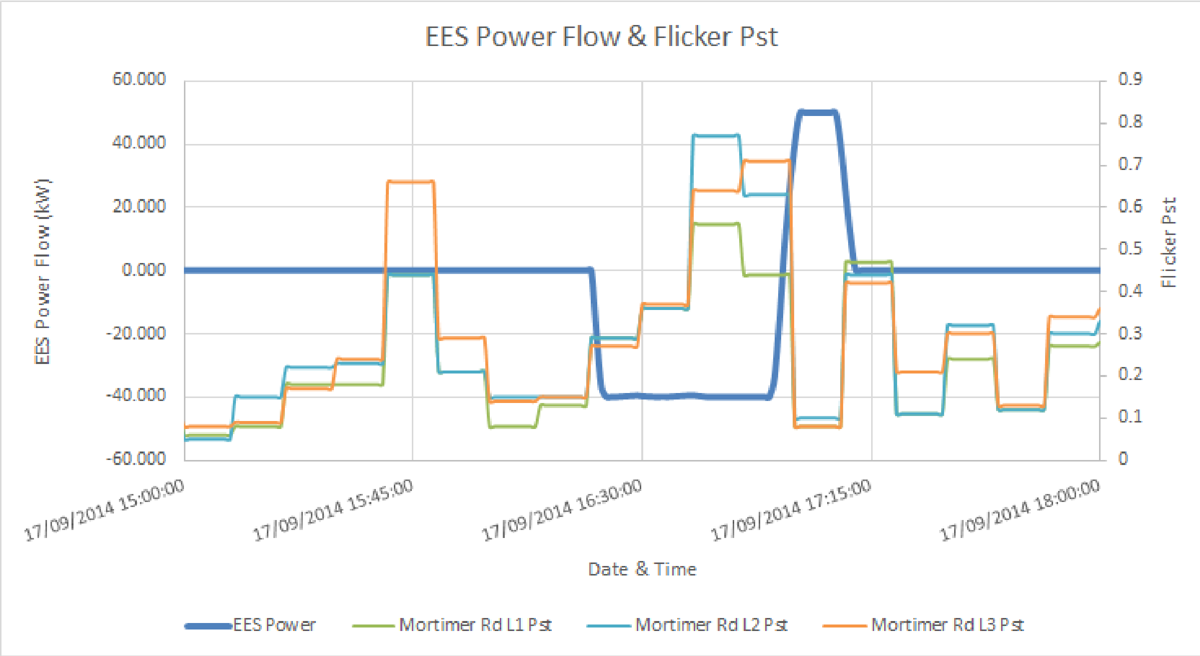

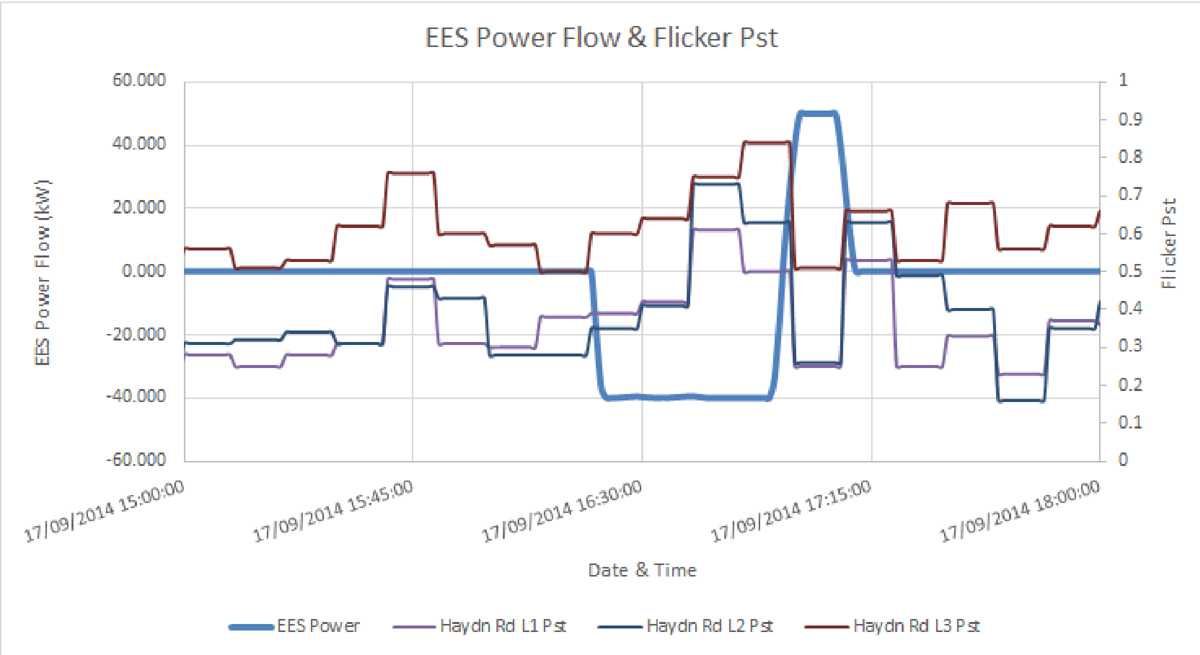

Figure 73 Short term flicker and EES charge discharge cycles

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5.2 Wooler Ramsey

The flicker levels experienced at the monitoring points associated with the Wooler Ramsey LV network are shown in Figure 74 below. The traces show the active and reactive power flows associated with the charge and discharge cycles applied to the EES system. The flicker levels recorded are generally low and the dramatic occasional spikes in the value of Pst are not associated with the operation of the EES.

Figure 75 shows the variation in the average values of Voltage Total Harmonic Distortion against the variation in the active and reactive power flows to and from the EES system. From the measurement data made available from the Historic Information System, this was the only EES system called upon to import and export reactive power. It can be seen that the levels of Total Harmonic Distortion vary independently of the direction magnitude and phase angle of the power flow to and from the EES.

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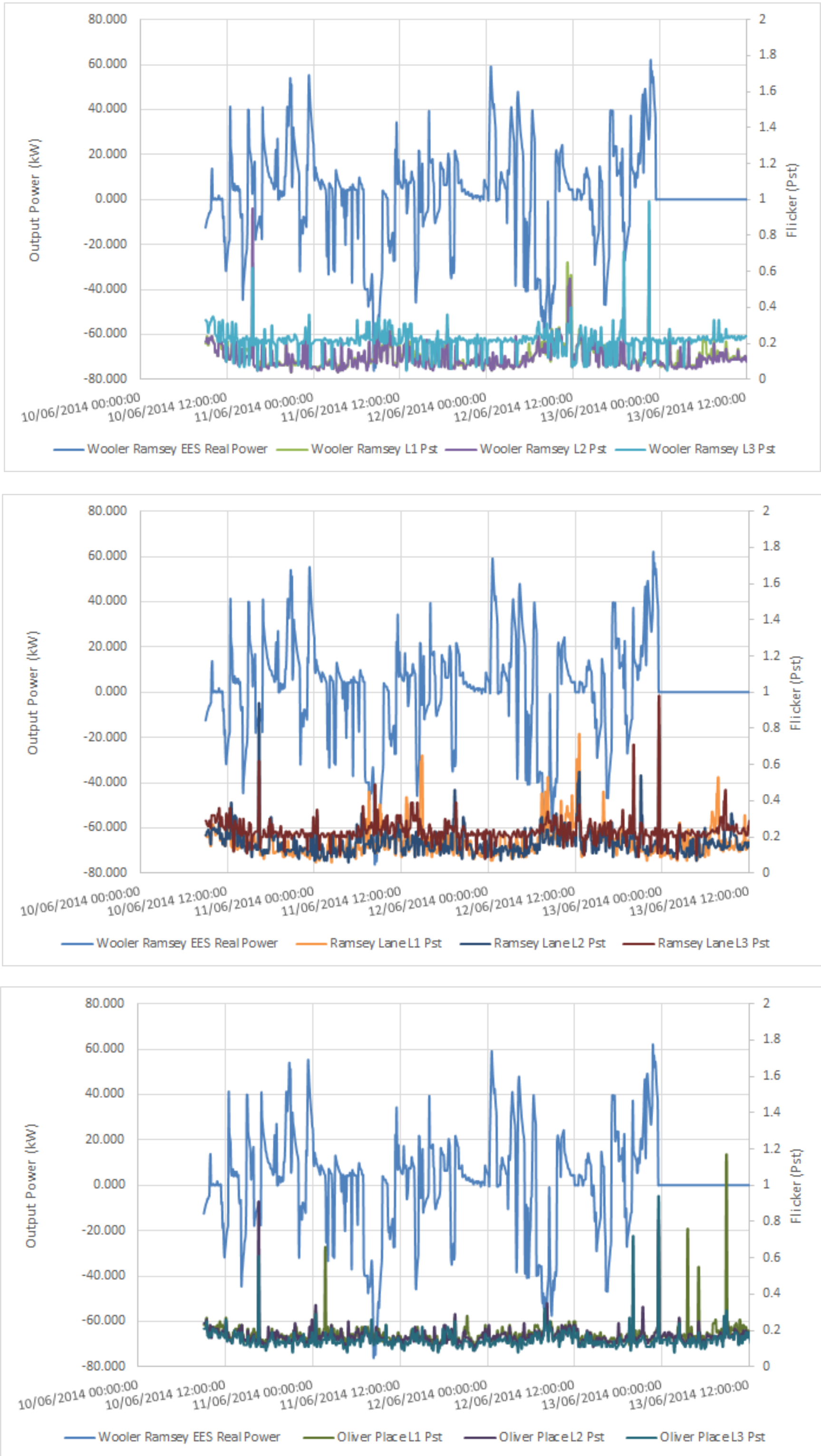

Figure 74 Flicker Levels and Active and Reactive Power flows from the Wooler Ramsey EES system

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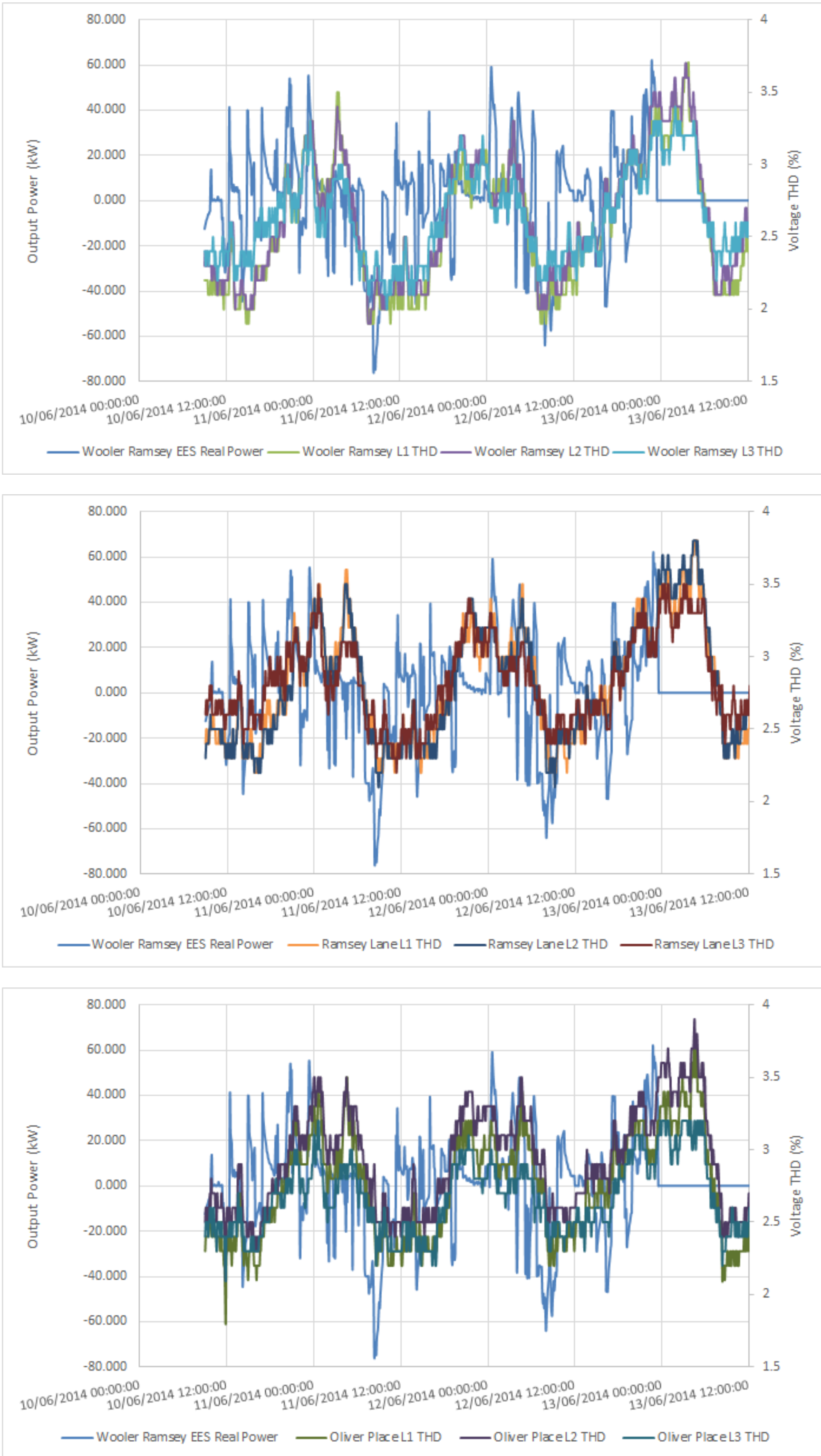

Figure 75 Voltage Total Harmonic Distortion and Active and Reactive Power Flows from EES system

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5.3 Wooler St Mary's

Figure 76 below shows the variation in Flicker levels recorded at monitoring points at Wooler Bridge and Wooler St. Mary's substations at either end of the feeder to which the EES system is connected and the variation in the power flows to and from the EES system. The general flicker levels are relatively low and vary independently of the operating mode of the EES.

Figure 77 maps the variation of the Voltage Total Harmonic Distortion against the power flows to and from the EES, it can be seen that the overall levels of distortion are relatively low and the variation which exists in these values are not dependent upon the operating mode of the EES system.

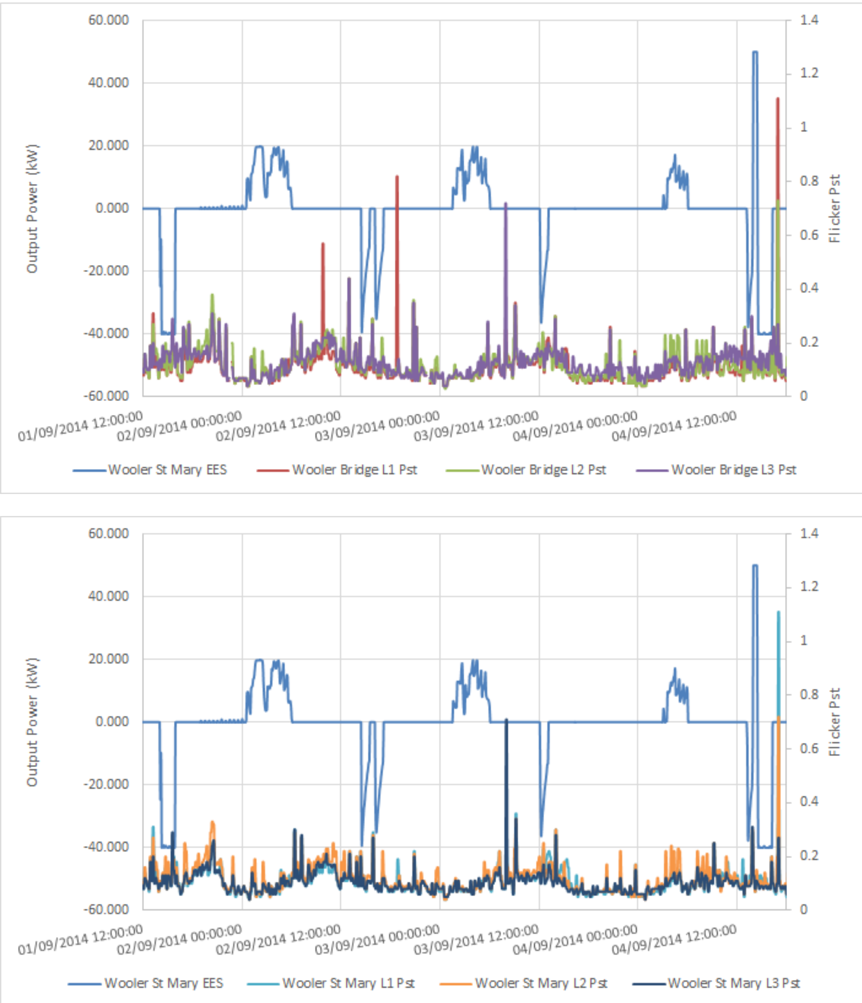

Figure 76 Flicker Levels and power flows from the EES system

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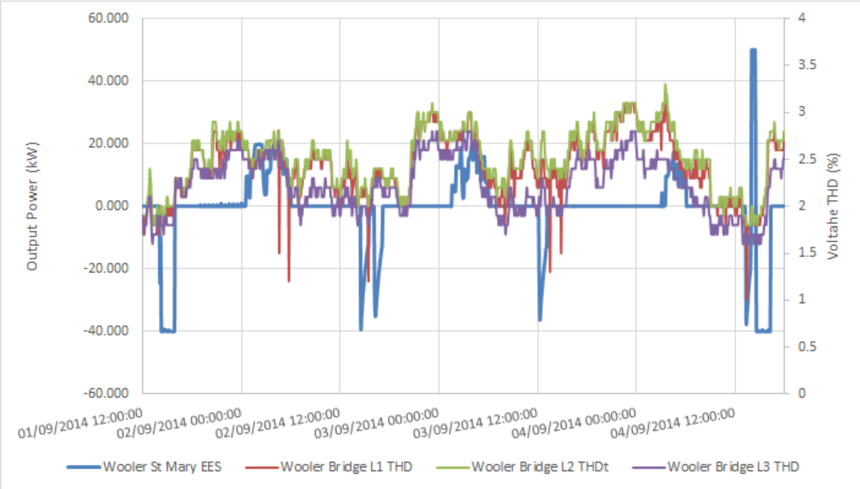

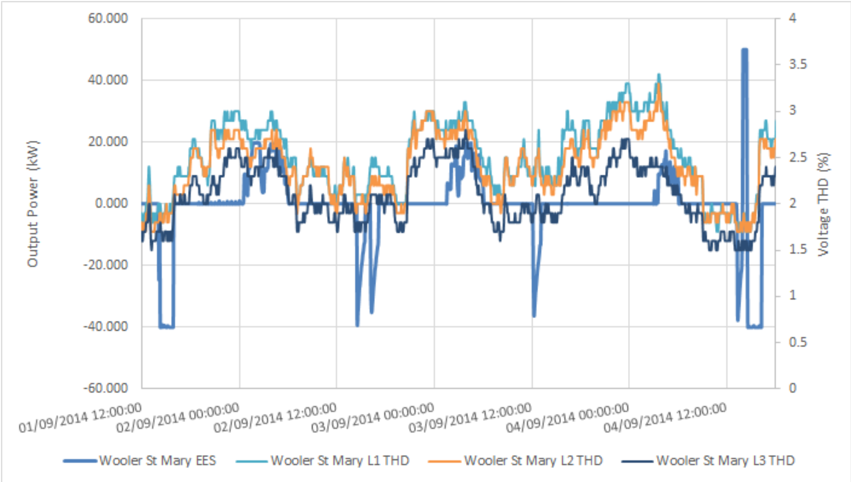

Figure 77 Variation in Voltage Total Harmonic Distortion and Power flows from the EES

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5.4 High Northgate

Figure 78 illustrates the variation in Flicker levels in comparison with variations in the power flow to and from the EES system. It can be seen that the flicker levels are unaffected by the mode of operation of the EES whether it be charging discharging or neither.

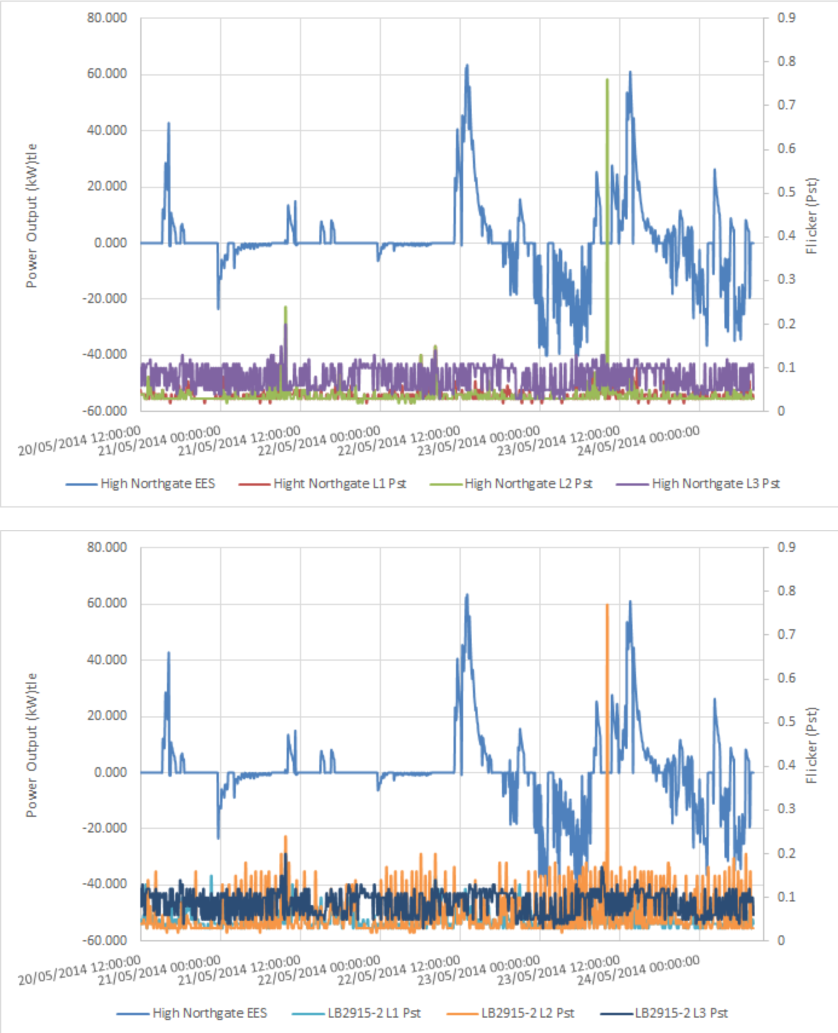

Figure 78 Flicker Levels and power flows from the EES system

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Similarly Figure 79 plots the variation seen in the level of Voltage Total Harmonic Distortion against the operation of the EES. Once again the levels of voltage distortion appear to vary independently of the mode of the EES system.

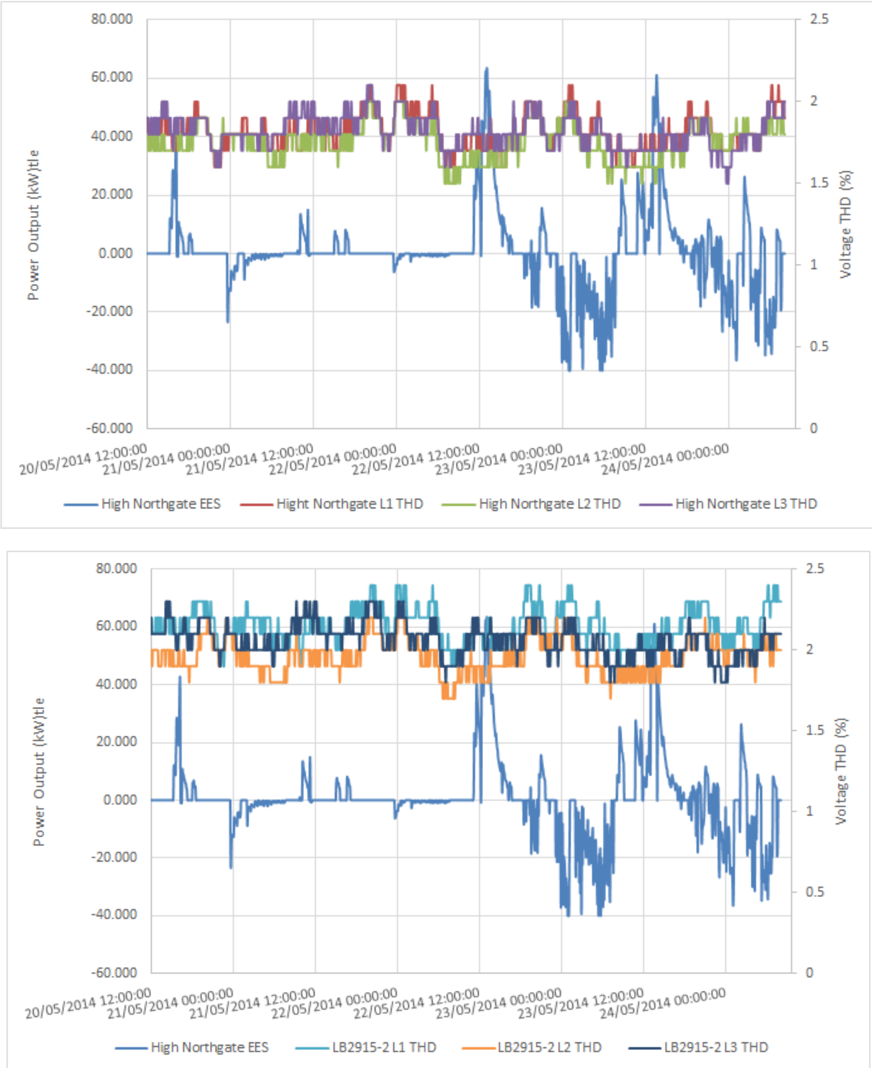

Figure 79 Variation in Voltage Total Harmonic Distortion and Power flows from the EES

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5.5 Harrowgate Hill

Figures 80 & 81 plot the variation in Flicker and Voltage Total Harmonic Distortion against the variation in power flow from the EES system, once again the variations experienced do not appear to have any relationship to the mode of operation of the EES system.

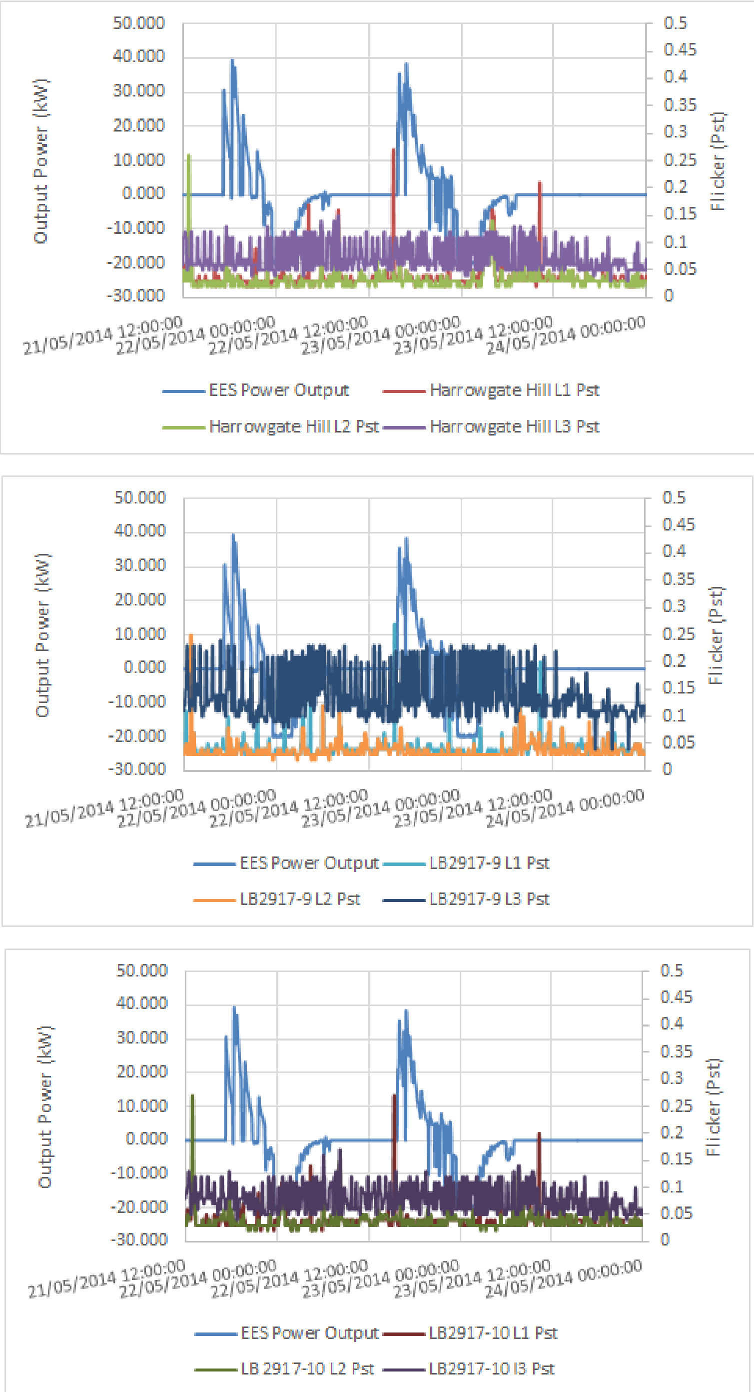

Figure 80 Flicker Levels and power flows from the EES system

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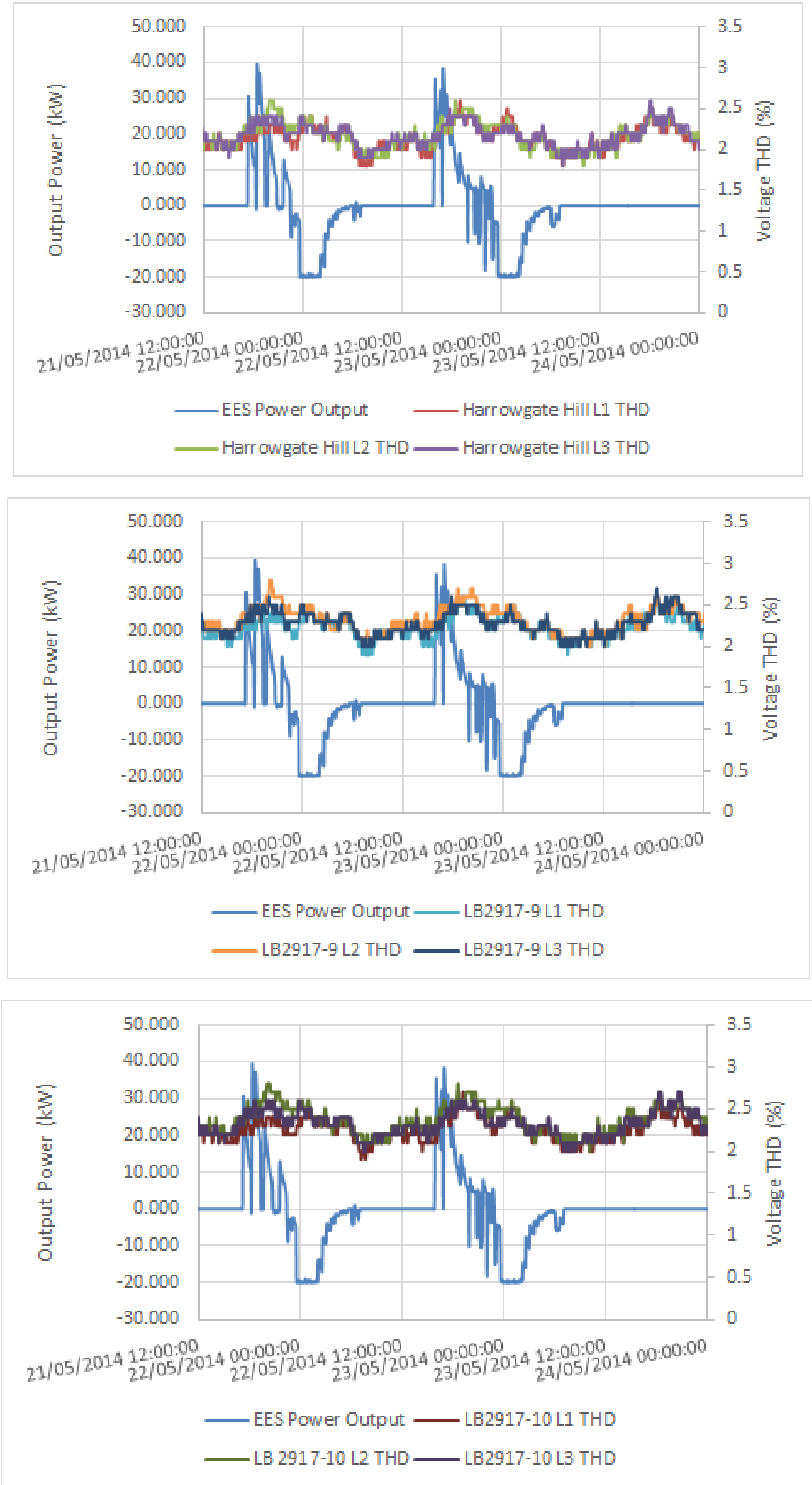

Figure 81 Variation in Voltage Total Harmonic Distortion and Power flows from the EES

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6 Implications for network design

The previous sections have reported on the results of a range of monitoring activities undertaken at individual domestic customers' premises and at locations on the LV network to establish what effects can be seen from the application of Low carbon Technologies with customers' installations and from interventions installed on the network with a view to counteracting any negative effects of LCTs. The results obtained from the monitoring activities suggest that in many cases the effect of individual LCTs at a customer's premises are small and indeed when the numbers are increased and clusters of the same LCT are deployed on to a network the effects are difficult if not impossible to discern from the cumulative effects of all the other loads already applied to the networks.

A notable exception to this observation in terms of the effects of an individual LCT has been seen with some specific heat pump installations. A relatively large capacity motor when compared to the service capacity without any form of soft start facility will almost inevitably cause significant voltage disturbances which may be enough to cause unacceptable levels of flicker particularly in situations where the set-up of the heat pump controls results in a cyclic operation with repeated starting of the motor. Where heat pumps have soft start facilities these issues can be substantially reduced if not entirely eliminated.

The terms of the CLNR project required that any clusters of Low Carbon Technologies should not be funded by the CLNR project. This limitation meant that there was little control over the choice of network and the resulting conditions to which the cluster was exposed. In the case of the heat pump clusters both of the clusters were installed fed from ground mounted substations via relatively short lengths of cable with a relatively large cross-sectional area. As a result the conditions measured may not be as onerous as could have been the case. In addition the heat pumps installed on the clusters were perhaps smaller than many. The clusters were made up of Heat King 6kW output heat pumps which have a claimed Coefficient of Performance of up to 5. Even allowing for the CoP to be 3 that is only a 2kW electrical load per customer. The winter during which the monitoring was undertaken was relatively mild so the heat pumps will not have had to work as hard to produce the heat output.

The experience of the heat pump which gave rise to a voltage complaint highlights the need to ensure that characteristics of the heat pump and the characteristics of the network to which it will be connected are compatible with one another. Unless the product standards or the EMC standards are written in such a way as to require effective soft start capabilities on larger capacity heat pumps there will be a need to consider the design of future networks to accommodate such devices and in particular the whether there may be a need to reduce the maximum acceptable supply impedance for new LV networks. For existing networks which might be subject to connection requests for larger less network friendly devices it is not easy to lower the maximum supply impedance without considerable disruption. Rather than having to change the design parameters of the network to facilitate the generation of the types of disturbances and distortion permitted whilst maintaining acceptable power Quality perhaps it would be better for the customers and the economy generally to consider whether the standards governing the design and operation of the equipment seeking a

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connection could be modified to make the impact acceptable at the current typical network characteristics. It was certainly the case that a wide range of characteristics could be applied in the case of the installation which generated the voltage complaint, ranging from 130A for uncontrolled starting reducing to 43A with the replacement heat pump of the same heat capacity having a soft start current of only 23A. To achieve a change such as this would require effective engagement in the standards making process both in terms of Electromagnetic Compatibility and even Product Standards on behalf of the UK Electricity Industry and it will not happen overnight.

6.1 Low Carbon Technology Clusters

6.1.1 New Build

For new build situations where a housing development is being built with Low Carbon Technologies such as Heat Pumps and PV generation from the outset then the network can readily be designed to take account of the effects of changes to the value of ADMD and customer demand profile informed by the CLNR project.

6.1.2 Existing Networks

For existing networks and in particular those constructed during periods when tapering of the cross-sectional area of cable cores in radial LV networks was prevalent, the increased overall demand and reduced diversity which may be expected for high penetrations may be a cause for some concern. The Heat pump clusters examined in this report have not demonstrated any significant issues with either disturbances or steady state voltage conditions, but it should be remembered that these clusters were located on relatively short main feeders with either 185sqmm or 300sqmm cables.

For smaller capacity heat pumps such as those which were present at the individual monitored customers' premises then it may be the case that these are connected without reference to the DNO as allowed for under the EMC directive where the requirements of a harmonised emissions standard have been met. These will still have a significant effect on the level of demand placed on the network by the customers. High penetrations of such devices on existing networks may be expected to have a negative effect on the maximum voltage drop along a LV feeder. Government incentives such as the Renewable Heat Incentive are designed to encourage the adoption of heat pumps

Higher capacity devices clearly have the potential to create larger issues for the same high levels of penetration but at least these devices should generally only be connected following dialogue with the host DNO.

6.2 Network Interventions

The network interventions employed in the CLNR project have not been targeted at improving Power Quality on the network but rather alleviating any voltage or network loading issues.

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The interventions seen on and whose effect has been monitored and commented on earlier in the report included Electrical Energy Storage, and a Voltage Regulator.

The EES systems were observed to have a small beneficial reduction in harmonic levels when they were connected to the network and did not exhibit any noticeable change in voltage total harmonic distortion levels when charging and discharging.

The voltage regulator did give rise to a significant voltage depression when it was switched out of circuit which gave rise to isolated peaks in Pst flicker levels although the peak levels were below planning limits.

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7 Conclusions and learning

This report describes the results of power quality measurements made to assess the impact of new 'Low Carbon Technologies' (LCTs) such as Heat Pumps, Photovoltaic Generation, microCHP and Electric Vehicles as well as the effects of network interventions such as Electric Energy Storage and Voltage Regulators on the distribution networks to which they have been applied.

Two heat pump clusters were monitored with slightly different results although the heat pumps employed on each were the same. Neither of the clusters resulted in excessive values of flicker being generated as a result of the operation of the heat pumps. Measurement of individual heat pump customers yielded variable results which appear to be dependent upon both the characteristics of the heat pump itself and the network to which it is connected.

The individual British Gas Customer measurements showed no adverse Power Quality effects with the heat pumps exhibiting very gentle starting characteristics. However monitoring of a single heat pump installation following a voltage complaint showed very different results in terms of the operating characteristics of the heat pump and the impact upon the network. The issues experienced in this case were a combination of the high starting current exhibited by the heat pump motor and the fact that the connection point was in a rural location where a higher supply impedance would be expected compared to more urban locations. The heat pump in question had a normal operating current of 16.07A, without any form of soft start applied the motor is stated by the manufacturer to have a starting current of up to 130A, even with the soft start facilities offered by the manufacturer a starting current of up to 43A was specified.

In the forthcoming review of ENA Engineering Recommendation P28 clear guidance on the requirements for connection of heat pumps must be developed. It is clear from the measurements which have been made and reviewed in this project that there is significant variation between the operating characteristics of different heat pump designs which will make some designs unsuitable for locations with a lower fault level and it is the assessment of this that this guidance must address. Any such guidance must take account of the requirements of the applicable EU directives.

The harmonised standards (IEC 61000-3-3 ed 3.0 2013 Electromagnetic Compatibility (EMC) Part 3-3: Limits – Limitation of voltage changes voltage fluctuations and flicker in public low voltage supply systems, for equipment with rated current ≤16A per phase and not subject to conditional connection & IEC 61000-3-11 ed 1.0 2000: Electromagnetic Compatibility (EMC) – Part 3-11 Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems – Equipment with rated current ≤75A and subject to conditional connection) which govern the permissible voltage disturbances from equipment under the terms of the Electromagnetic Compatibility (EMC) Directive do not at present contain detailed requirements for the testing of heat pumps in particular those which employ auxiliary electric heating elements where they may have a separate electrical supply but are switched on from a single controller. It is stated in the EMC Directive that such arrangements should be tested as a single unit. However, some manufacturers are claiming that since the auxiliary heater need not be one of their units they should be tested and assessed

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separately for compliance with the requirements of the standards drawing an analogy with a computer and a printer. This approach effectively gives the whole system two bites at the emissions cherry and may lead to systems being wrongly declared compliant with the requirements of EN 61000-3-3 allowing unconditional connection. It is essential, if we are to avoid situations where equipment is declared suitable for unconditional connection due to a test regime which is apparently at odds with the EMC Directive guidance and subsequently causes problems in real life operation, that this loophole must be closed with defined testing requirements at the very least requiring the testing of such units as one whole system in line with the requirements of the EMC directive. To achieve this it is necessary for the UK Electricity Industry to effectively engage with appropriate standards committees and to seek a coordinated approach from Eurelectric.

Photovoltaic generators should present less direct concern in this regard as the threshold where the requirements of the governing EMC standards change coincides with the capacity limit for the inform and fit process described in Engineering Recommendation G83 and enshrined in the Electricity Safety Quality and Continuity Regulations. As such any larger capacity installations which hope to benefit from Feed in Tariff payments should have gone through the process of applying for a connection under G59/3 even if it is proposed to use type tested equipment which does not require witness testing as part of the connection process.

Electric Vehicles may present an interesting challenge in regard to preparing guidance on the provision of connections to control harmonic emissions and voltage disturbances on the network. In the clusters and in the case of each of the individual customers monitored the charger was limited to 16A capacity and as such the car and charger should be tested against EN 61000-3-2 and EN 61000-3-3 using the reference supply impedance, which according to IEC TR 60725 >95% of UK customers have a supply impedance at or below this value, to determine compliance. However in the case of a higher capacity charger the standards require either testing with the reference supply impedance demonstrating that the disturbance and harmonic emissions remain below limits or determination of the maximum supply impedance at which the acceptable limits are achieved. However, the charging point is largely a passive element in this arrangement with the power electronics controlling the charge of the batteries being located in the car. There arises therefore a question of how, if indeed it proves to be necessary at all, a DNO will be able to manage the connection of such a car to their network. The charging point having been installed, if and when the customer subsequently changes their car for another model the characteristics of the car may be different rather than the charging point which is essentially passive. It should be noted that as this project has not measured any charging conditions in excess of the 16A capacity there is no evidence that higher capacity chargers will necessarily present any particular power quality challenges and that the issue may be more a question of managing the current capacity of the network as the energy capacity of batteries increases as it must inevitably do if the range capacity of EVs is to be substantially increased, but nevertheless the existing approach to managing connection of distorting and/or disturbing loads and ensuring that the proposed connection point has a suitably low supply impedance doesn’t work well if that load is by its very nature movable.

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The initial connection of the Electrical Energy storage devices was noticed during commissioning to have a small beneficial effect in terms of the harmonic emissions at the point of connection as the internal filters associated with the units acted to mitigate existing background levels by a small but measurable amount.

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