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Transforming the electricity network

Primary Networks Power Quality Analysis

NIA Project Close Down Report

March 2018 – June 2021

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Western Power Distribution 2021

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1. Executive Summary

The Primary Networks Power Quality Analysis (PNPQA) project was funded through Ofgem's Network Innovation Allowance (NIA). PNPQA was registered in March 2018 and was completed in June 2021 within the original budget of £1,358,400.

The PNPQA project aimed to reduce uncertainties around the power quality (PQ) within Primary Networks (typically 33 kV) and facilitate increased integration levels of low carbon technologies (LCTs). LCTs are often interfaced using power electronics, which may have positive or negative impacts on PQ. Understanding present and future PQ issues associated with LCTs requires widespread PQ monitoring; however, existing business practice is to temporarily install a PQ monitor at a single location within a network for a short period (typically a week) to gain background measurements, with manual data retrieval and analysis. Scaling up this approach for continuous monitoring at multiple sites would be prohibitively time- and resource-intensive. Furthermore, there is some uncertainty as to whether the voltage transformers (VTs) used to capture PQ measurements are accurately passing through voltage waveforms.

The project's aims were achieved by developing, deploying, and utilising a monitoring and analysis system for assessing PQ within Primary Networks and through laboratory testing of VTs to better understand their harmonic performance and applicability for capturing accurate PQ measurements.

The developed PQ monitoring and analysis system was trialled for over a year in two areas of Primary Network that were selected based on their contrasting LCT penetrations. The data gathered was analysed and also fed in to future-looking power system studies to reveal insights into the PQ characteristics of Primary Networks generally and the PQ impacts of LCTs both now and in the future. The analysis revealed that PQ could vary substantially across a network area, particularly in the presence of LCTs. For example, there were instances of LCTs eroding up to 50% of the planning level margin, and the studies revealed that these margins could be eroded completely by 2030. However, the studies highlighted significant uncertainty with respect to the aggregation of LV-connected LCTs and their impact on higher voltage levels. Furthermore, the data analysis indicated an often non-linear relationship between LCT behaviour and PQ impact; for example, sometimes LCTs would have the largest impact at a partial power output level.

PQ was found to vary substantially across a year, and single week-long snapshots were found to be inappropriate for capturing representative PQ data at some sites. For example across the weeks in a year one site saw a 50.90% difference in the 5th voltage harmonic with respect to the planning level.

The laboratory testing of VTs showed that the frequency response of the VTs used by us was generally acceptable for PQ monitoring up to the 50th harmonic; however, large errors were seen at higher frequencies up to the 100th harmonic and the construction of some VTs meant they blocked triplens harmonics (odd multiples of 3).
The project successfully delivered a system of communicating PQ monitors and automated PQ data retrieval and analysis software, the learning is currently being adopted for Business-as-Usual (BaU) within our RIIO-ED2 business plan. The PQ analysis software is also being adopted by another Network Licensee (UK Power Networks).

2. Project Background

2.1. Problem

The harmonic content of waveforms and power quality (such as flicker, voltage sags and swells, voltage unbalance) within the primary network is not routinely monitored at present. However, we are now required to publish harmonic data in order to facilitate LCT connections.

In addition, there is uncertainty that power quality (PQ) monitors are giving an accurate reflection of power quality and harmonics in different levels of the distribution network. This uncertainty arises from the transducers providing inputs to the monitors, rather than the monitors themselves.

The impact of power electronic devices on the harmonics and power quality of primary networks is currently uncertain. As more and more low carbon technologies (LCTs) are connected with power electronic inverters, the effects on the network, moving forwards, are increasingly unclear. In some situations, the interaction of devices may be constructive and reduce harmonic / power quality issues. In other situations, the devices may interact in a more destructive way. There is also uncertainty surrounding the localisation of harmonic / power quality issues and whether these issues will become more widespread.

Existing business practices use snapshots of PQ data for analysis (for example, a week of data is used to represent the entire year of network operation). The major drawback with this approach is that the data captured during the short monitoring period may not be truly representative of the worst-case network operating conditions, seen during other times of the year. In addition, current business practices are labour-intensive in terms of retrieving data from site and analysing the data. Moreover, present techniques do not give us full visibility of power quality / harmonics away from the LCT points of connection.

2.2. Business Case

Over recent years there has been a sharp increase in the amount of LCTs connected to the electricity network as part of the transition to a low carbon economy. Significantly more LCTs will need to connect in order for the United Kingdom (UK) to reach its decarbonisation goals. Connections of LCT generators are set to continue at a pace; for instance, since PNPQA was registered, National Grid revised up their estimate of LCT generation capacity by 2030 from 83GW to 117GW, which is nearly double the present total network capacity. Additionally, the UK Government's Clean Growth Strategy targets electrification of transport and heating, which indicates there will be a significant increase in LCT demand connections.

LCTs are often connected to the network using power electronic interfaces that have different characteristics to the types of generators and demands that connected in the past. The impact of LCTs on power quality (such as harmonics, flicker, voltage sags and swells, and voltage unbalance) within primary networks is uncertain, particularly the future impacts of increased LCT integration.

In order to facilitate LCT connections, we are required to publish PQ information; however, current business practices would make this labour- and cost- intensive to achieve fully. At present PQ monitoring is limited in both space and time, typically with a single site being monitored in an area for a week per year, or less. As a result, worst-case operating conditions may not be captured, and there is little visibility of PQ away from LCT points of connection. Data retrieval requires site visits and analysis of PQ data is not automated, making the process labour-intensive. In addition, there is uncertainty that the network equipment used for PQ monitoring is providing an accurate picture of PQ within the networks. PNPQA aimed to overcome these shortcomings and provide widespread visibility of PQ within Primary Networks in a much more labour- and cost-efficient way than simply scaling up the present approach.

2.3. Project Structure

PNPQA was split in to four phases:

1. Design – this first phase of the project included testing the harmonic performance of VTs, selection of trial areas and sites, specifying PQ monitor interfaces and PQ analysis software;
2. Build – this second phase included developing interfaces to enable remote communications from PQ monitors, purchasing and installing PQ monitors, developing software to automate the retrieval and analysis of PQ monitor data, and building power system and LCT models for future-looking PQ studies;
3. Trial – this third phase of the project combined a wide scale trial of communicating power quality monitors with software to automate the collection and analysis of PQ data, along with modelling and analysis to understand the future impact of increased LCTs on Primary Networks; additionally, this phase also included follow-up VT harmonic testing; and
4. Report – this final phase of the project included dissemination events, creation of policies for business-as-usual adoption, and producing the close down report.

3. Scope and Objectives

The project's original scope consisted of the following work areas:

- Investigating transducers (VTs etc.) to confirm that harmonics are being passed through to power quality monitors without introducing further harmonics or eliminating them;
- Selecting two areas of our network (BSPs through to the LV side of Primary substations) for comparative assessments of harmonics and power quality. One area will be selected as a 'control' case with a low penetration of LCTs, whereas the other area will have a high penetration of LCTs;
- Creating detailed models of the two areas for power quality and harmonics analysis;
- Installing communicating power quality monitors within the two areas to generate data for comparison with the models. Also, comparing co-located power quality monitors with each other for consistency of results;
- Generating power quality heat maps and decision support tools, including the modelling of future impacts of LCTs (with a 2030 horizon) based on sources such as our own network strategy and future networks teamsand Department of Energy & Climate Change (DECC) future energy scenarios;
- Quantifying the harmonic content contribution of different types of power electronic devices and creating a series of templates for use in future analysis; and
- Automating data retrieval and analysis tasks, which are currently manual and time-intensive, to allow valuable engineer resource to be used more effectively.

Table 3-1 lists the project's objectives and their status at the end of the project. All objectives have been fulfilled.

Table 3-1: Status of project objectives

Objective	Status
Understand the power quality / harmonics impact of LCTs throughout primary networks in a systematic way;	✓
Understand the behaviour of PQ monitoring transducers in a systematic way;	✓
Automate power quality / harmonics data retrieval and analysis processes;	✓
Develop a decision support tool for modelling and forecasting harmonic / PQ effects	✓

4. Success Criteria

Table 4-1 lists the project's success criteria and their status at project end. All success criteria have been fulfilled.

Table 4-1: Status of project success criteria

Success Criteria	Status
Impact of LCTs on power quality and harmonics within primary networks better understood	✓
Power quality monitors installed at trial locations and remote retrieval of data successfully demonstrated	✓
Tools for automating power quality data retrieval and analysis demonstrated	✓
Policies created to implement project outputs in the business	✓

5. Details of the Work Carried Out

5.1. Work Pacakge 1 - Design

5.1.1. Initial VT Testing

For PQ monitoring, it may only be practical to use existing VTs to obtain voltage measurements; however, the harmonic performance requirements of these VTs may not have been specified or guaranteed, and little data is available on their performance. Therefore, to gain a better understanding of VT performance and their influence on harmonic measurements, several VTs, representative of those used on our network, were laboratory tested as part of PNPQA. Testing of VT harmonic performance initially took place at The University of Manchester (UoM), based on previous work done there for National Grid. Follow-up testing was performed by the National Physical Laboratory (NPL) – please refer to section 5.1.6 for details.

5.1.2. Test circuit and general principles

The test procedure developed by the UoM involved generating voltage waveforms with a single frequency (harmonic), injecting these in to the VT being tested, and measuring the input and output voltages at the terminals of the VT. Figure 5-1 is a schematic view of the test circuit used by the UoM for VT testing, which comprised of the following elements:

1. Two oscilloscopes were used to measure the magnitudes of the input and output of the voltage transformers. These were a visual aid to confirm the voltages that were generated and recorded by the data acquisition (DAQ) board.
2. The DAQ board was used to both inject the harmonic content into the voltage transformer (via the amplifiers (3) and HV transformers (5)) and record the input HV voltages into the test objects (via the HV dividers (6)) and the outputs from the VTs (via the 10:1 probes (8)).
3. Two American Audio VLP2500 amplifiers (two channels each). Peak output of 130 V pk. Both channels on amplifier 1 were utilised (to generate voltage inputs for phase 1 and phase 2), whilst only a single channel on amplifier 2 was utilised to generate voltage inputs for phase 3.
4. In an event of a breakdown, the output of the amplifier was connected to a current limiting resistor. These resistors would protect the amplifier from any sudden current increase due to breakdowns of voltage flashovers on the HV side of the circuit.
5. Three 30 kV (rms) STL test transformers were used to step-up the input voltages for injection into the high voltage end of each test object. The transformers have a ratio of 110 V/ 30,000 V. The 110 V input side of the transformers were connected to the amplifier (via the current limiting resistor).
6. In order to monitor (via oscilloscopes) and record the input voltages (via DAQ board), 3 high voltage dividers were included before the test object. The dividers had an input to output ratio of 10,000:1.
7. The test object (VTs).
8. 10:1 Oscilloscope probe for reading voltage from voltage transformer LV end, connected to the oscilloscopes and DAQ board.

The UoM used two different DAQ boards and associated 10:1 probes. The original DAQ board was not impedance matched to the HV dividers or 10:1 probes, which was determined to influence the results sufficiently that a different DAQ board was required (with impedance matched inputs and improved 10:1 probes) and the VTs re-tested.

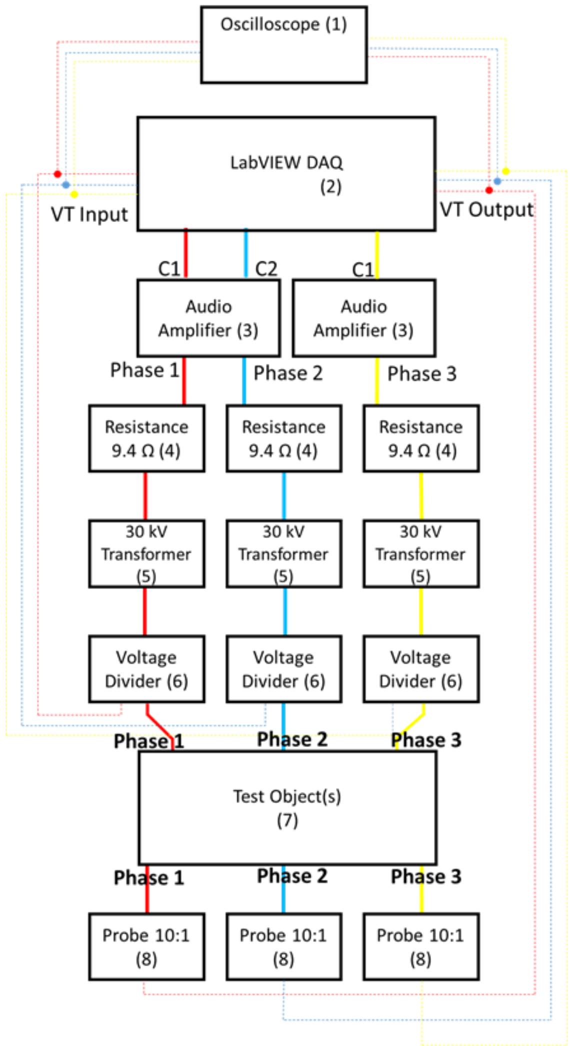

Figure 5-1: Test circuit used for VT testing at The University of Manchester

5.1.3. VTs tested

Five VTs representative of those in use within WPD's distribution networks were sourced either new or from decommissioned spares and scrap, to be used for testing. However, only three were tested using both the old and new DAQ boards. One VT (a used 11 kV oil-filled VT) was found to have an insulation fault and could not be tested. Another VT, a large 33 kV 3 phase unit, was tested using the old DAQ board but had been scrapped by the time the new DAQ board was available.

The three VTs tested were:

1. A 11 kV 3-phase cast-resin VT, which had been previously used within switchgear (an 11 kV metering unit);
2. A 33 kV 1-phase cast-resin VT, which was sourced new from a manufacturer; and
3. A second 33 kV 1-phase cast-resin VT, which was sourced new from a different manufacturer.

5.1.4. Results

Figure 5-2 shows the frequency response of the 3-phase 11 kV VT as tested at the UoM. The frequency response results obtained using the old DAQ system are shown up to the 50th harmonic order (2500 Hz), whilst the results from when the new DAQ system was used go up to the 100th harmonic order (5000 Hz). The y-axis shows the normalised ratio, which quantifies the relationship between the actual output of the VT and the expected output based on the nameplate ratio. A normalised ratio of 1.0 indicates the magnitude of the output is as expected; however, values less than 1.0 – as shown in the figure for higher frequencies – indicate the output is lower than expected.

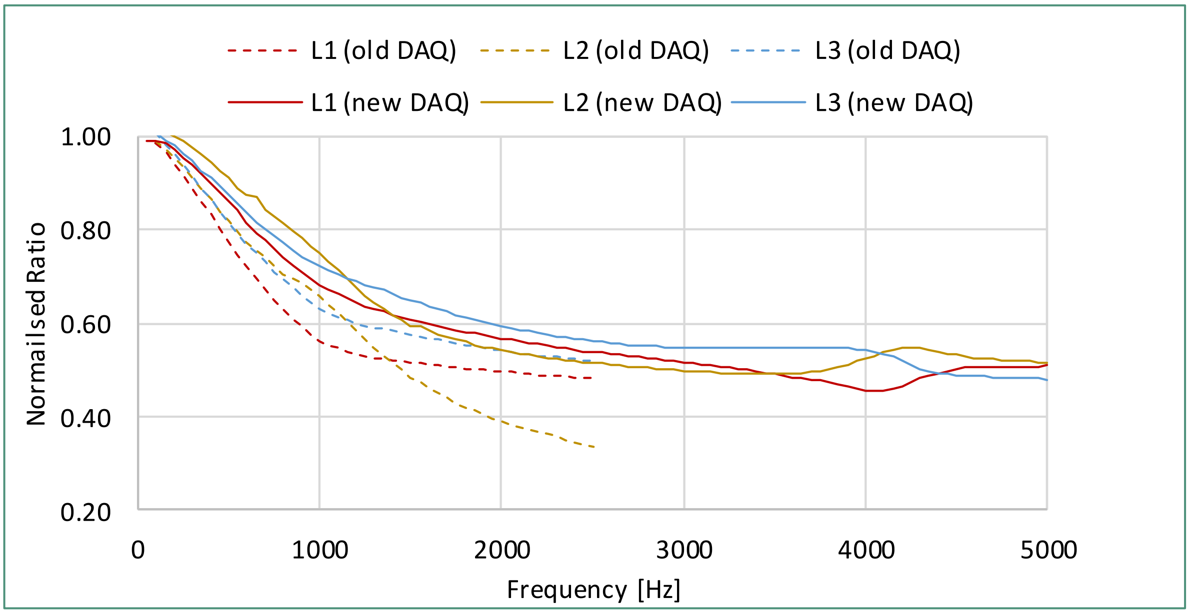

Figure 5-2: Magnitude frequency response of the 11 kV 3-ph VT

The magnitude frequency response shown in Figure 5-2 has similar patterns in the results from the old and new DAQ systems.

Firstly, as the frequency increases, there is increasing attenuation of the output signal, shown by the normalised ratio decreasing in Figure 5-2. Although the downward trend is similar, the attenuation is less with the new DAQ system, and at the 50th harmonic the minimum normalised ratio is 0.515 (L2) rather than 0.337 (L2) with the old DAQ system.

A second similarity in the results shown in Figure 5-2 is that the pattern of the ordering of the phases and the points at which they cross are approximately the same. Using the old DAQ system, L2 starts with higher values than L1 and L3, and then noticeably diverges below L1 and L3, and has the lowest values at 1.4 kHz and beyond. With the new DAQ system L2 does start higher and then crosses L1 and L3 at a similar frequency, but the divergence is less and all phases have similar values up to around 3.5 kHz. At 3.5-4.5 kHz the behaviour changes and the response curves diverge and then converge in reversed order, changing from (highest values first) L3, L1, L2 to L2, L1, L3.

The magnitude frequency responses from the UoM laboratory testing for the first and second 1-phase 33 kV VTs are shown in Figure 5-3 and Figure 5-4, respectively. The figures show the results obtained up to the 100th harmonic using the new DAQ system, and up to the 50th harmonic using the old DAQ system.

The results for the 1-ph 33 kV VTs are consistent with the trends seen in the results for the 3-phase 33 kV VT. As frequency increases, a reduction of normalised ratio is seen using both the new and old DAQ system; however, the reduction is less pronounced when measured using the new DAQ system. At the 50th harmonic (2500 Hz), the normalised ratio is 53.3% of the expected value for VT #1 (compared with 39.1% when measured using the old DAQ system), whilst for VT #2 the normalised ratio is 53.0% of the expected value (compared with 28.2% when measured using the old DAQ system).

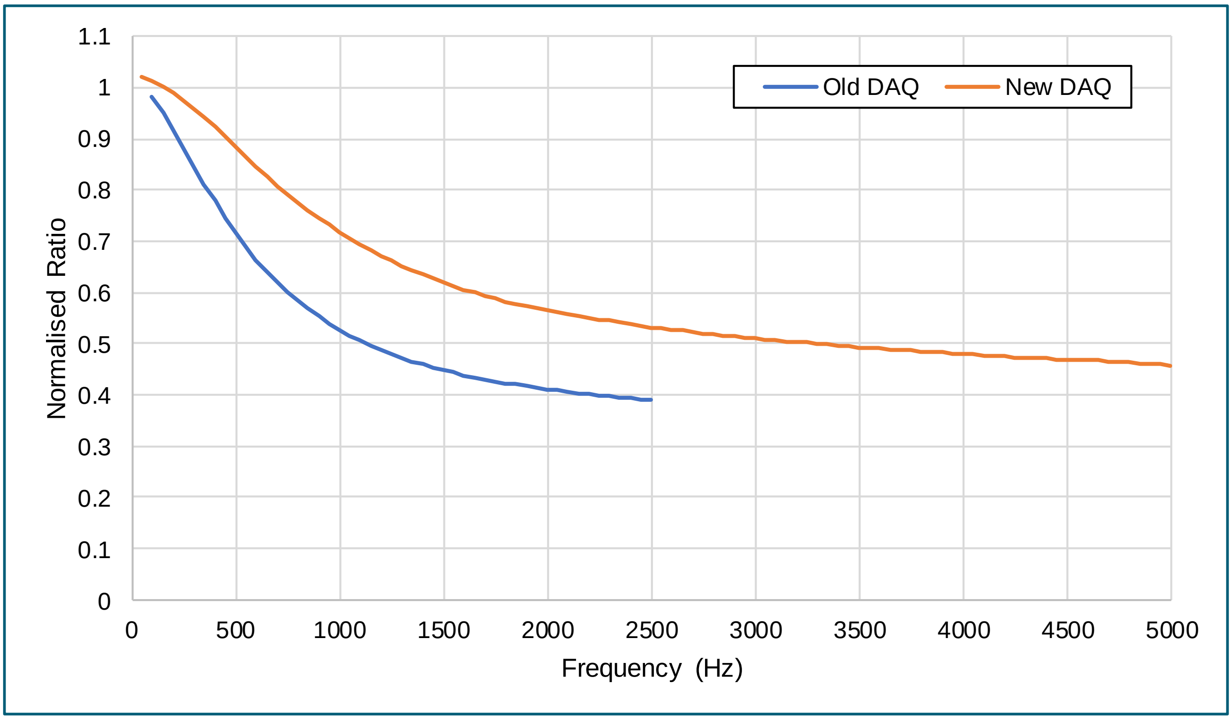

Figure 5-3: Magnitude frequency response of the 33 kV 1-ph VT #1

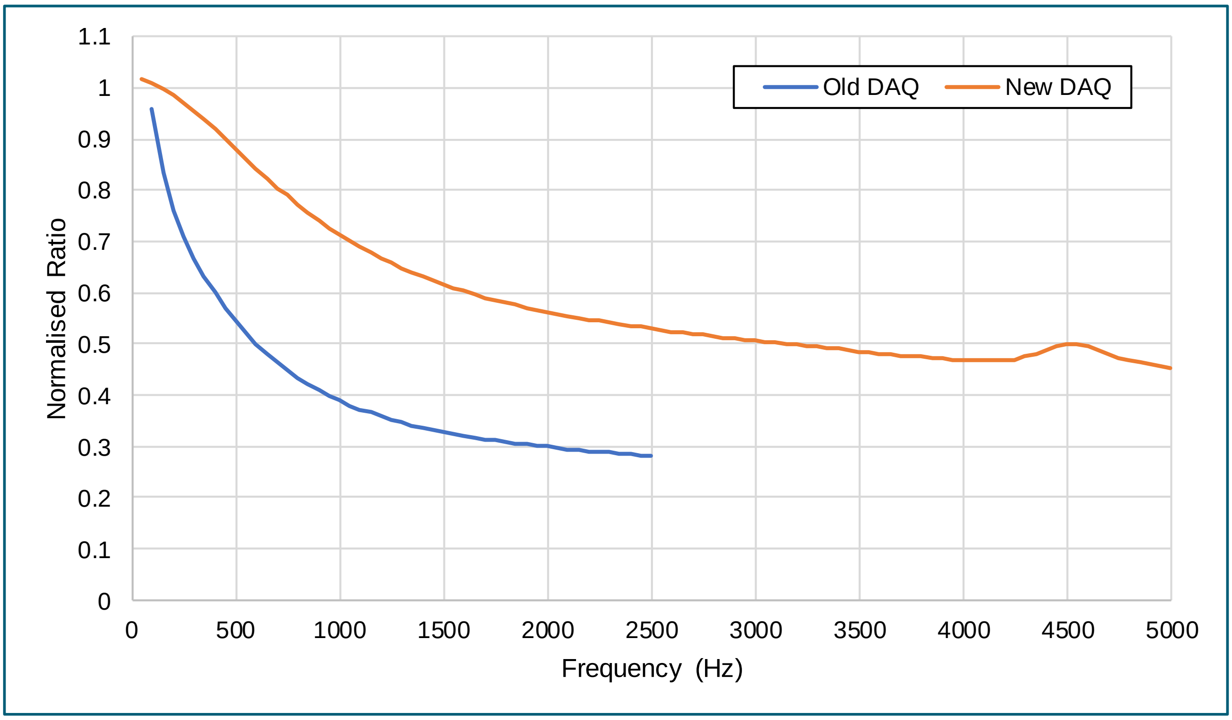

Figure 5-4: Magnitude frequency response of the 33 kV 1-ph VT #2

5.1.5. Conclusions

The tests at the UoM indicated that VTs attenuate the magnitude of higher-frequency harmonics, to the extent where the output at the 50th harmonic could be around 50% of the value that would be expected from the nominal turns ratio of the VT. The implication of this is that harmonic voltage measurements from VTs may be under-reporting the actual harmonics on the system. However, there was some uncertainty in this finding as the large difference in results between the old and the new DAQ system indicated that the test circuit was having a large influence on the results and the test equipment used was only calibrated at 50 Hz and not at harmonic frequencies.

Due to the potential significance of the findings and remaining uncertainties, follow-up VT testing at a separate facility was undertaken, which is detailed in section 5.1.6.

5.1.6. Follow-up VT Testing

The National Physical Laboratory (NPL) was engaged to perform VT testing following on from the work done at the UoM. The purpose of the follow-up testing was two-fold: 1) reduce the uncertainty around the test equipment and therefore validate the results obtained at the UoM, 2) investigate some further aspects of VT harmonic response that were highlighted by the UoM testing and the PQ monitoring trials.

The testing at NPL was split in to three stages:

1. Testing the impact that the burden applied to the secondary winding of the VTs has on the voltage ratio and phase angle between the primary and secondary windings (section 5.1.9).
2. Testing the frequency response of each of the VTs, checking for spurious frequencies generated on the secondary windings that were not present on the primary windings and for the cancelling of the triplens harmonics (section 5.1.10).
3. Testing the impact that the voltage magnitude applied to the primary winding of the VTs and the length of cable on the secondary side have on the voltage ratio and phase angle between the primary and secondary windings (section 5.1.11).

5.1.7. VTs Tested

Five VTs from different manufacturers were tested. These are described in Table 5-1. VTs 3-5 are the same as tested at the UoM, whilst the others were sourced from within WPD from decommissioned spares and scrap.

Table 5-1: Summary of the VT voltages and rated burdens

VT Number	Insulation	Rated Voltage (kV)	Rated Burden (VA)	Number of phases
1	Oil filled	33	200	3
2	Oil filled	33	75	3
3	Cast resin	33	52	1
4	Cast resin	11	50	3
5	Cast resin	33	25	1

5.1.8. Test Setup

The test setup used for the 3-phase VTs is shown in Figure 5-5. The voltage sources were phase-locked to a central clock via an isolator. Each phase was connected to a digitiser on the primary and secondary sides of the VT for measurements.

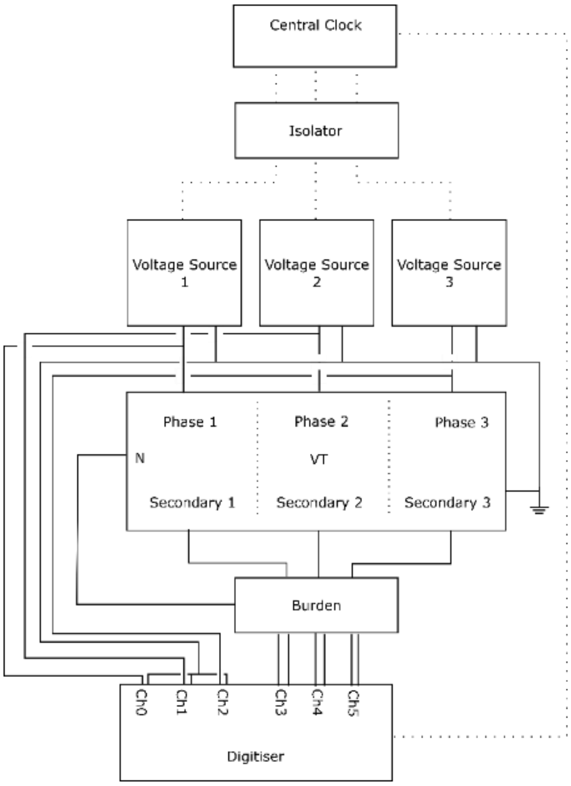

Figure 5-5: 3-phase VT test setup, with solid lines showing voltage connections and dotted lines showing timing signals

5.1.9. Impact of burden

100 V was applied to the three phases of the VTs' primary windings, approximately 120° apart, at 50 Hz and frequencies from 500 Hz to 5 kHz in 500 Hz steps. At each frequency the voltage at the primary and secondary windings and the phase angle of the secondary voltage relative to the primary voltage were measured. This was repeated with nine different burdens applied to the secondary winding of the VT. The burdens applied are shown in Table 5-2. The first burden was the high impedance of the digitiser measurement instrument, five burdens were resistors providing a given percentage of the VT's rated burden and three burdens were resistor-inductor combinations providing the equivalent impedance of a given number of protection relays in parallel.

Table 5-2: Impedance of burdens tested

Burden	Impedance				
Digitiser measurement instrument	High impedance (~10 MΩ)				
	Resistance (Ω)				
	VT #1	VT #2	VT #3	VT #4	VT #5
10% of VT rated burden	201.7	537.8	1613.3	806.7	1613.3
25% of VT rated burden	80.7	215.1	645.3	322.7	645.3
50% of VT rated burden	40.3	107.6	322.7	161.3	322.7

75% of VT rated burden	26.9	71.7	215.1	107.6	215.1
100% of VT rated burden	20.2	53.8	161.3	80.7	161.3
	Resistance (Ω)			**Inductance (H)**	
1 protection relay	1097			2.7	
2 protection relays	5334			11.9	
3 protection relays	24125			39.6	

It was found that there was a measurable change in both voltage ratio and phase angle between secondary and primary windings of a VT when changing the burden. In general, when applying a burden with a lower impedance, then there was a reduction in the measured voltage ratio between the secondary and primary side.

The most extreme cases measured were when the frequency applied caused a resonance within the VT. One such case is shown in Figure 5-6 and Figure 5-7. In this case the lowest impedance burden caused the VT to measure 12% higher than nominal and the highest impedance burden caused the VT to measure 168% higher than nominal, which was probably caused by the lack of resistive damping. In the same case, the phase angle difference between the secondary and primary windings shifted in a range of 0.3 radians (17°) from the highest to lowest impedances.

NPL suggested that the burden used for the rest of the project be approximately equivalent to three protection relays provided in parallel because:

- The impedance is equivalent to real world relays.
- The protection relays tested all had individual impedances which were significantly lower than the 10% of the rated burden.
- If a VT is only loaded with protection relays, then is unlikely for VT's to have burdens which are a significant proportion of rated burden.
- The suggested burden made detection of resonances easier to detect.

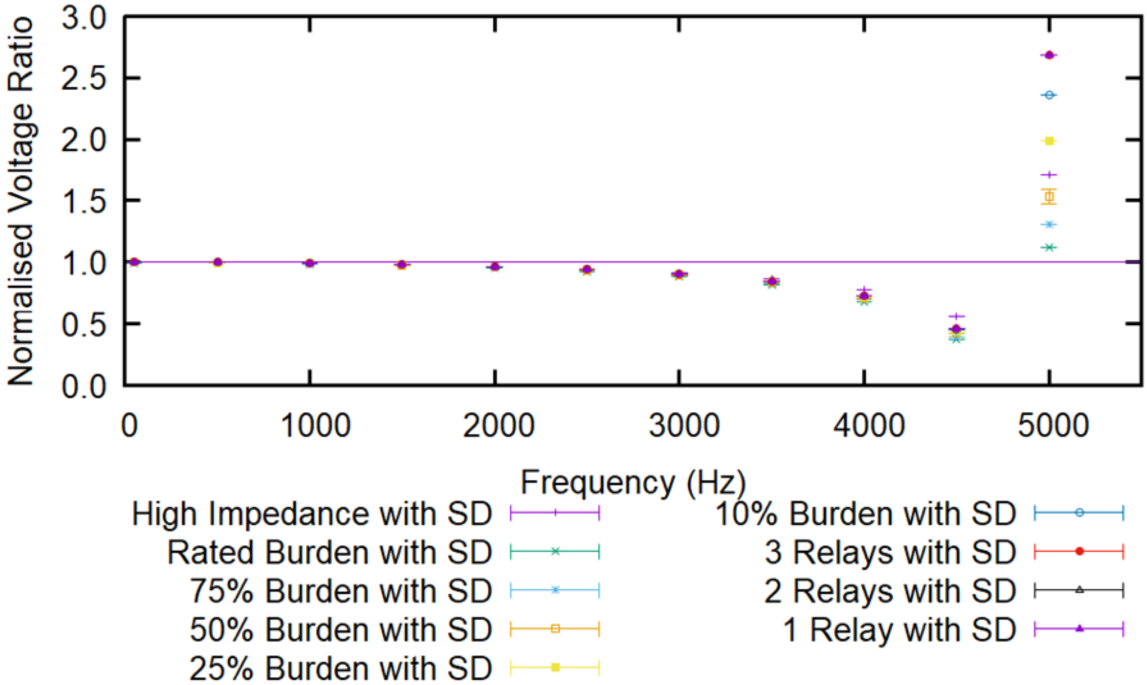

Figure 5-6: Ratio of secondary to primary voltage for phase 3 on VT #2, for various frequencies and burdens. The horizontal line shows the nominal ratio.

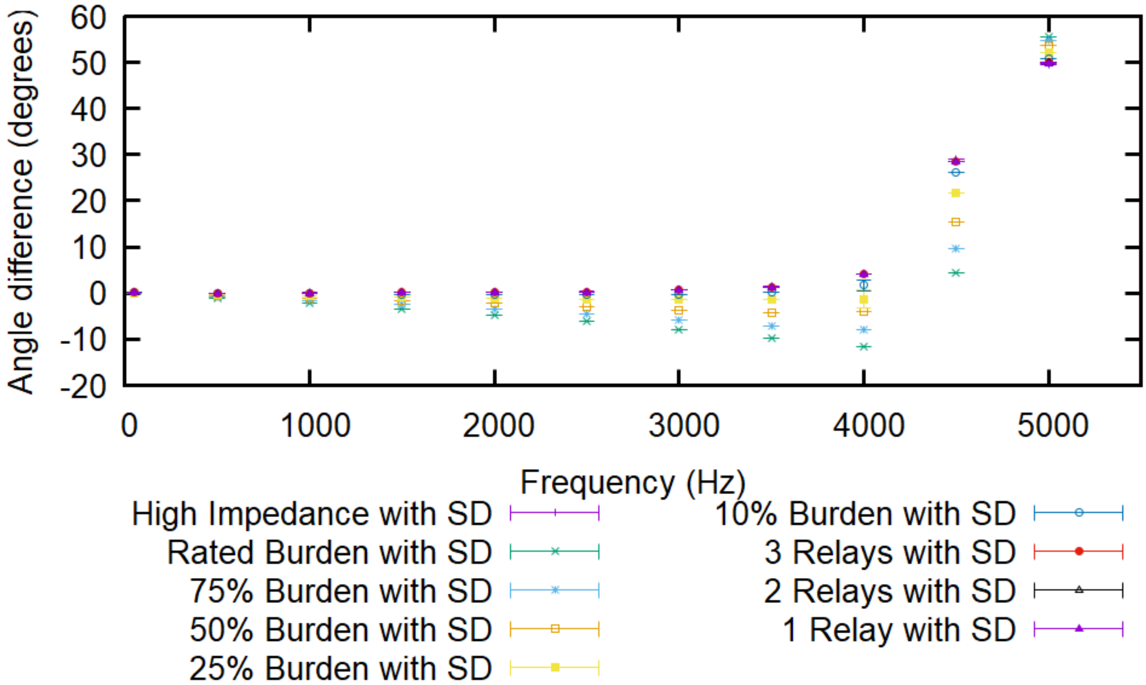

Figure 5-7: Phase angle separation between secondary and primary windings for phase 3 on VT#2 for various frequencies and burdens.

5.1.10. Frequency Response

To represent positive and negative phase sequence harmonics, 100V was applied to the three phases of the VTs' primary windings, approximately 120° apart, at frequencies from 50 Hz to 5 kHz in 50 Hz steps. A burden approximately equivalent to three protection relays provided in parallel was applied to the secondary winding. At each frequency the voltage at the primary and secondary windings and the phase angle of the secondary voltage relative to the primary voltage were measured.
The three phase VTs were also tested for triplen harmonics, from 150 Hz to 4950 Hz in steps of 150 Hz. All the three phases were energised with zero degrees between them.

The positive and negative sequence frame gain plot for the five VTs tested showed that all but one has a resonance up to 5 kHz. These results are shown in shown in Figure 5-8, and the highest observed gain was greater than 2.5 (over reading the harmonic present by more than 150%). At this resonant mode the phase angle difference between the secondary and primary windings of the VT was greater than 90 degrees, shown in Figure 5-9.

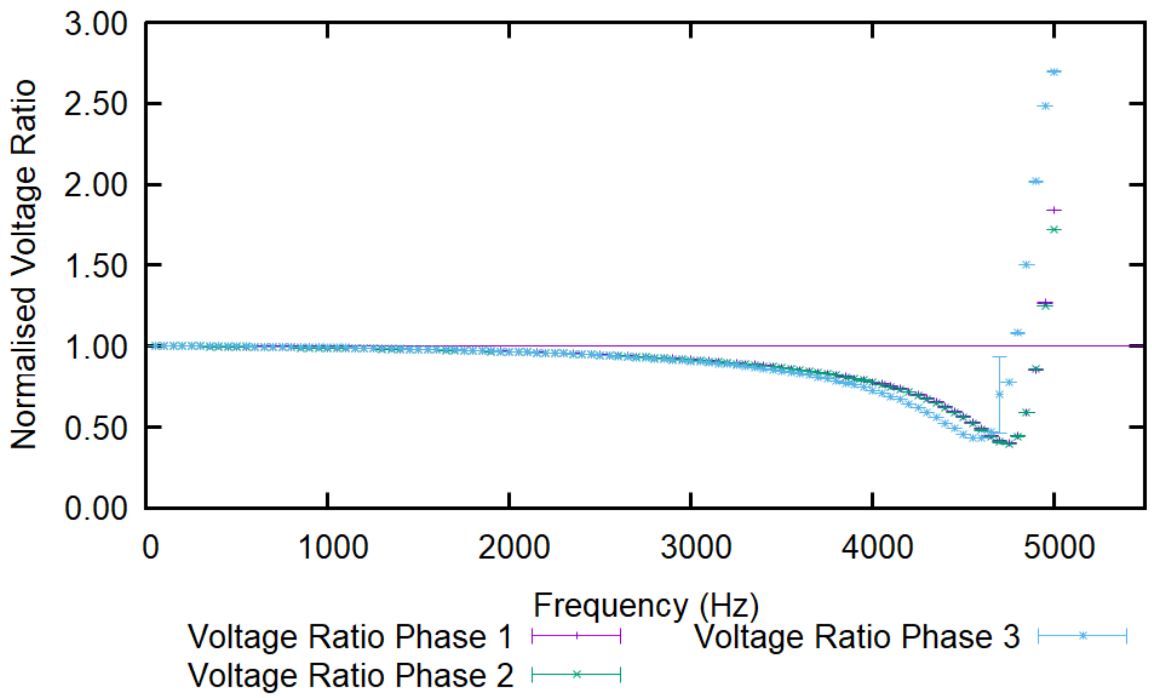

Figure 5-8: Ratio of secondary to primary voltage on VT #2 for various frequencies and all phases. The horizontal line shows the nominal ratio.

The measured output from the secondary windings was checked for spurious frequencies which were not energised on the primary winding and none were found.

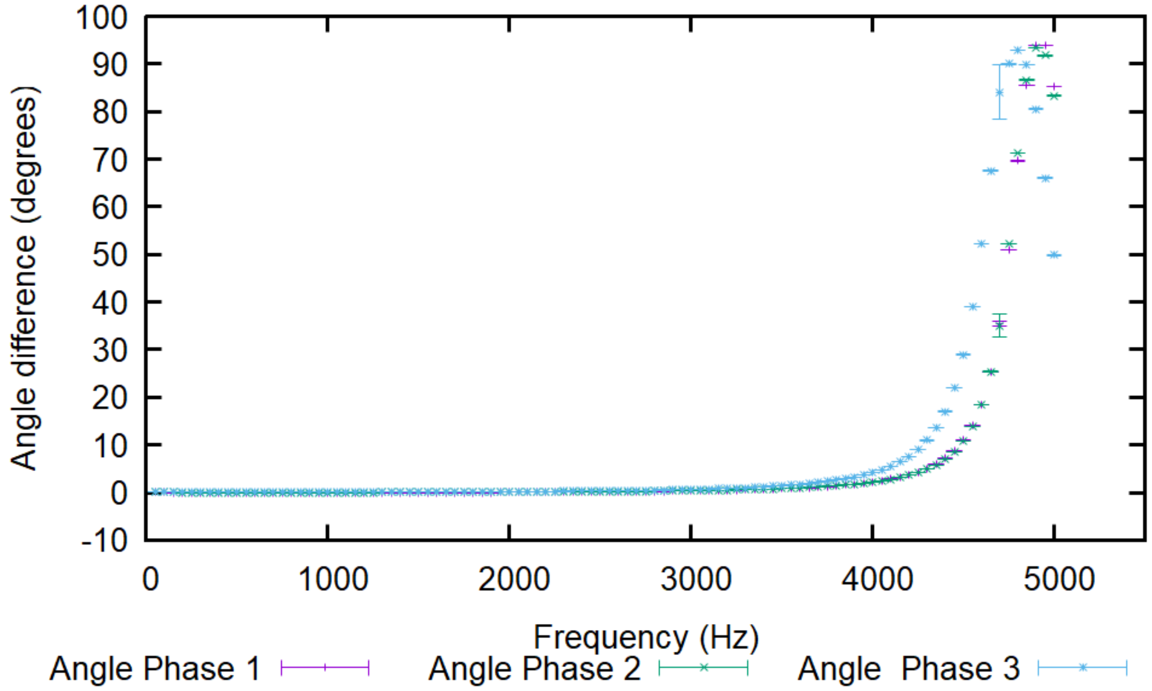

Figure 5-9: Phase angle separation between secondary and primary windings for all phases on VT #2 for various frequencies.

This exercise was repeated for the zero sequence frame. This was done by applying harmonic voltages with zero-degree separation between phases for each three phase VT. The normally held assumption is that balanced voltages with zero-degree separation between phases on the primary windings will cancel out and there will be no voltage present on the secondary windings. This assumption was correct at frequencies below 1 kHz. However, at frequencies between 1 kHz and 5 kHz circuit gain factors began to exceed 4.5 (over reading the harmonic by more than 350%) were measured, shown in Figure 5-10. The internal configuration of the VT is crucial in understanding the in-phase testing as one VT tested demonstrated no cancelling out on the secondary windings and behaved as three single phase VTs, shown in Figure 5-11.

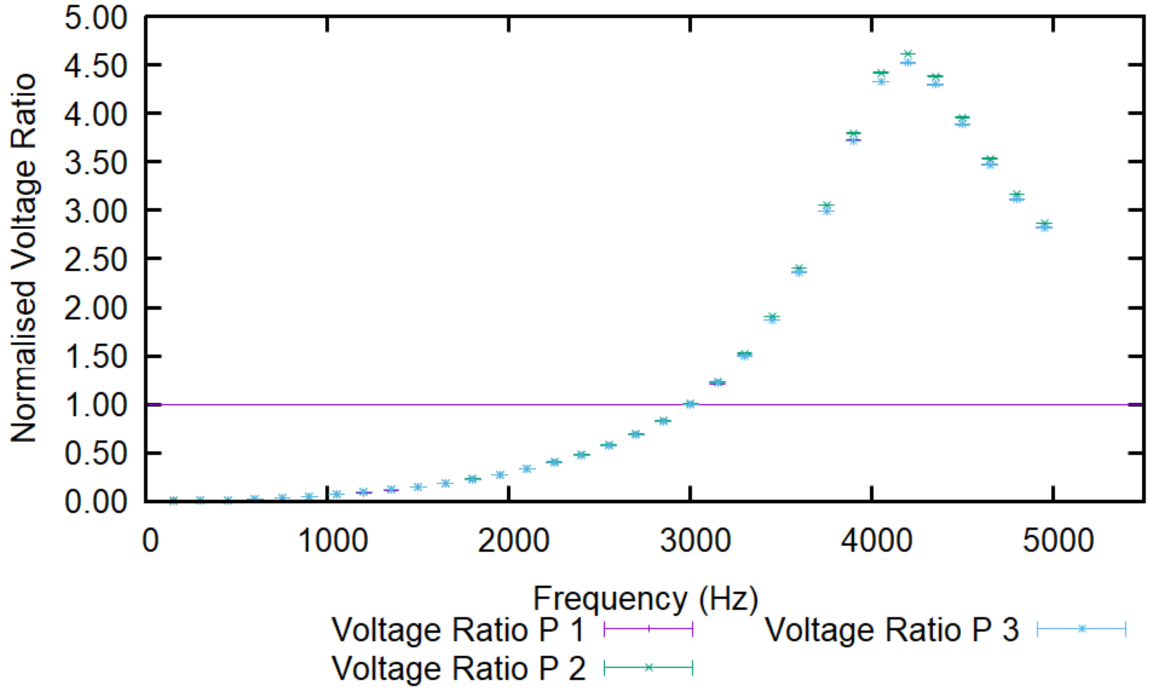

Figure 5-10: Ratio of secondary to primary voltage for VT #4, for various triplen frequencies.

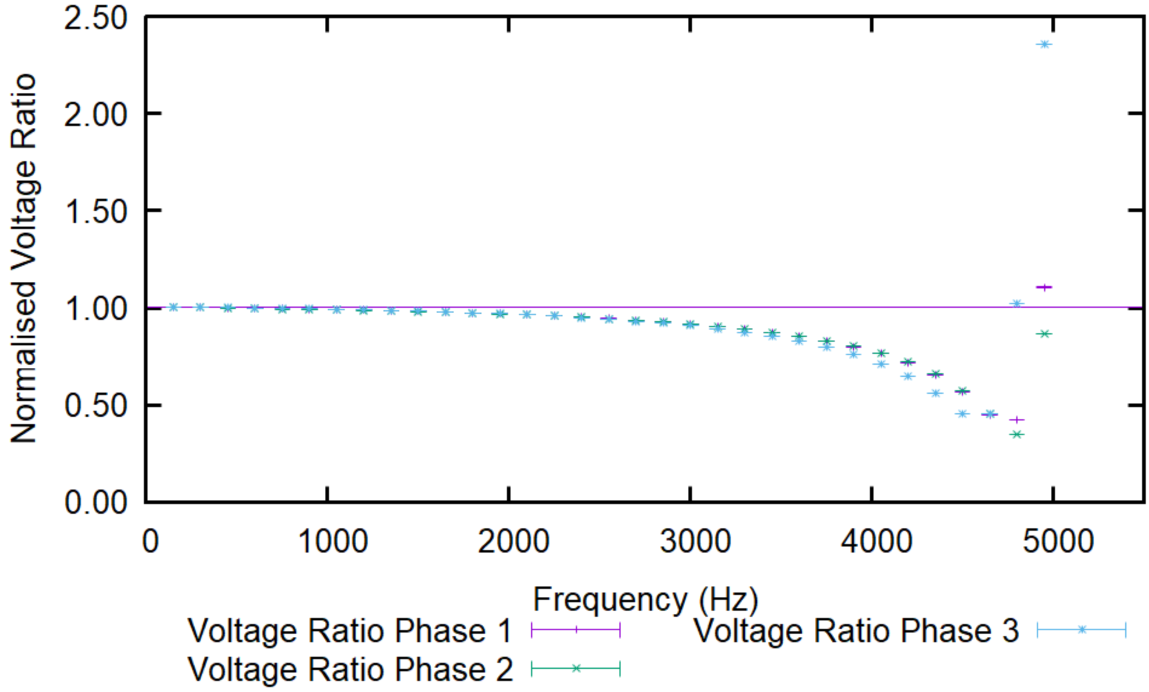

Figure 5-11: Ratio of secondary to primary voltage for VT #2, for various triplen frequencies.

5.1.11. Impact of Voltage Magnitude

Voltages of magnitude 10 V, 50 V, 100 V, 150 V and 200 V were applied to the three phases of the VTs' primary windings, approximately 120° apart, at 50 Hz and frequencies from 500 Hz to 5 kHz in 500 Hz steps. A burden approximately equivalent to three protection relays provided in parallel was applied to the secondary winding. At each voltage and frequency setting the voltage at the primary and secondary windings and the phase angle of the secondary voltage relative to the primary voltage were measured.

For the VTs tested, it was found that applying different primary voltages gave rise to a small variation of normalised voltage ratios between secondary and primary windings of about ±1%. An example of this is shown in Figure 5-12. The highest deviations were found when the lowest primary voltage of 10 V was applied. For VT's that had a resonant mode, the associated gain factors were all less than 1.035.

The largest shift in phase angles between secondary and primary windings was less than ±1.2 degrees, however this was also for a 10 V primary voltage at 50 Hz. At any other measured primary voltage and frequency, the spread of phase angles between secondary and primary windings was less than ±0.2 degrees. This is shown in Figure 5-13.

Secondary wiring testing was also completed. Different lengths of multi-core cable were used between the secondary windings of the VTs and the burden. 100V was applied at 50 Hz and frequencies from 500 Hz to 5 kHz in 500 Hz steps. A burden equivalent to one protection relay in parallel (B1) and three protection relays in parallel (B2) were applied to the secondary winding. At each frequency and burden a nominal current of 1 A at 50 Hz was passed through the cable and back to simulate the use of some cores in the multicore cable for a current transformer secondary wiring. This was repeated for multi-core cable lengths of 10 m, 20 m and 50 m.

The additional impedance connected to the secondary wiring caused the spread of normalised voltage ratios for different secondary wiring configurations to increase with frequency. The largest spread of values for secondary wiring was less than ±3% of the normalised voltage ratio (Figure 5-14) and had a phase angle difference of ±2.5° (Figure 5-15).

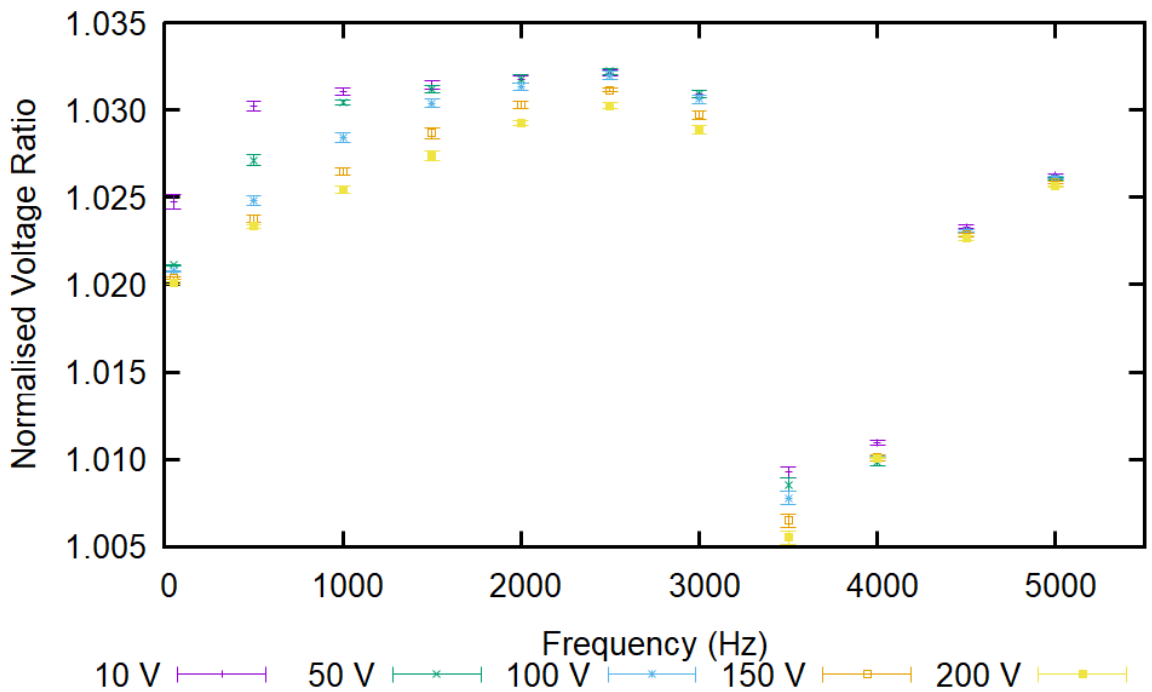

Figure 5-12: Ratio of secondary to primary voltage phase 1 of VT #1, for various primary voltages and frequencies.

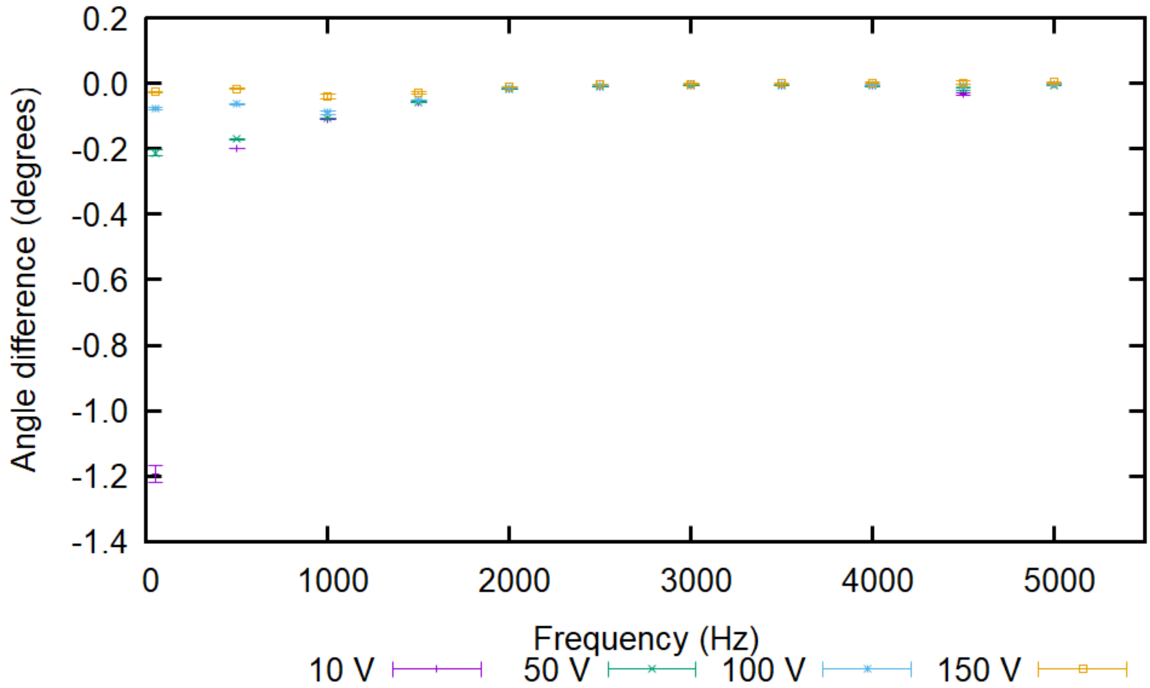

Figure 5-13: Comparison of phase angle difference between secondary and primary voltage for phase 3 of VT #2 to 200V, for various applied primary voltages.

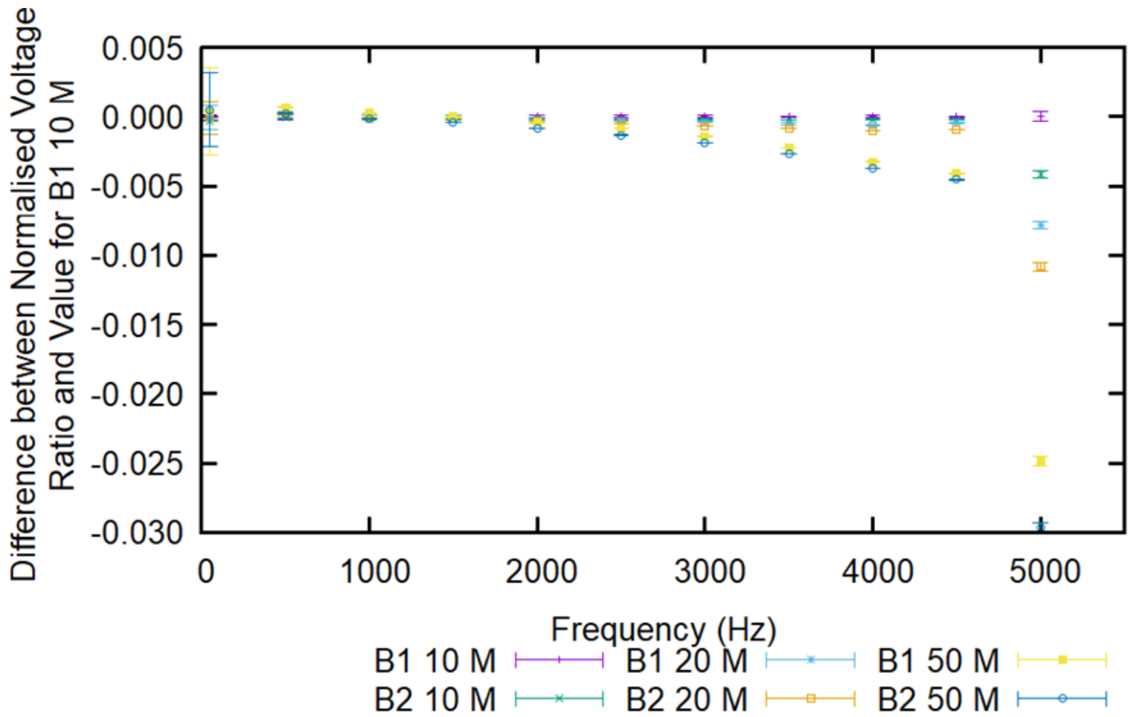

Figure 5-14: Comparison of ratio of secondary to primary voltage for phase 2 of VT #2 to B1 10M, for secondary wiring configurations and frequencies.

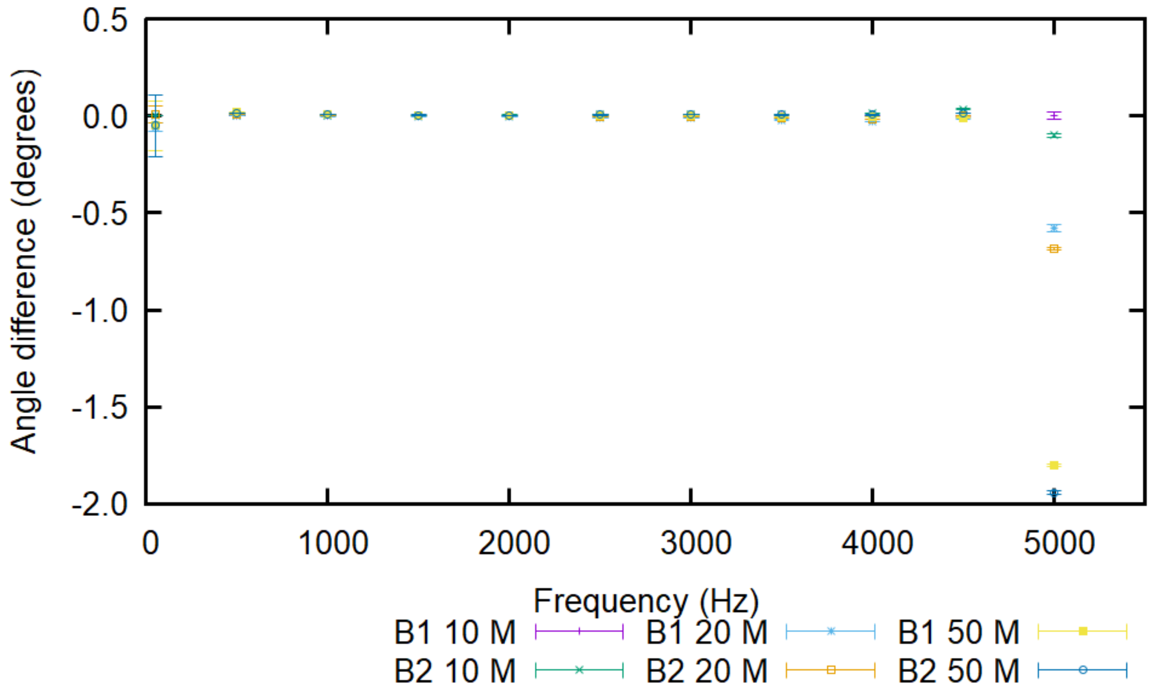

Figure 5-15: Comparison of phase angle difference between secondary and primary voltage for phase 2 of VT #2 to B1 10M, for various secondary wiring configurations and frequencies.

To have confidence that power quality (PQ) monitoring has accuracy greater than ±1% from VTs in the field, it is necessary to measure all the installed equipment together including the applied burden and the connected length of multicore cable. Verification of the impact of actual primary voltage amplitude on the secondary winding is also necessary.

5.1.12. Trial Area and Site Selection

In order to fulfil the aims of the project, it was vital that the PQ monitoring trial took place in two areas of Primary Network that contrasted in the amount of LCTs within them but were otherwise comparable. Therefore, a selection exercise took place to choose two network areas to focus on and decide which sites within each area would have monitoring installed.

The initial step was to develop selection criteria, which were based on the requirements set in the original NIA registration and formed the basis of the selection process:

1. **Selection criterion 1 – LCT penetration**: The NIA registration stated that “two contrasting areas” of “Primary Network” would be used for the trials, one “with a high penetration of LCTs” and the other “with a low penetration of LCTs”. Two scoring metrics were developed to assess different areas of Primary Network (33 kV networks in the West Midlands licence area for PNPQA) against these requirements, based on demand and generation:
    a. “LCT Dominance” score: For this, areas scored higher if they had significant connected capacities of LCT distributed generation (DG) at 33 kV and 11 kV in comparison to the firm capacity of the infeeding substation, and also if LCT DG outweighed non-LCT DG (e.g. diesel, gas turbines); and

b. “Demand Dominance” score: For this, areas scored higher if DG penetration was low compared to the demand within the area, and if any DG that was present was not LCT-based.

2. **Selection criterion 2 – additional features**: The “LCT Dominance” and “Demand Dominance” scoring based on generation and demand were adjusted based on additional features such as the presence of rapid EV chargers, new LCTs about to connect, and the presence of existing PQ issues. The adjusted scores for each of the 33 kV network areas considered are shown in Figure 5-16.
3. **Selection criterion 3 – similar networks**: The NIA registration called for the two network areas to allow for “comparisons to be made”; therefore, they should be similar except for the penetrations of LCTs. Similarity was assessed by:
    a. The network areas were compared against each other using several metrics: the total circuit length, the proportion of circuits that were overhead line, and the infeeding substation demand;
    b. Based on the similarity metrics, four groups of areas were found that shared similar values across all three metrics;
    c. Two of these groups were ignored as their characteristics limited the learning that they were likely to deliver: either the total circuit lengths were short (<40 km) – with therefore little network to monitor – or the areas were too dissimilar to all the other areas – so any learning was less easily generalised; and
    d. The remaining two groups contained areas that contained predominantly overhead lines (>70%) and had total circuit lengths of either 40-80 km or 100-180 km. The top-rating “high” and “low” LCT areas from each group were selected as candidates for assessment in more detail according to the final selection criterion below.
4. **Selection criterion 4 – usable sites**: For a candidate area to be used as a trial area for PNPQA, it had to be feasible to monitor PQ at the sites within the area. This was assessed in two stages, with the top-rated areas targeted first:
    a. Desktop analysis of asset and site information, to identify what equipment should be available on site (VTs and CTs) for PQ monitoring; and
    b. Site surveys, which included:
        i. Verification of equipment available on site;
        ii. Checking secondary terminals for VT and CT connections;
        iii. Checking possible installation space, access to power, and external access (e.g. for antenna connections);
        iv. Checking mobile communication signal strength; and
        v. Checking substation layout and running arrangement.

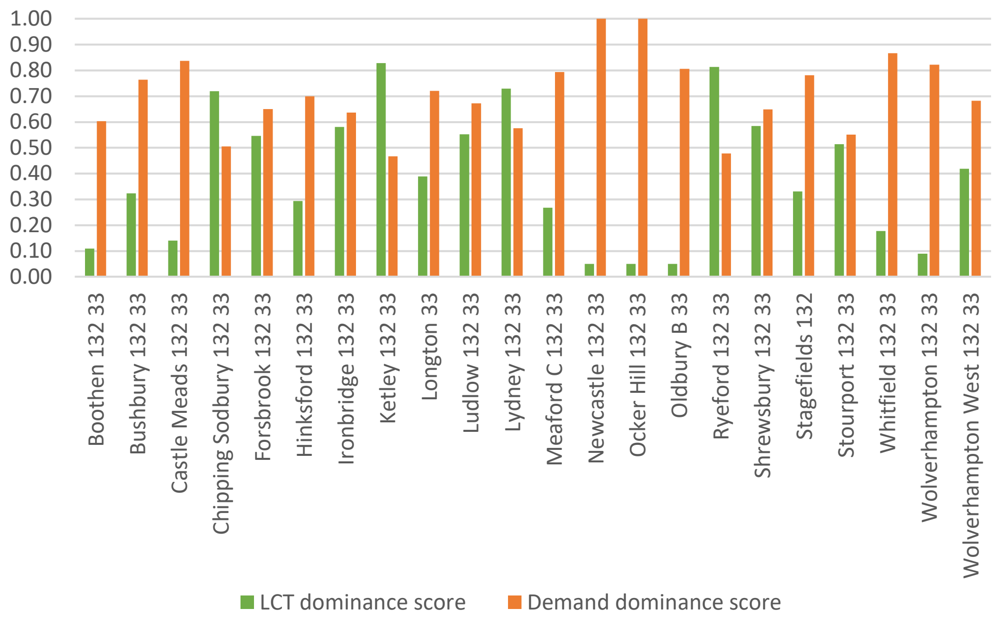

Figure 5-16: LCT and demand scoring for the 33 kV network areas (BSPs) in WPD's West Midlands licence area

Two strong candidate areas emerged from the group of areas with total circuit lengths of 100-180 km:

1. "High" LCT: the network fed from Ryeford BSP, centred around Stroud, Gloucestershire, and extending to the Severn in the west; and
2. "Low" LCT: the network fed from Meaford C BSP, which lies between Market Drayton, Stafford, and Stoke-on-Trent.

Site surveys to all the 33 kV sites in the two trial areas were completed to assess their suitability for installation and operation of communicating PQ monitor equipment. The surveys confirmed that most or all the sites were suitable so therefore the Ryeford and Meaford C were confirmed as the trial areas for the project.

In addition to the 33 kV sites within the trial areas, several other sites were identified that featured LCTs that were not present in the trial areas such as onshore wind, battery energy storage, and large electric vehicle (EV) charging stations. Furthermore, there was scope to increase the number of monitoring points within the trial areas so additional 11 kV sites were identified, some of which featured LCTs of interest. These additional sites were included in the PQ monitor trial in order to gather valuable data on the characteristics of LCTs and the 11 kV networks downstream of the 33 kV Primary Networks.

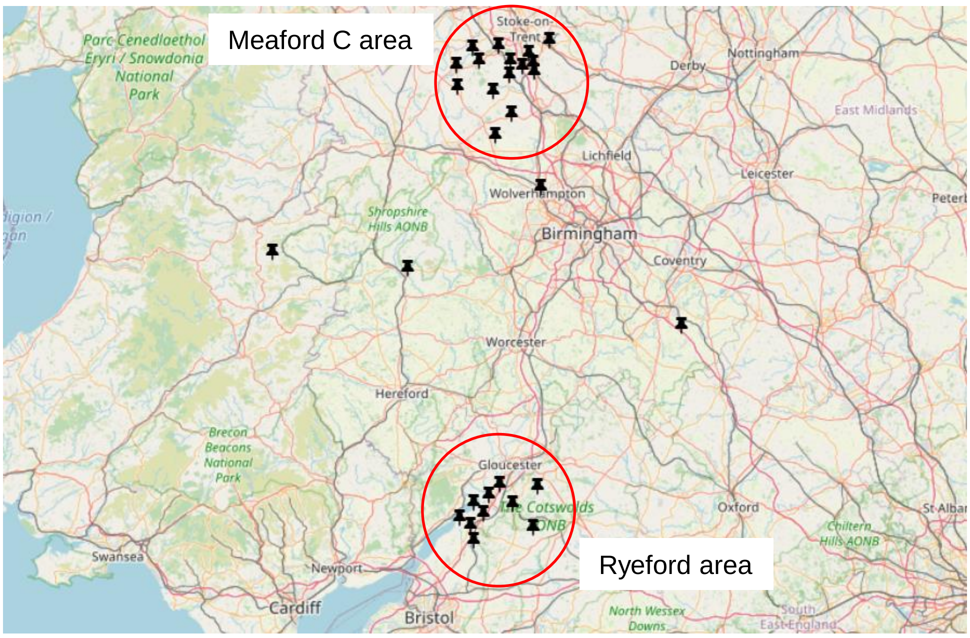

Figure 5-17: Location of PQ monitor installations selected for the PNPQA project, with main trial areas indicated

Figure 5-17 shows the extent of the 46 installation locations across 37 sites that were identified for the PQ monitor trial, of which 33 sites were within the two trial areas.

5.2. Work Package 2 - Build

5.2.1. Monitoring Pilot

In order to gain some early learning with a communicating power quality monitor, a pilot trial of with a single monitor was completed.

An Outram PM7000 PQ monitor was installed at Meaford C substation in June 2018. The installation is shown in Figure 5-18. Voltage and current measurement connections were made in to the indoor 33 kV switchgear, and the PQ monitor was connected to a Nortech Envoy communication hub to provide remote data access over the mobile telephone network. The interface between the Envoy and PM7000 had been developed during a previous project.

Figure 5-18: Pilot PQ monitor installation at Meaford C. From left to right: connections in to VT secondary wiring; current clamps around CT secondary wiring; Envoy communications hub and PM7000 PQ monitor installed on top of switchgear.

The Envoy communications hub regularly collected data from the PQ monitor and transmitted the data to Nortech's iHost web-based control and monitoring platform, which allowed measurements to be viewed online and downloaded in bulk for offline analysis. Figure 5-19 shows an example display of voltage data on iHost for a week-long period, with new data samples taken every 10 minutes.

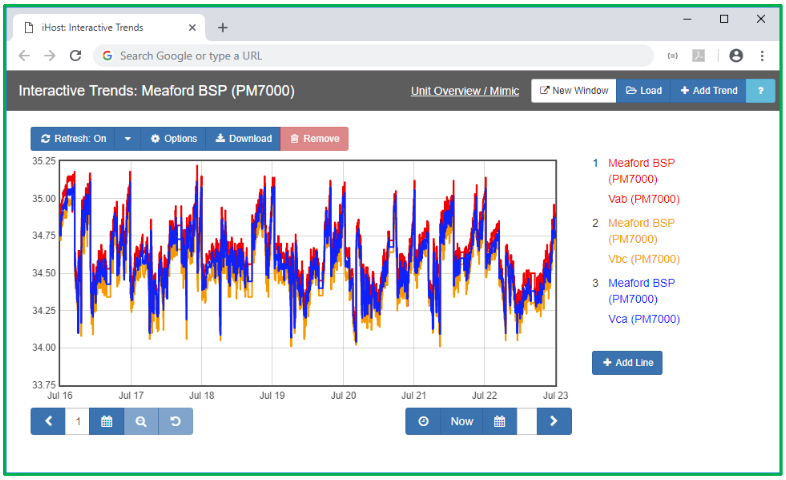

Figure 5-19: Monitored voltage profiles for an example week viewed on iHost.

Harmonic data collected during the pilot trial revealed some interesting trends. For example, how harmonics varied across a week, shown for an example week in Figure 5-20. The variation across the week was particularly apparent for the 5th harmonic order. Further analysis revealed the 5th harmonic was negatively correlated with the substation loading, particularly the reactive power flow. At times of high loading, the 5th harmonic was suppressed, whereas during low loading (evenings and weekends) the magnitude of the 5th harmonic increased significantly, almost doubling.

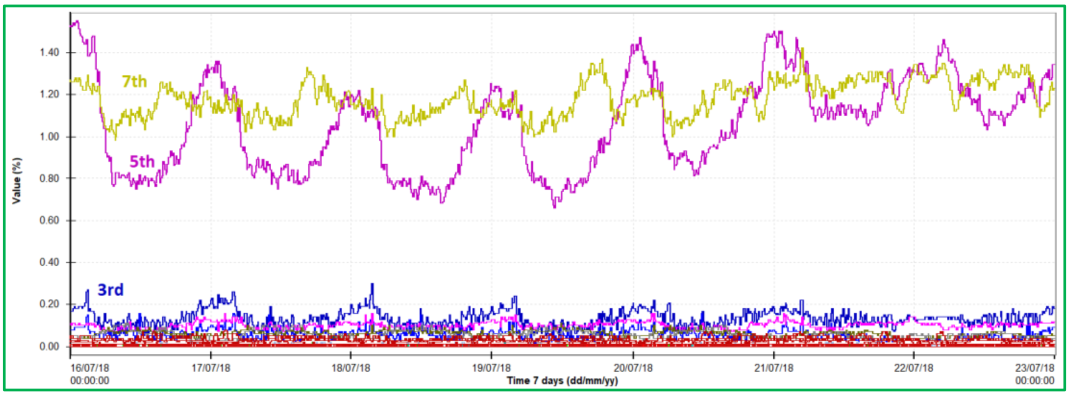

Figure 5-20: Harmonic profiles for an example week (10 minute samples, displayed in Pronto).

A particularly interesting early piece of learning from the pilot trial was how the timing of the monitoring period affected the results. Typically, power quality monitoring and assessments are done for week-long periods; however, the pilot trial ran for many weeks, so there was enough data to investigate whether choosing different week-long windows would affect the overall results of analysing the harmonics.

To assess this effect, the 10-minute interval Vab harmonic data for the 3rd, 5th, and 7th harmonic orders was analysed using a “sliding window” approach. This approach calculated the summary statistics (95th percentile values) for all possible week-long “window” periods of data within six weeks of monitoring data, with the start date and time “slid” by 10 minutes for each window.

The results of the "sliding window" analysis are shown in Figure 5-21, which shows that the start time of a standard week-long monitoring period did have an effect on the 95th percentile values, which were typical summary statistics for PQ data. Figure 5-22 summarises the effect on the 95th percentile values, in terms of the maximum, minimum, and average (mean) values for all possible week-long windows within the six weeks of data. The most significant difference in the figure is for the 3rd harmonic order, where the maximum value was 21.1% higher relative to the minimum. For the 5th harmonic order, the relative difference was 7.9% and for the 7th harmonic order the difference was 12.2%.

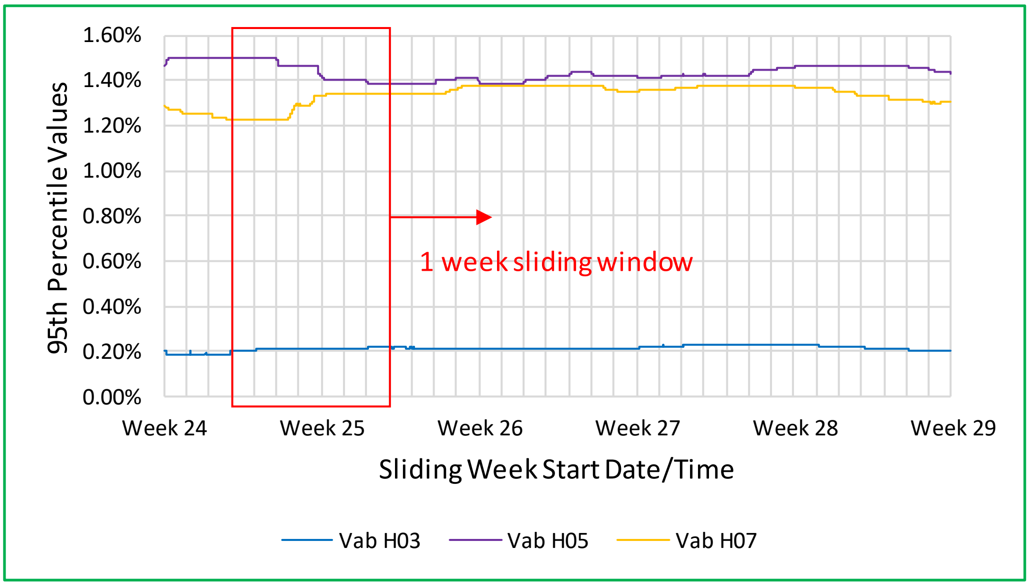

Figure 5-21: Effect on voltage harmonic summary statistics (95th percentile values) by changing the start date and time of a standard week-long monitoring window (Vab, based on 10 minute interval data).

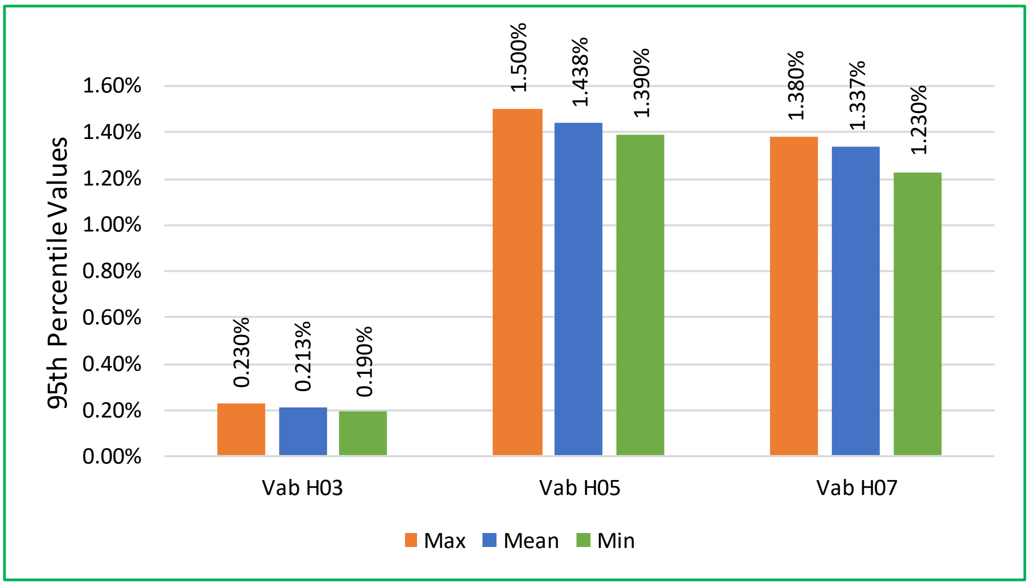

Figure 5-22: Summary of effect on harmonic summary statistics by changing the start date and time of a standard week-long monitoring window (Vab, based on 10 minute interval data).

The pilot trial also provided valuable experience and learning for the project team around installation practicalities, expected data volumes, PQ monitor integration, and PQ analysis processes, which were all useful for the upcoming project activities.

The Outram PM7000 PQ monitor was left in situ at Meaford C substation following the pilot trial and the data continued to be collected remotely in to Nortech's iHost web-based control and monitoring platform via a Nortech Envoy communications hub. The monitor was not the same as those used for the main monitoring trial and was not supported in the software being developed for the project so it was removed and replaced with a PSL PQube3 for the main trial in September 2019.

5.2.2. PQ Monitor Integration

An overall architecture for the PQ monitoring and communication solution for the widescale trial was outlined. A high-level summary of this architecture is shown in Figure 5-23.

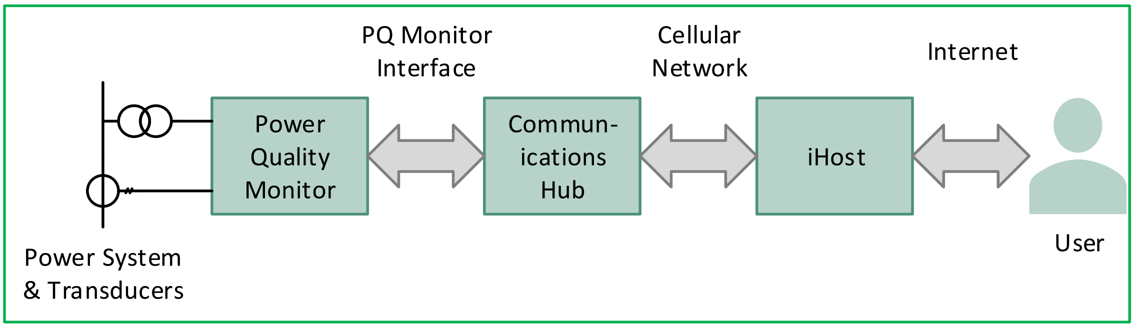

Figure 5-23: Summary of overall architecture for PNPQA PQ monitoring and communication.

A market review of PQ monitors was completed, which revealed several potential manufacturers and also the range of features available on the market.

Three PQ monitors from different manufacturers were obtained for bench testing of interfaces by Nortech. Bench testing was carried out, which confirmed it is feasible to interface with each of the three monitors to obtain PQ data for remote communication. However, the testing also revealed it is not possible to remotely update the configuration of at least one of the monitors due to a proprietary protocol being used.

Figure 5-24: The three PQ monitors being used for the project, from left to right: the a-eberle PQI-DA smart, the PSL PQube3, and the Siemens SICAM Q200

Figure 5-24 shows the three different PQ monitors that were used for the project, from a-eberle, PSL (now Powerside), and Siemens. These PQ monitors use different interfaces for exposing PQ data including continuous measurements (such as harmonic voltages recorded every 10 minutes) and event recordings (such as voltage and current waveforms captured during an interruption).

Nortech's Envoy communications hub was used to enable remote communications with the PQ monitors. New firmware for the Envoy was developed for interfacing with the PQ monitors to retrieve PQ data, store that locally, then upload the data to a centralised monitoring platform (Nortech's iHost) over the 4G communications network. The interfaces developed for each monitor comprised:

1. For the a-eberle PQI-DA smart, interfacing was done using the IEC 61850 protocol to continuously poll for new measurements whilst using IEC 61850's file transfer mechanism to obtain event recordings stored as COMTRADE files.
2. For the PSL PQube3, FTP was used to access daily CSV-format data recordings that contained continuous measurements and event recordings.
3. For the Siemens SICAM Q200, IEC 61850 file transfer was used to obtain continuous measurements (as a daily PQDIF file) and event recordings (as COMTRADE files).

The interfaces were bench tested before being used as part of the PQ monitoring trial.

5.2.3. PQ Analysis Automation Software

PNPQA developed software to automate the collection, analysis, and presentation of PQ monitoring data.

Meetings were held with PQ experts with WPD Primary System Design (PSD) to understand current processes and future expectations, in order to capture requirements for the automation software. These requirements were developed into a requirements specification for the software, which stated the high-level requirements for six main features that were to be developed:

1. PQ Data Ingest: This is a background feature that takes data from different PQ monitors and puts them in to a common format within the software's time-series database, making the data available for the other analysis features.
2. PQ Trends: This allows a user to plot a variety of PQ data from PQ monitors as time-line and bar charts.
3. PQ Dashboard: This allows a user to get a quick overview of any recent PQ issues and the health of the PQ monitoring system.
4. PQ Heat Maps: This allows a user to get a geographical and visual summary of PQ health within the network.
5. PQ Events Browser: This allows a user to find PQ events that have been reported by PQ monitors, such as interruptions, and view the data associated with those events including voltage and current waveforms.
6. PQ Assessment: A tool to perform ER G5/5 harmonic connection assessments using data gathered from PQ monitors.

Through the course of the project, two additional reporting features were added into the scope of the software:

1. An EN 50160 report, and
2. An ER G5/5 background data report.

The PQ analysis software formed part of Nortech's iHost monitoring and control platform. A project-specific iHost server was set up and made operational.

Detailed functional specifications were developed for all the defined features and they were developed and deployed to the project's iHost server.

The PQ Data Ingest and PQ Trends features allowed data from the PQ monitors already installed as part of the project to be displayed and interrogated. The data ingest was verified by comparing data from examples of each monitor, which were installed to monitor the same circuit at Netherhills Primary. Figure 5-25 is an example of a PQ Trend showing voltage harmonics for a single phase: at the top is a time-series plot of the 2nd-50th harmonic orders over a week, whilst below that is a bar-chart summarising the 95th percentile values of the same harmonic data.

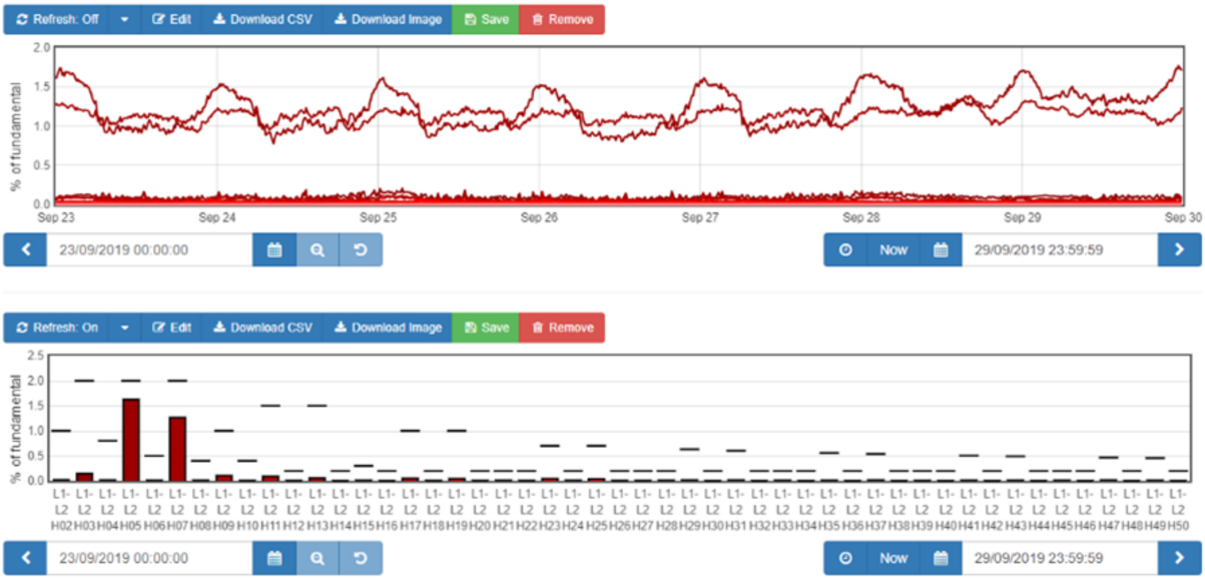

Figure 5-25: Example PQ Trend showing a week of harmonic data as time-series and bar plots

Figure 5-26 is an example of the PQ Dashboard. The top two rows summarise the state of monitored PQ in the power system over different time ranges (previous day, previous 7 days, and previous 30 days), and the bottom two rows summarise the state of the PQ monitoring system.

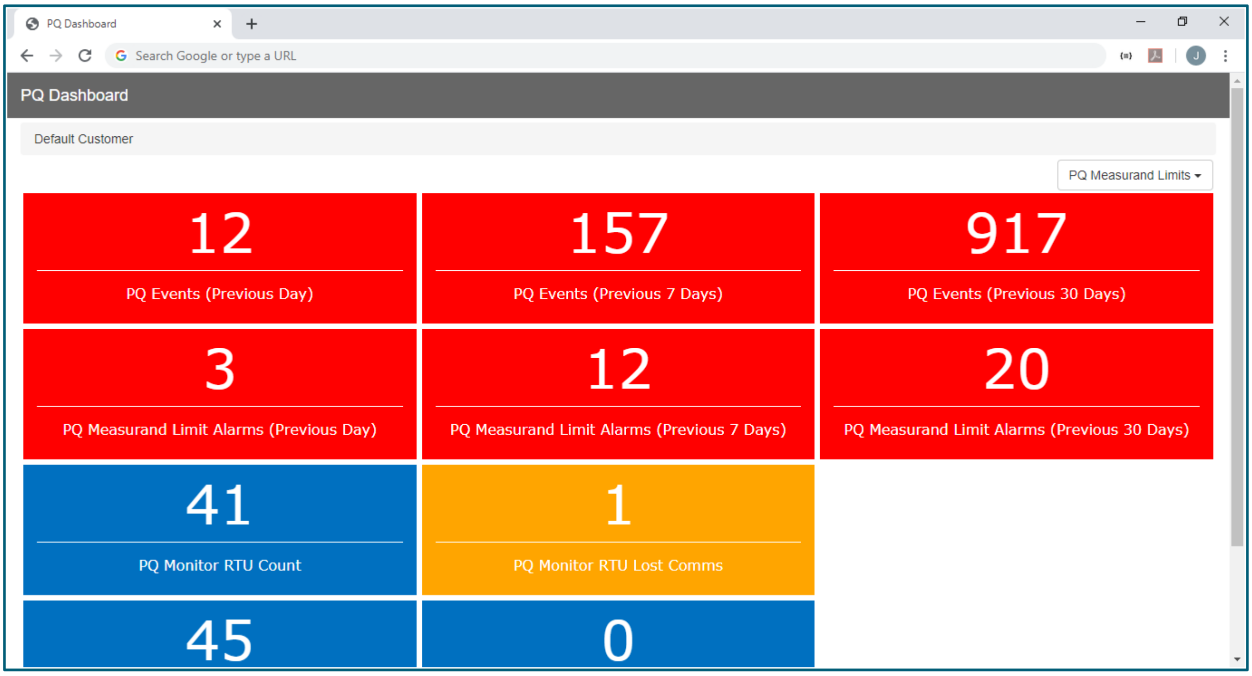

Figure 5-26: Example of the PQ Dashboard

Figure 5-27 is an example of a PQ Heat Map, showing the variation of 5th harmonic voltages across the trial sites for a set time period (in this case, the previous 7 days). The colour of the marker for each site indicates the 95th percentile value of the 5th harmonic voltage at each site, from blue (low) to red (high).

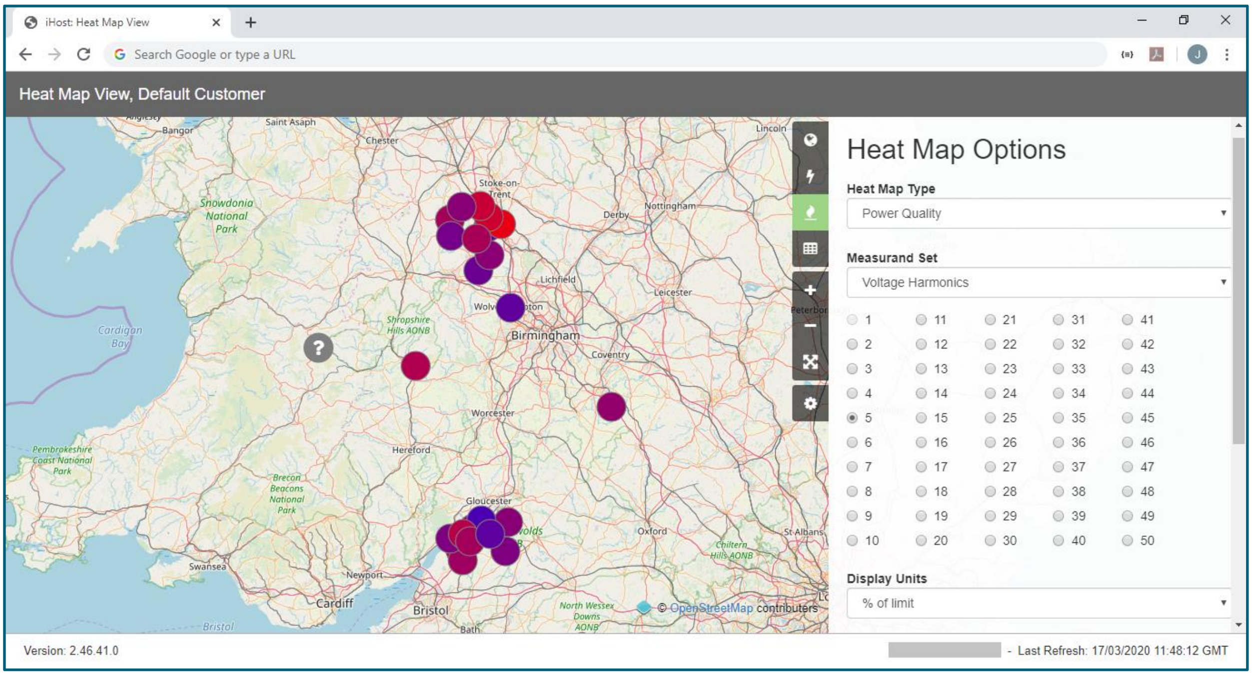

Figure 5-27: Example PQ Heat Map, showing variation in 5th harmonic voltages across the trial sites

The PQ Events Viewer includes an event recordings viewer and an events timeline browser. Figure 5-28 is an example of the event recordings viewer in use, displaying voltage and current waveform data.

Figure 5-28: Event Recordings Viewer displaying a voltage and current waveform data

The event timeline browser provides an alternative to a conventional event list for viewing the history of events across multiple monitoring locations. Figure 5-29 is an example view from the timeline browser, which is a matrix representing monitors (and groups of monitors) from top-to-bottom and time from left-to-right. Each cell in the matrix is the intersection of a monitor (or group) and a particular time span; if there are events for that monitor and time span, then the cell is coloured accordingly. For instance, in the Figure, the time span from 15:00 to 18:00 on the 8th September is selected for the Market Drayton PQ monitor. Selecting that cell will bring up a list of events and event recordings that match that location and time, such as what is shown in Figure 5-30.

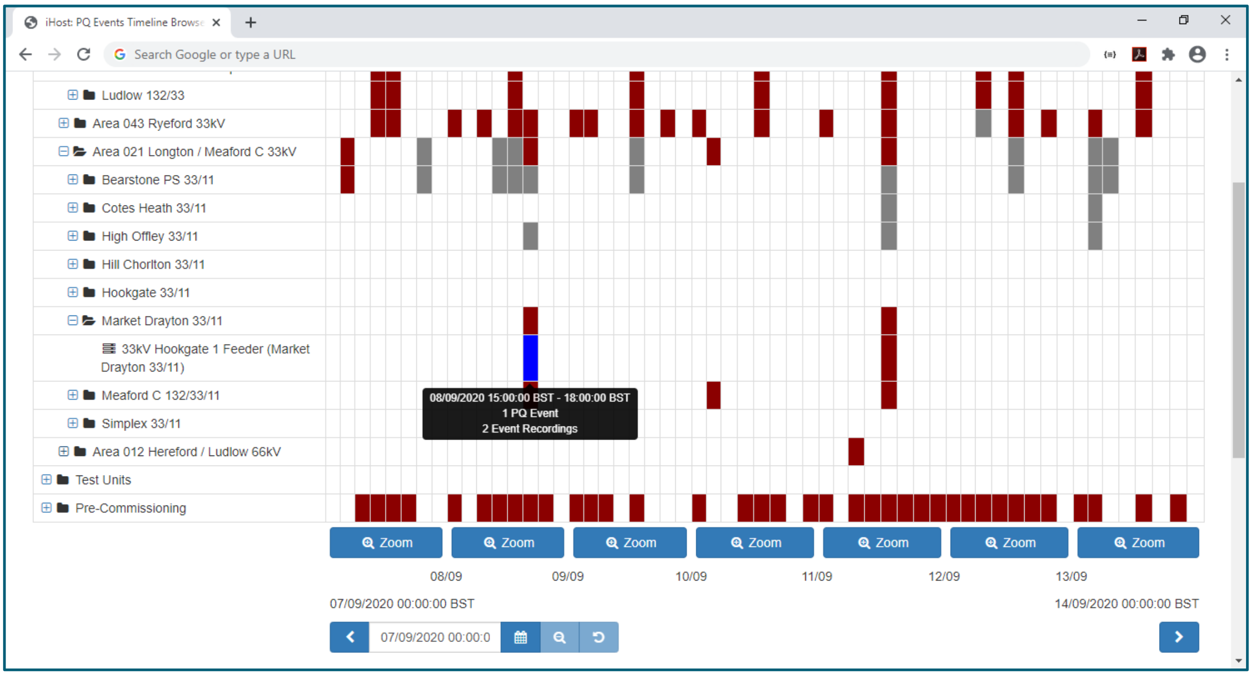

Figure 5-29: Event Timeline Browser view of events recorded during the week commencing 7th September 2020

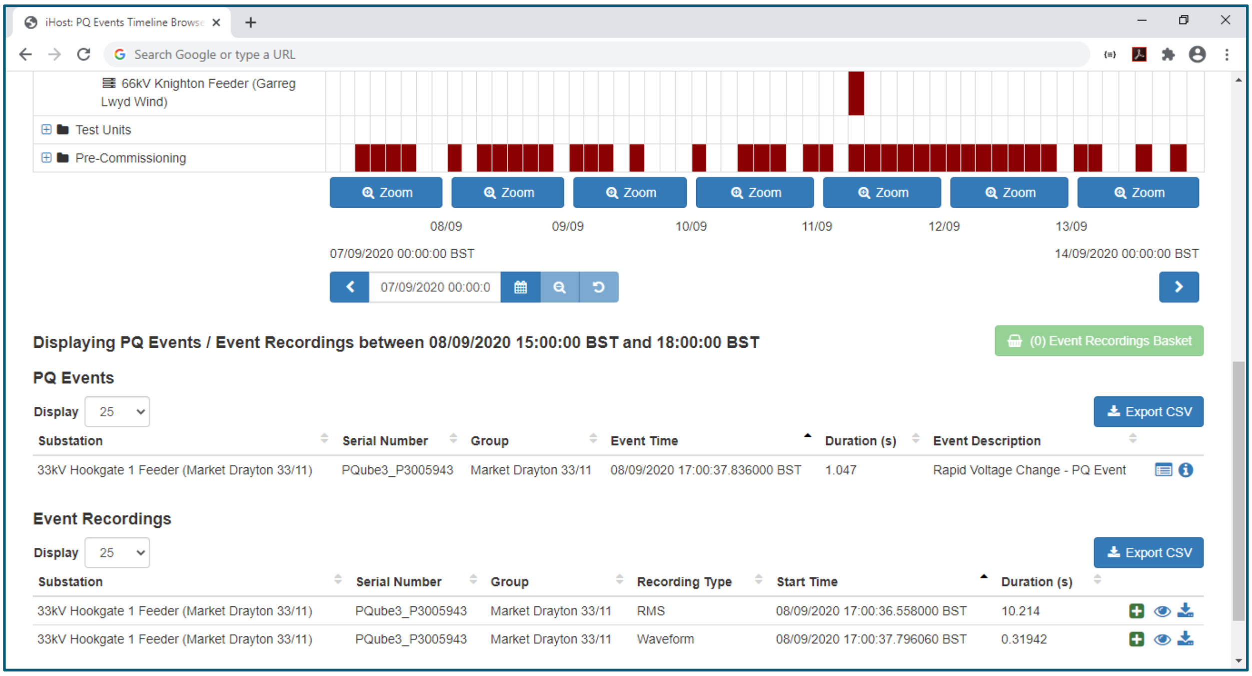

Figure 5-30: Events and event recordings list within the event timeline browser for a selected monitor and time span

The PQ Assessment Tool allows a user to perform an ER G5/5 Stage 2C power quality assessment within the iHost software environment, without using external tools, which is an important stage in evaluating some customer connection requests. A user can customise a run of the PQ Assessment Tool within iHost (an example of this is shown in Figure 5-31), and then generate a report in Microsoft Excel workbook (*.xlsx) and Adobe Acrobat document (*.pdf) formats (an example of a PDF report is shown in Figure 5-32).

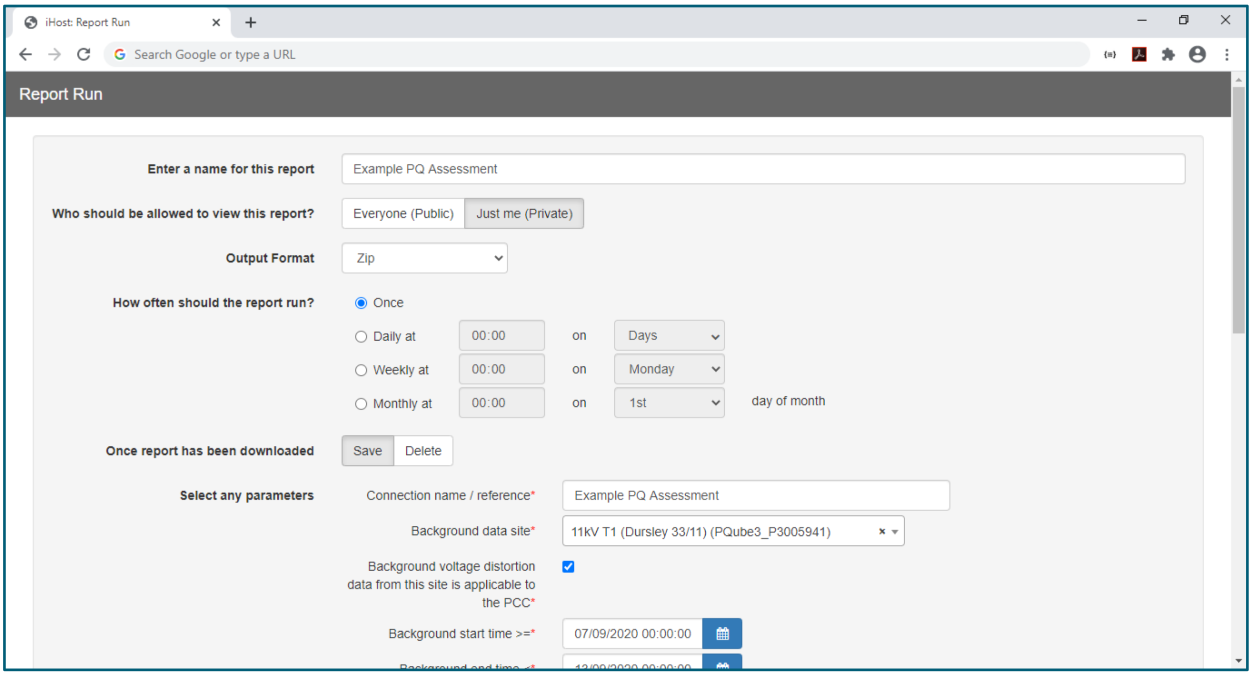

Figure 5-31: PQ Assessment Tool set up page

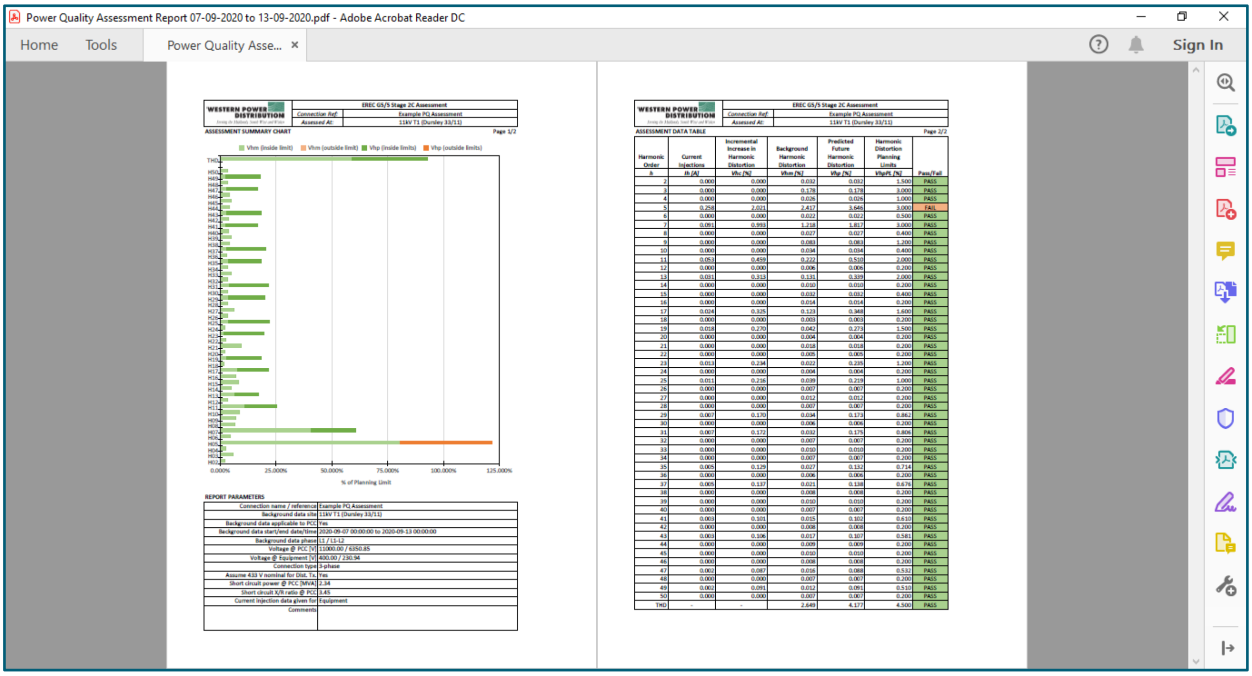

Figure 5-32: Example PDF report generated by the PQ Assessment Tool

The PQ analysis automation software features developed were trialled on an ad hoc basis by WPD and Nortech staff, and based on the feedback from this testing some of the existing software features were enhanced:

- PQ Data Ingest and PQ Trends were updated to support minimum and maximum measurements for selected measurands such as RMS voltage and current. This is useful, for example, when analysing the data to find short duration current spikes and voltage dips indicative of fault activity, such as the plot of RMS current shown in Figure 5-33.
- PQ Heat Maps was updated with revised colour gradients and an optional legend to make the display more understandable. An example of the updated PQ Heat Maps display is shown in Figure 5-34, which is a heat map of voltage THD (Total Harmonic Distortion) in the Ryeford trial area.

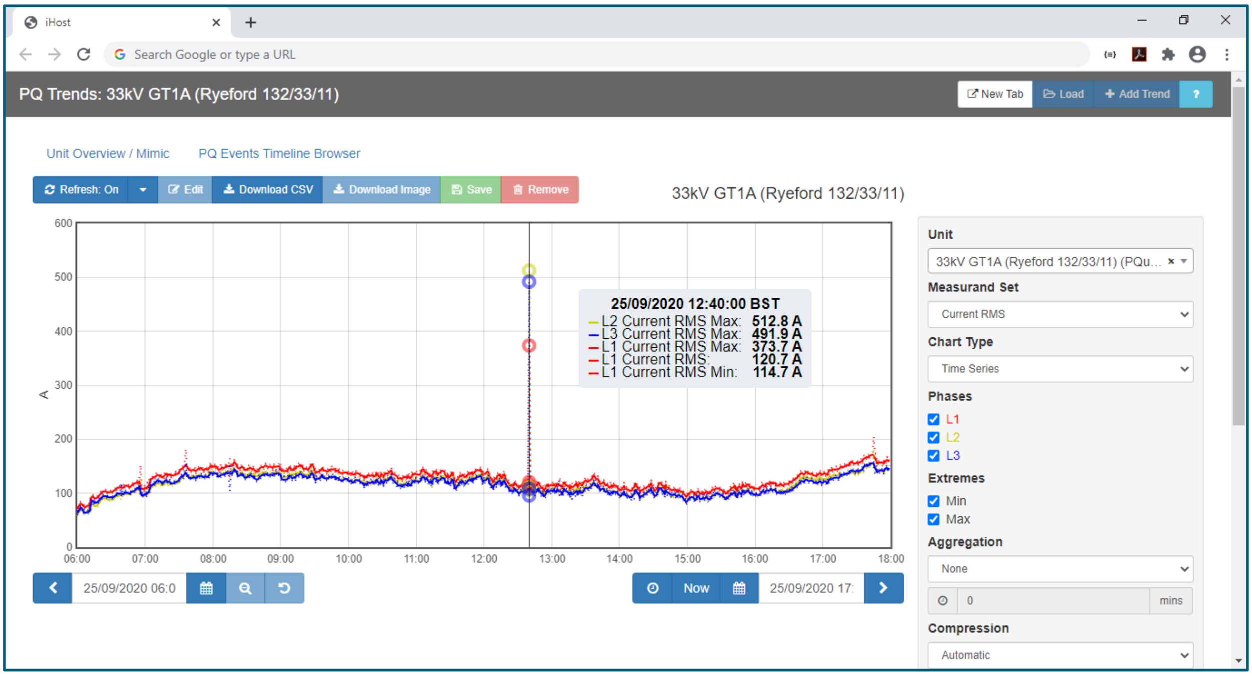

Figure 5-33: Updated PQ Trends with min and max data displayed for RMS current, including a current spike likely due to fault activity

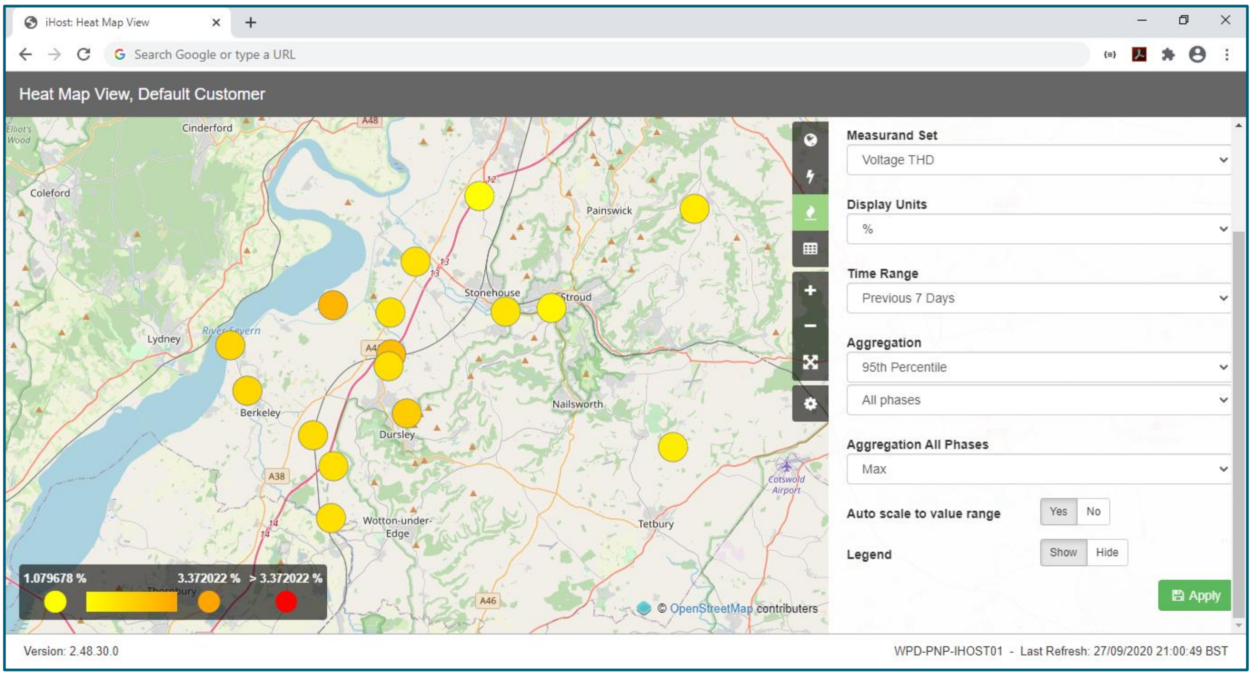

Figure 5-34: PQ Heat Map of voltage THD including updated colour gradients and legend

5.2.4. Modelling & Studies

This project activity was concerned with future-looking power quality studies to assess the potential future impacts of LCTs on Primary Networks. The studies were performed on models representing the two main trial areas for the project, and considered locational, temporal, technological, and scale effects of increased LCT penetrations on PQ up to the year 2030

A scoping exercise was completed to define the modelling and study requirements and aims. Following this, a review of available power system analysis tools concluded with the recommendation that DIgSILENT PowerFactory should be used as the power system analysis tool for the project, as it could provide the modelling sophistication and flexibility needed.

Project-specific power system models have been constructed in DIgSILENT PowerFactory to represent the two main trial areas. The models are focused on the Primary networks (33 kV) but also include upstream 132 kV and busbars representing the interface points with the transmission system and with the 11 kV distribution system. The models were constructed by replicating network schematics within PowerFactory, for example Figure 5-35 is an example of a substation schematic built in PowerFactory, in this case the 33 kV and 11 kV busbars at Meaford C BSP. Line parameters were set in the model by interrogating GIS (geographic information system) data for network assets, which yielded per-section data including conductor type and section length. This data was validated against existing network models in IPSA, that were not specific to PQ studies.

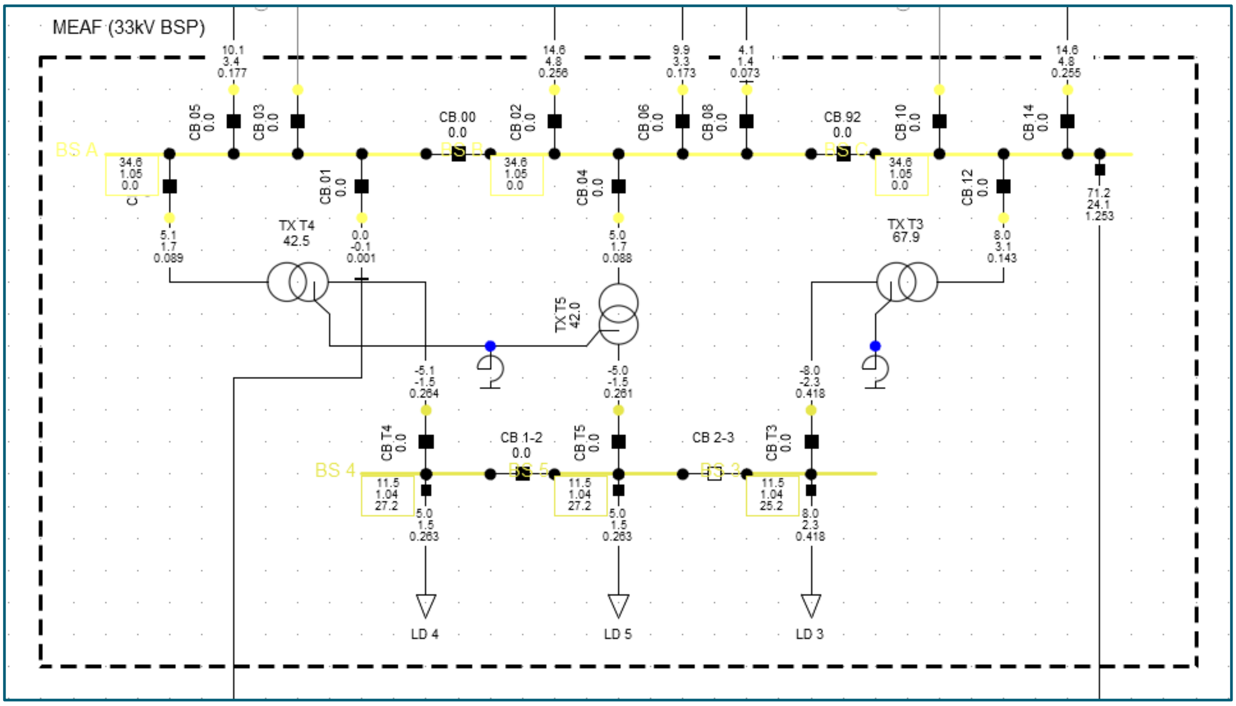

Figure 5-35: A section of the power system model for the Meaford C trial area, showing Meaford C BSP 33 kV elements

Data for LCT harmonic current injections have been obtained from publicly available sources such as the ENA type register, conference publications, and the monitoring data gathered from LCTs as part of the project's trials.

The amount of each LCT type to apply within the models was estimated for the years 2025 and 2030 under four energy scenarios defined in our Distribution Future Energy Scenarios (DFES), which are in turn derived from National Grid's Future Energy Scenarios (FES).

Rather than studying a single snapshot in time (such as a single maximum demand snapshot, and a single maximum generation snapshot), the PNPQA studies have used a time-based approach where four representative days – winter maximum demand, summer maximum demand, summer maximum generation, and intermediate warm peak demand – are studied for each scenario and year, with each day having power profiles for each load and generator at a half-hour time resolution. This is the same approach used in WPD's Shaping Sub-transmission strategic network planning studies.

As Figure 5-36 and Figure 5-37 show for the Meaford C and Ryeford 33 kV network models respectively, the results of the studies indicate that by 2030 there is the potential for some voltage harmonics to rise above the planning levels (according to ER G5/5). A mix of coincident EV and heat pump demand in the LV network is behind most of the rise in voltage harmonics, as well as solar PV to some extent.

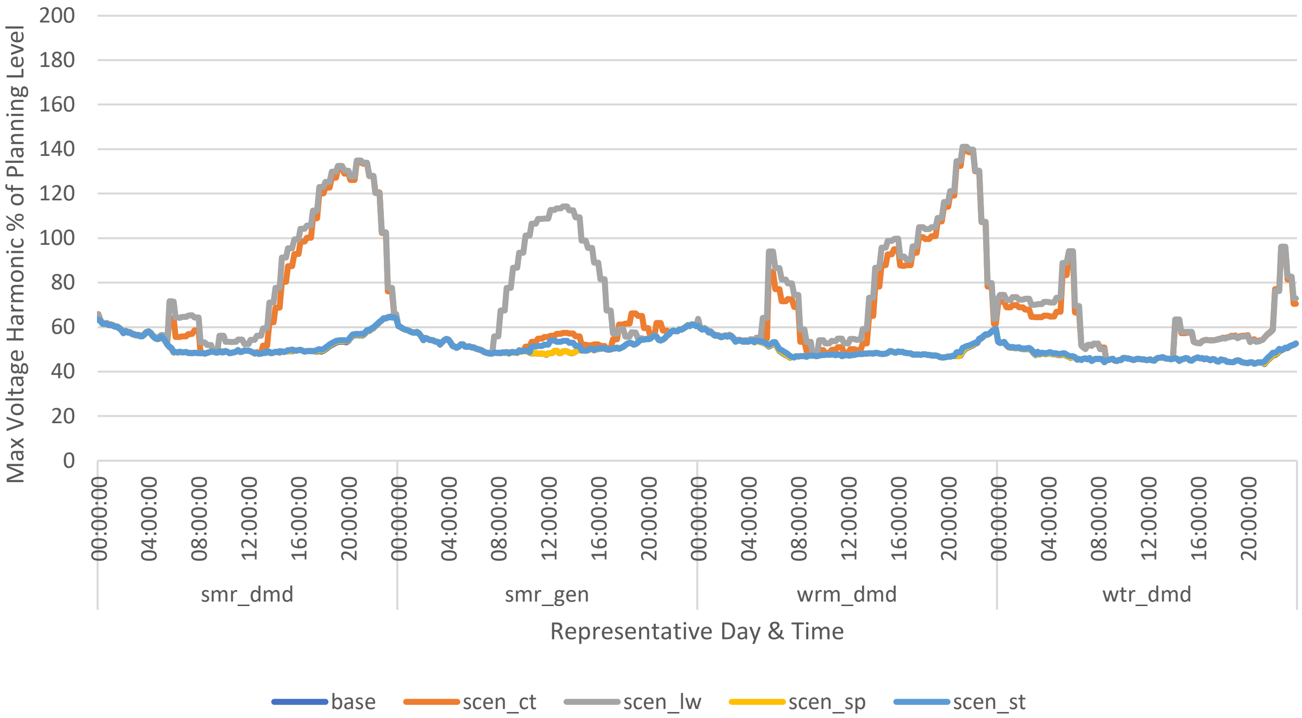

Figure 5-36: Estimated maximum harmonic voltages for the 2030 scenarios in the Meaford C 33 kV network

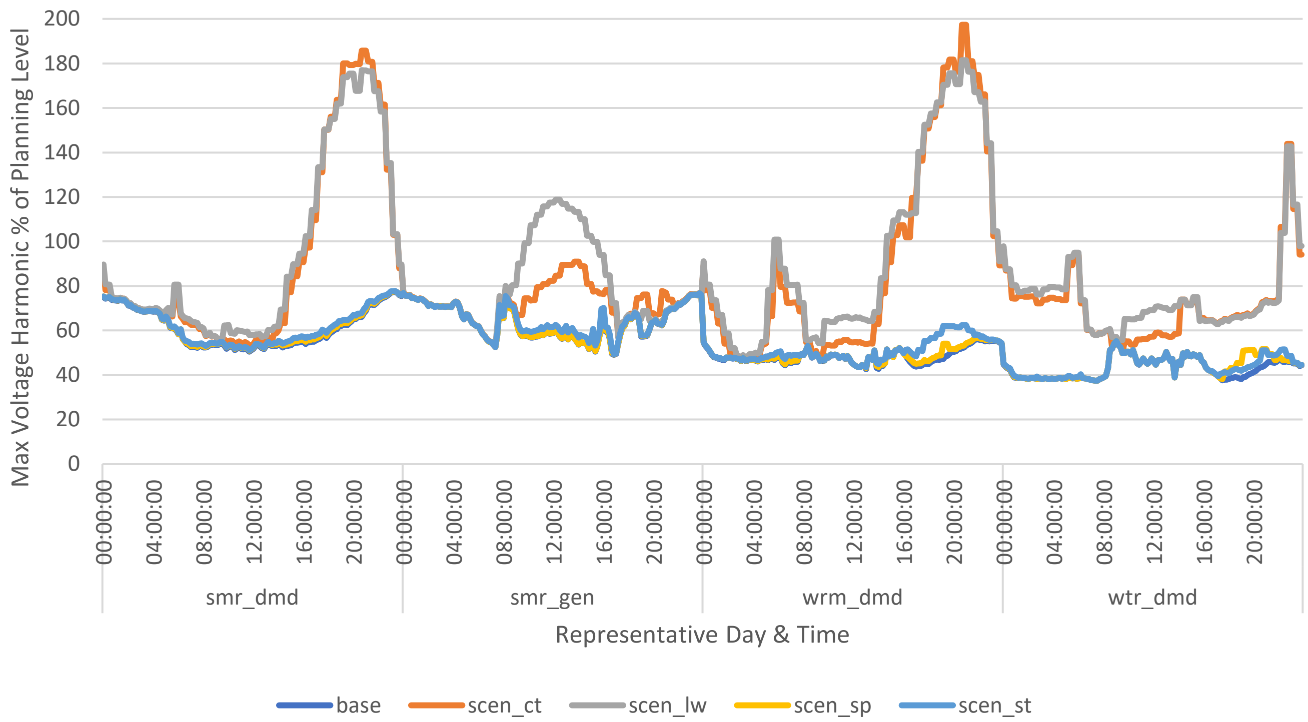

Figure 5-37: Estimated maximum harmonic voltages for the 2030 scenarios in the Ryeford 33 kV network

As well as potential future PQ issues that potentially need mitigation, the study has identified that there is still uncertainty about the PQ impact of LV connected LCTs – which will be increasing substantially – on the local LV network but especially on upstream primary networks. This uncertainty includes the variation in harmonic current transfer as a function of the fundamental current, the nature of aggregation of multiple LCTs in the LV network, and the transfer of the aggregated harmonics in to the 11 kV network and above.

5.3. Work Package 3 - Trial

5.3.1. PQ Monitor Trial

This activity was concerned primarily with purchasing and building hardware, and the physical installation of PQ monitoring equipment in the trial sites.

The PQ monitors were ordered and delivered, and the communications hardware assembled. Nortech designed enclosures for two of the different monitors that converted the units from being DIN-rail mounted and requiring wiring on site to portable units with pluggable connectors, for ease of installation. Figure 5-38 is a photo of a PQ monitor enclosure alongside a Nortech Envoy communications hub.

Figure 5-38: Envoy communications hub and prototype PQ monitor enclosure

Detailed analysis of site surveys and WPD substation information allowed installation locations for the PQ monitors in the trial areas to be determined. This followed on from the trial area and site selection activity and included an additional level of detail such as proposed VT and current transformer (CT) connection points and the positioning of monitors.

Four different installation types were identified and outline schematics for these were produced. Of these, two were chosen for use in the project. The first type were the “plug & play” installations where non-fixed monitors were temporarily connected to VT secondary circuits using test leads and, optionally, currents were monitored via clip-on sensors around CT secondary circuit wiring. The majority of the PQ monitor installations within the project were the “plug & play” type – totalling 39 monitors across 32 sites. There were seven sites where a “plug & play” type installation was not possible due to the switchgear used, and at these sites a fixed “PQ panel” was installed, which consisted of a wallbox containing 1 or 2 monitors and fixed wiring to tap in to VT and CT secondary circuits.

Discussions with WPD’s Engineering Design and Projects teams took place for them to perform the PQ monitor installations and enabling works where required, such as detailed design work, wiring in existing VTs, making modifications to existing VT and CT wiring on site, or installing a PQ monitoring panel.

Figure 5-39 is an annotated example of plug & play installation at Meaford C.

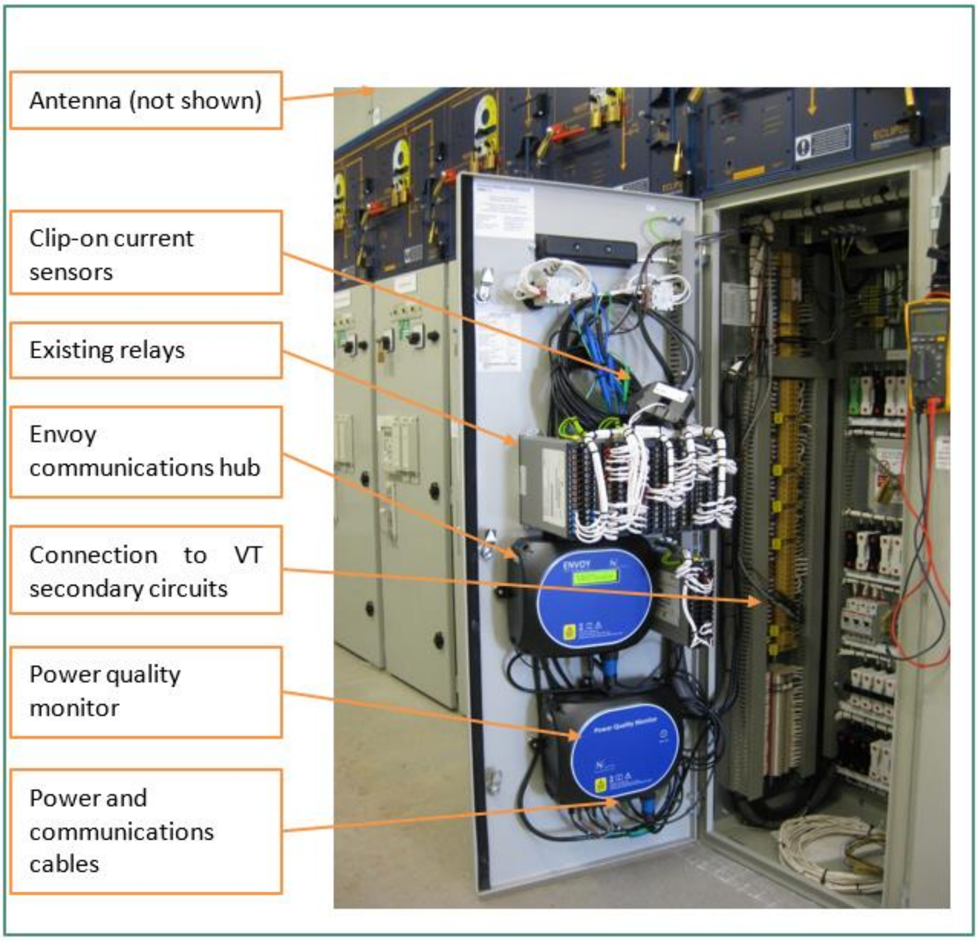

Figure 5-39: Example plug & play PQ monitor installation

In addition to plug & play installations at 33 kV, some were installed at 11 kV, such as the installation shown in Figure 5-40.

Figure 5-40: Plug & play PQ monitor installation at an 11 kV distribution substation

Installations of PQ monitors in the two trial areas were initially planned to complete in the first half of 2019; however, the installations were delayed to later in 2019 due to two main factors. The first factor leading to a delay was the timescales associated with identifying, assigning, and then awaiting installation resources to become available for both types of installations.

The second factor leading to a delay in installing PQ monitors for the main trial was the engineering design and equipment manufacturing times associated with the PQ panels. Designs for the panels were prepared, including general arrangement drawings (an example of this is shown in Figure 5-41), wiring diagrams, and site-specific interface drawings.

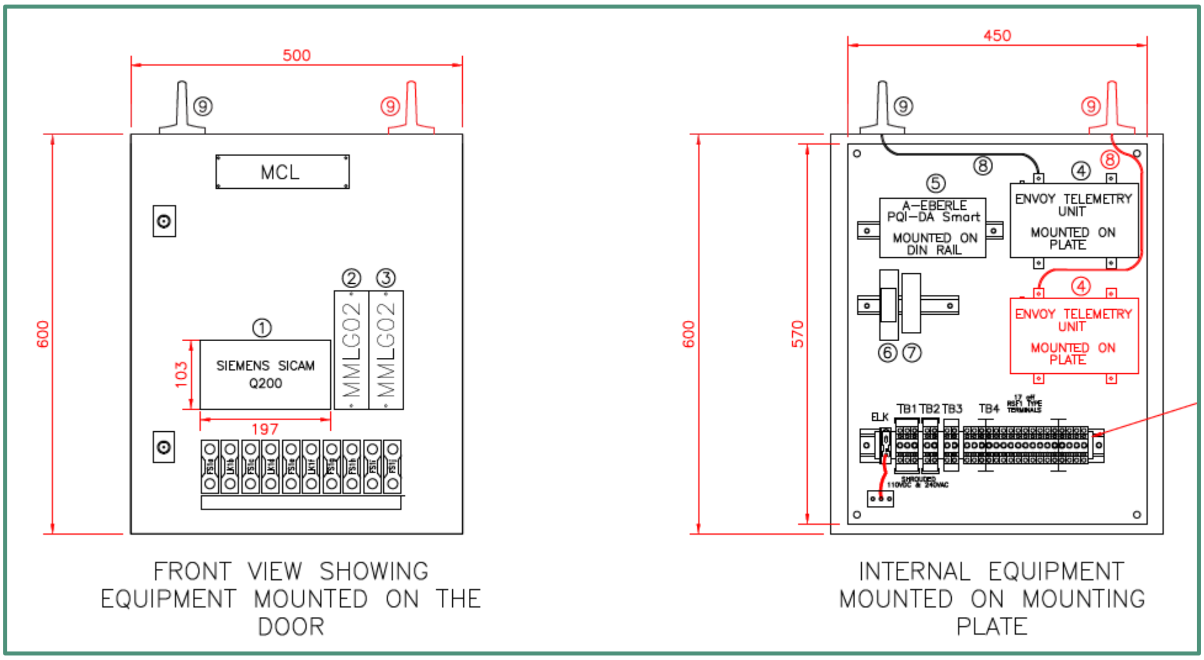

Figure 5-41: Example general arrangement drawing for PQ panel

Figure 5-42 shows an example of an installed PQ panel (in particular, the panel at Hookgate primary in the Meaford C trial area) and the interposing CTs that sit between existing CT secondary circuits and the CT secondary circuits running to the PQ panels.

(a) PQ panel with PQ monitor (b) Interposing CTs

Figure 5-42: Example PQ panel and interposing CTs

Table 5-3 is a summary of the installations of the PQ monitors for the project across the different trial areas and sites, and voltage levels.

Table 5-3: Summary of PQ monitor installations

Area / Site(s)	Plug & Play Monitors Installed / Total	PQ Panel Monitors Installed / Total
Ryeford area (high LCT) BSP & Primaries (33 kV)	15 / 15	5 / 5
Ryeford area (high LCT) Distribution substations (11 kV)	3 / 3	-
Meaford C area (low LCT) BSP & Primaries (33 kV)	7 / 7	2 / 2
Meaford C area (low LCT) Distribution substations (11 kV)	9 / 9	-
Energy storage	3 / 3	-
Wind farm	1 / 1	-
EV rapid charger	1 / 1	-
SUB-TOTALS	**39 / 39**	**7 / 7**

5.4. Work Package 4 – Report

5.4.1. PQ Monitor Trial Data Analysis

This activity was concerned with analysing the PQ data collected by the monitors installed for the trial.

A scoping document was prepared to formulate questions to frame the analysis and to outline the methods that were to be used to answer them. Four questions were formulated, based on the project's registration document:

1. What PQ impacts are LCTs having on networks?
2. Are week-long snapshots sufficient to capture representative PQ data?
3. Do multiple monitors in a network area deliver useful extra visibility?
4. How do the different PQ monitors compare?

The data analysis work was performed on data extracted from the online iHost monitoring database and storing the data in offline archives, in order to speed up the analysis by removing the need for repeated large data requests over the internet. The project used the Hierarchical Data Format (HDF) for the offline data archives. HDF is typically used for transferring large scientific datasets and offers a number of benefits over other file formats that are often used such as CSV (Comma-Separated Values) band JSON (JavaScript Object Notation). One major benefit is that numeric data is stored directly as numeric data, rather than being encoded as text, which significantly reduces the storage space requirements. Another key benefit is the hierarchical structure of a HDF file allows multiple datasets to be stored in the same file and retrieved separately, rather than requiring the whole file to be read into memory, reducing access time and memory requirements.

Python scripts were developed to automate the processing of data from the HDF data archives, calculate various statistics, and produce charts of the data for inclusion in the data analysis report.

The analysis of the data allowed the four questions to be answered, and summaries of the analysis answering each question are provided below. The full report containing the data analysis has been appended to this report.

5.4.2. Question 1: What PQ impacts are LCTs having on networks?

In summary, the data gathered through the project provides a mixed picture with respect to the impact of the LCTs that were monitored. Some LCTs are producing harmonic currents that are significantly affecting voltage distortion within distribution networks, sometimes eroding 50% or more of the planning level margin for particular harmonic orders. The data suggests flicker and voltage unbalance was more sensitive to non-LCT factors. . The analysis of the data also highlighted the non-linear relationship between device power output and current harmonics, and therefore voltage harmonics; for instance, it was observed that sometimes LCTs would have the largest impact at a partial power output level, rather than maximum output.

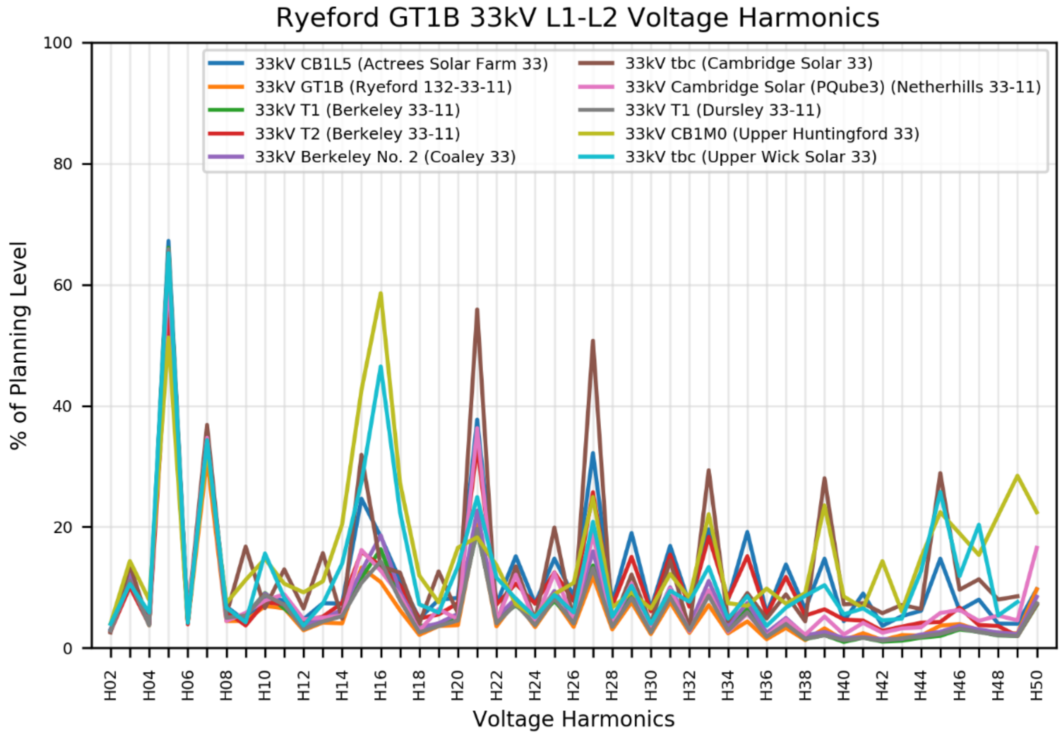

Figure 5-43: Overall voltage harmonic aggregates (95th percentile values) for Ryeford 33 kV GT1B group sites

The most striking difference between areas with and without LCTs was for voltage harmonics. In the Ryeford network area (on the side fed by GT1B), which has four 33 kV solar PV sites, there were substantial variations in the voltage harmonic magnitudes for several harmonic orders across the network area. This can be seen in Figure 5-43, which is a plot of the 95th percentile aggregate values of voltage harmonics for the sites in that area, derived from analysing all the available monitoring data from the trial. As can be seen in the figure, the aggregate values for each of the 15th, 16th, 21st and 27th harmonic orders vary significantly across the network area, and the higher magnitudes are associated with the solar PV sites. For instance, Upper Huntingford (solar PV) is strongly associated with the 16th harmonic order, with an overall 95th percentile aggregate value of 58.57% of the ER G5/5 planning level, whilst at the BSP this harmonic only has a value of 10.89%. Another solar PV site in the area, Cambridge Solar, is associated with triplen harmonics, particularly the 21st and 27th (this has an overall aggregate of 50.74% at the solar site versus 11.84% at the BSP).

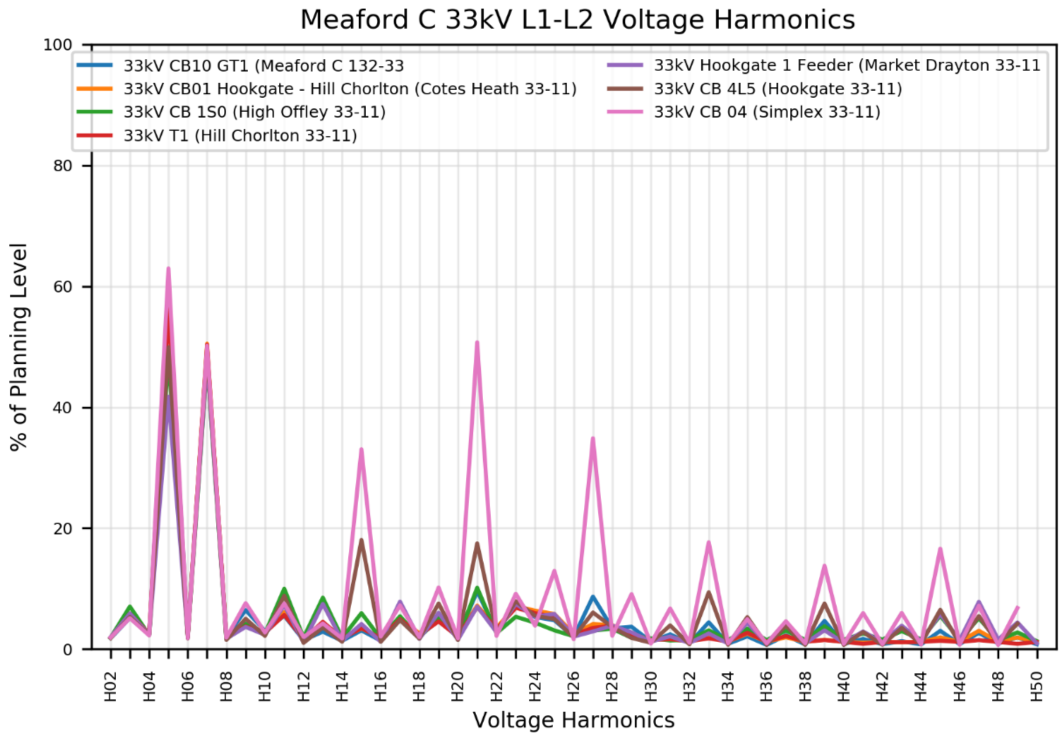

Figure 5-44: Overall voltage harmonic aggregates for Meaford C 33 kV sites

Conversely, in the Meaford C network area, which has no 33 kV LCTs, the aggregate values of the voltage harmonics generally did not vary much across the network area. This can be seen in Figure 5-44, where the variation between the sites is typically <10% of the planning level for each voltage harmonic order (note the triplen harmonics at Hookgate and Simplex may be spuriously high due to VT wiring arrangements). The 5th and 7th voltage harmonics had large magnitudes in the Meaford C and Ryeford areas, and the presence of LCTs did not have much of an effect on the aggregate values of these harmonics.

There was no strong evidence in the trial data that the LCTs monitored during the project had a substantial effect on voltage unbalance or flicker. Some of highest levels of voltage unbalance were seen in the Meaford C 33 kV network area, which has no 33 kV LCTs. Flicker often had high levels in the Ryeford 33 kV network area, but this was due to a disturbing load coupled through the transmission network rather than being due to the 33 kV LCTs in that area.

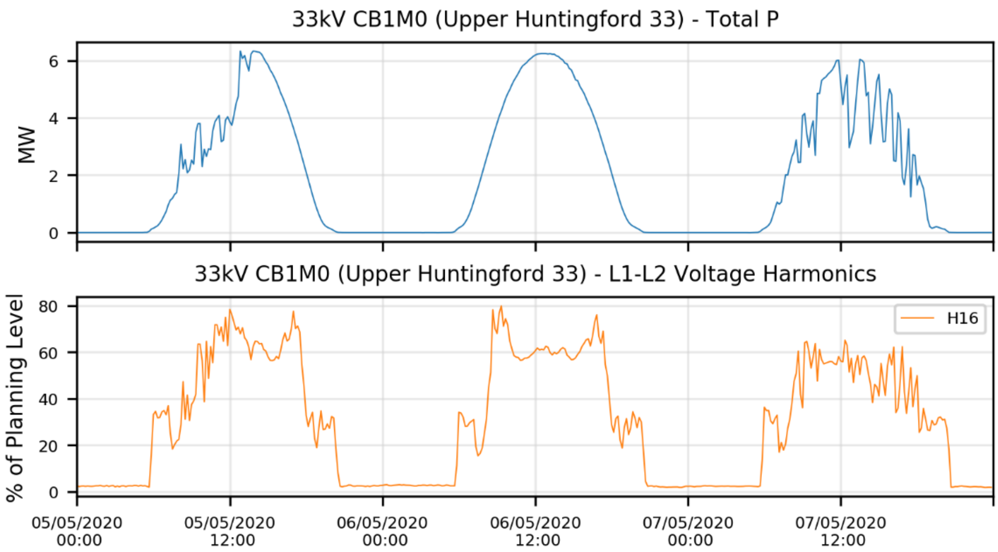

Figure 5-45: Time series plot of power and voltage harmonic H16 at Upper Huntingford solar for three sunny days in May 2020

Time-series analysis of the monitoring data showed the timing of changes of certain voltage harmonics corresponded with the output behaviour of LCTs, reinforcing the findings that high magnitudes of certain voltage harmonics are associated with LCTs. For instance, the 16th voltage harmonic at Upper Huntingford solar was clearly a function of the power output of that site, as can be seen in Figure 5-45. However, as the figure shows under closer examination, the relationship between LCT power output (or draw) and the effect on voltage harmonics might not be straightforwardly linear; for instance, as shown in the figure the peak harmonic voltage may not correspond to peak power at one site.

The often non-linear relationship between fundamental current, harmonic currents, and harmonic voltages was examined further through correlation analysis, using both 10 minute averaged measurements and phasors derived from snapshot waveform captures. For some harmonic orders such as the 5th and 7th, the harmonic currents were strongly correlated with the fundamental currents of the LCTs. Figure 5-46 is an example of this, and is a scatter plot of all the available 10 minute average values for fundamental current and the 7th harmonic current at Upper Wick Solar. As can be seen in the figure, when the fundamental current has higher values, so does the harmonic current. The two measurands are strongly correlated (indicated by the R value approaching 1.0) although the relationship is non-linear. Interestingly, the 7th harmonic current has almost no correlation with the 7th harmonic voltage at this site, as can be seen in the scatter plot of those two measurands shown as Figure 5-47.

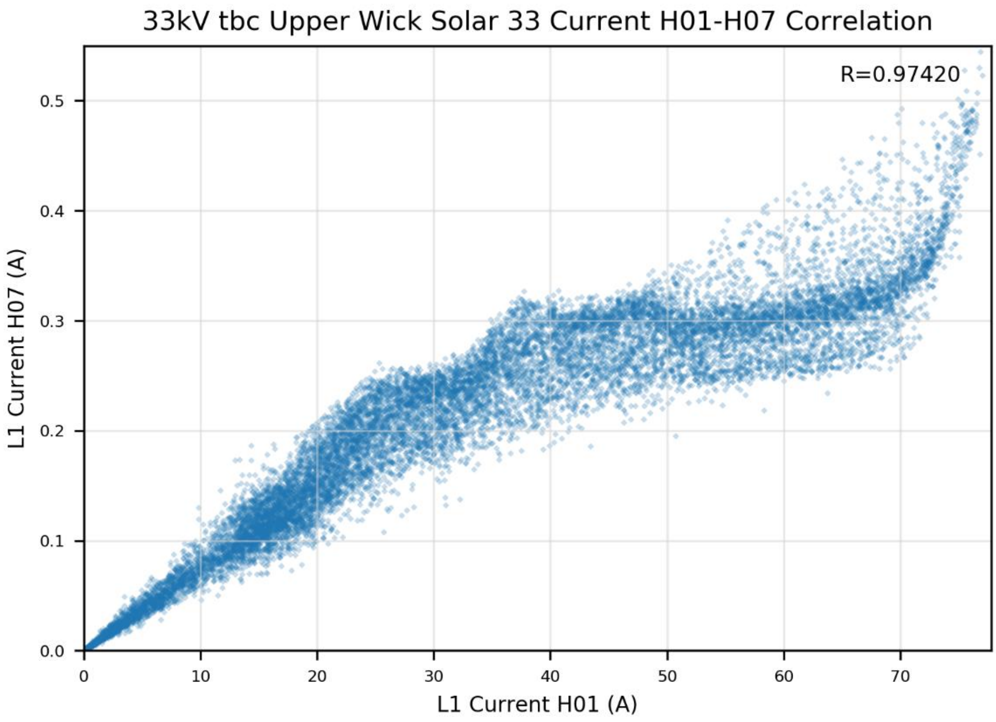

Figure 5-46: Scatter plot of fundamental current (H01) vs. harmonic current H07 for Upper Wick Solar

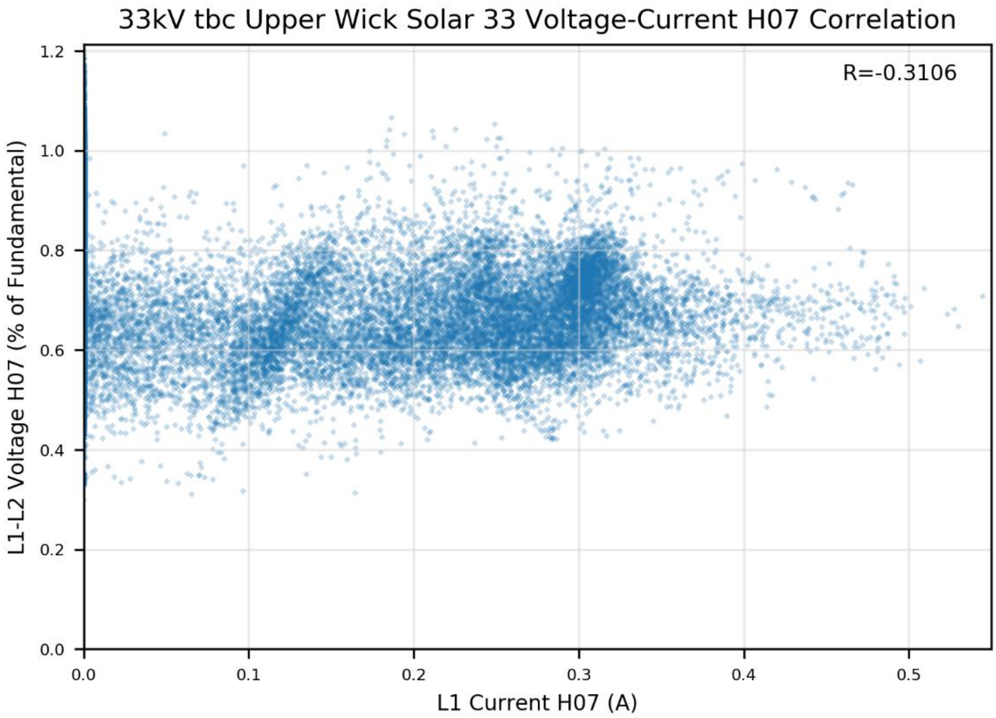

Figure 5-47: Scatter plot of harmonic current H07 vs. harmonic voltage H07 for Upper Wick Solar

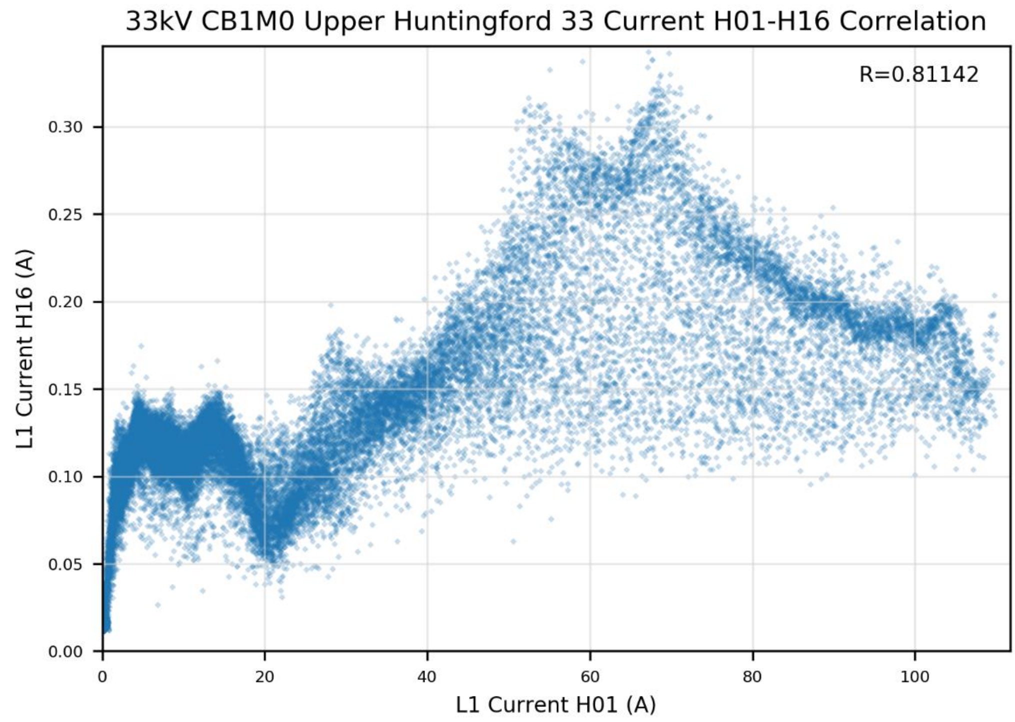

Figure 5-48: Scatter plot of fundamental current (H01) vs. harmonic current H16 for Upper Huntingford solar

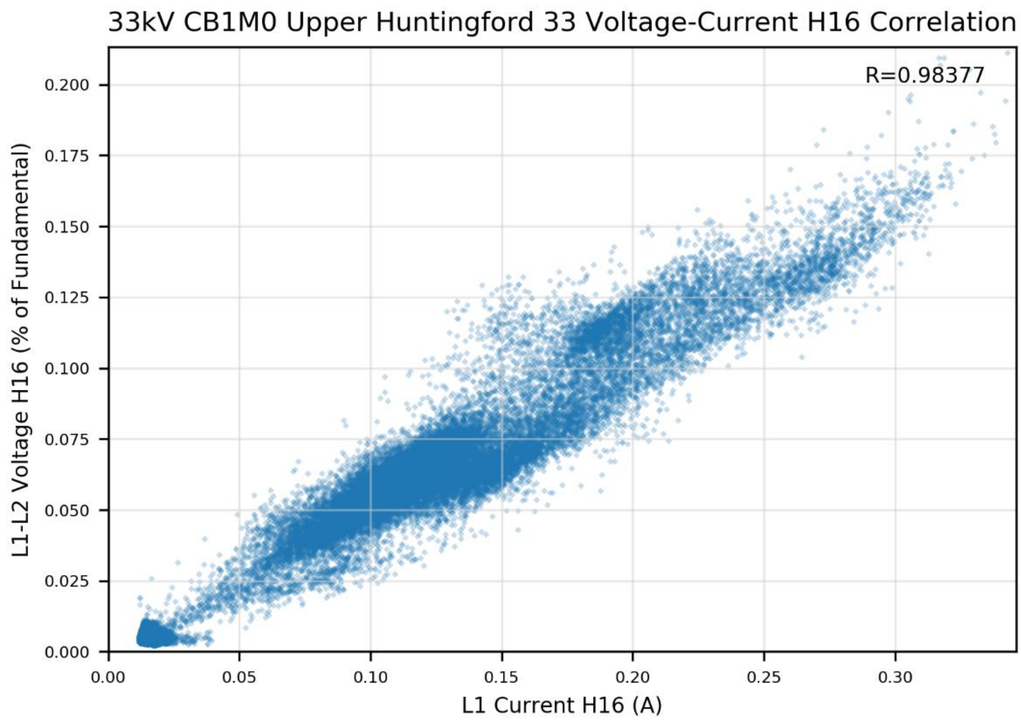

Figure 5-49: Scatter plot of harmonic current H16 vs. harmonic voltage H16 for Upper Huntingford solar

For other harmonic orders, the harmonic currents were a function of the fundamental, but with non-linear and sometimes non-monotonic characteristics. Figure 5-48 is an example of this for the fundamental and 16th harmonic currents at Upper Huntingford solar, and has the peak harmonic currents being at partial power levels, and reducing as the power level steps up. Many harmonic orders showed very little correlation between the LCT fundamental and harmonic currents, likely due to the harmonic currents being strongly influenced by existing harmonic distortion. The harmonic currents and voltages were often well correlated, such as can be seen in Figure 5-49 for the 16th harmonic currents and voltages at Upper Huntingford solar.

The harmonic voltage and current correlation and phasor analysis showed that LCTs are clearly having an effect at particular harmonic orders, but it is not necessarily always the case that the effect results in increased harmonic distortion. At some sites particular harmonic currents – the 3rd, 5th, and 7th at Upper Huntingford solar, for example – were observed to regularly lag the harmonic voltages, equivalent to the LCT acting as an inductive current sink and therefore acting to decrease harmonic distortion. There was also data that was consistent with some sites absorbing the harmonic currents produced by other sites.

The main conclusion from the correlation and phasor analysis was to highlight that the relationship between fundamental current, harmonic currents, and harmonic voltages is complex at the individual site level, and even more so when looking at those relationships within a group of sites. As more power-electronic based LCTs of different types are added to the network – such as at LV, where there could be hundreds or even thousands of devices within a single LV network – how the LCTs interact and aggregate will be important to understand for planning and operational purposes.

5.4.3. Question 2: Are single weeklong snapshots sufficient to capture representative PQ data?

In summary, the analysis of data gathered during the PNPQA project suggest that single week-long snapshots may be insufficient to capture PQ data that is representative of the prevailing PQ conditions in a network, as substantial variations in PQ measurements have been seen for different week-long periods during the monitoring period.

To answer this question, "sliding window" analysis was applied to each measurand of interest separately. This method takes a "window" in time (e.g. a week-long period) from within a longer time-series dataset and "slides" the window from the start to the end of the dataset. Each time the window is slid – typically by a fixed step such as 1 week at a time – the summary statistics (e.g. 95th percentile values) are calculated for the window's current position. Figure 5-50 is an example time-series plot of raw voltage THD data for Meaford C 33 kV BSP and weekly aggregates (95th percentile values of the values for the week the follows) calculated using sliding window analysis.

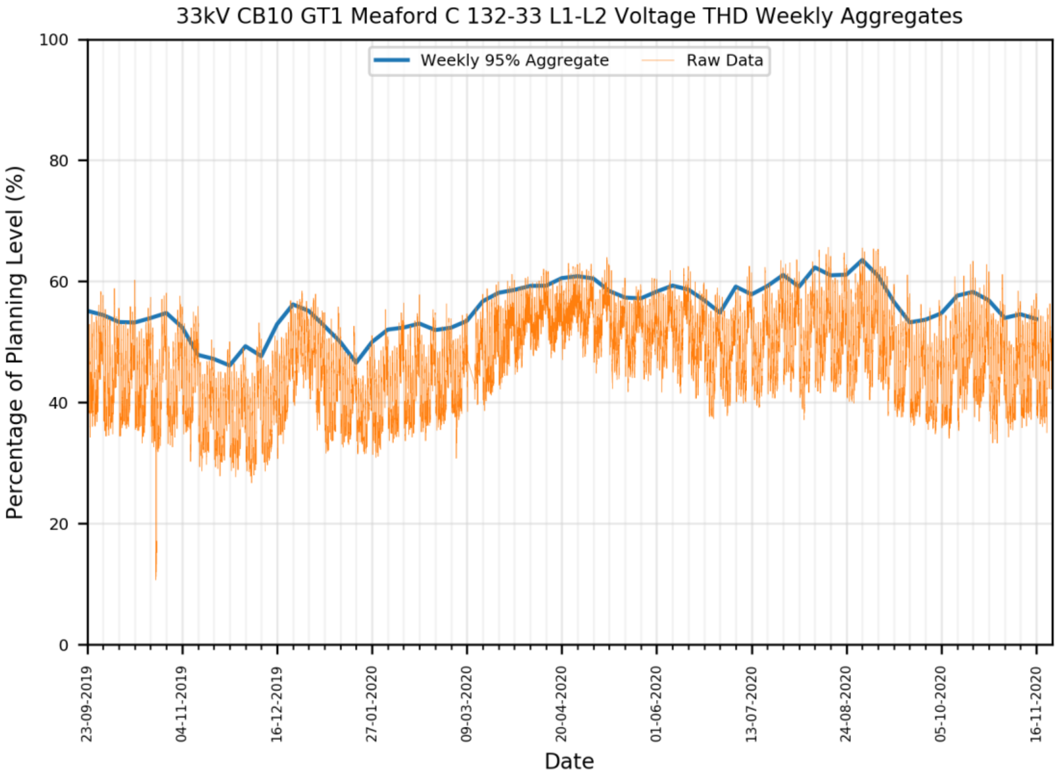

Figure 5-50: Time series plot of voltage THD (L1-L2) for Meaford C 33 kV BSP showing raw data (10 minute resolution) and weekly 95th percentile aggregates

The distribution of the values of the weekly aggregates can either be presented as a histogram (Figure 5-51 is an example using the same data as Figure 5-50) or as a box plot (Figure 5-52 is an annotated example using the same data).

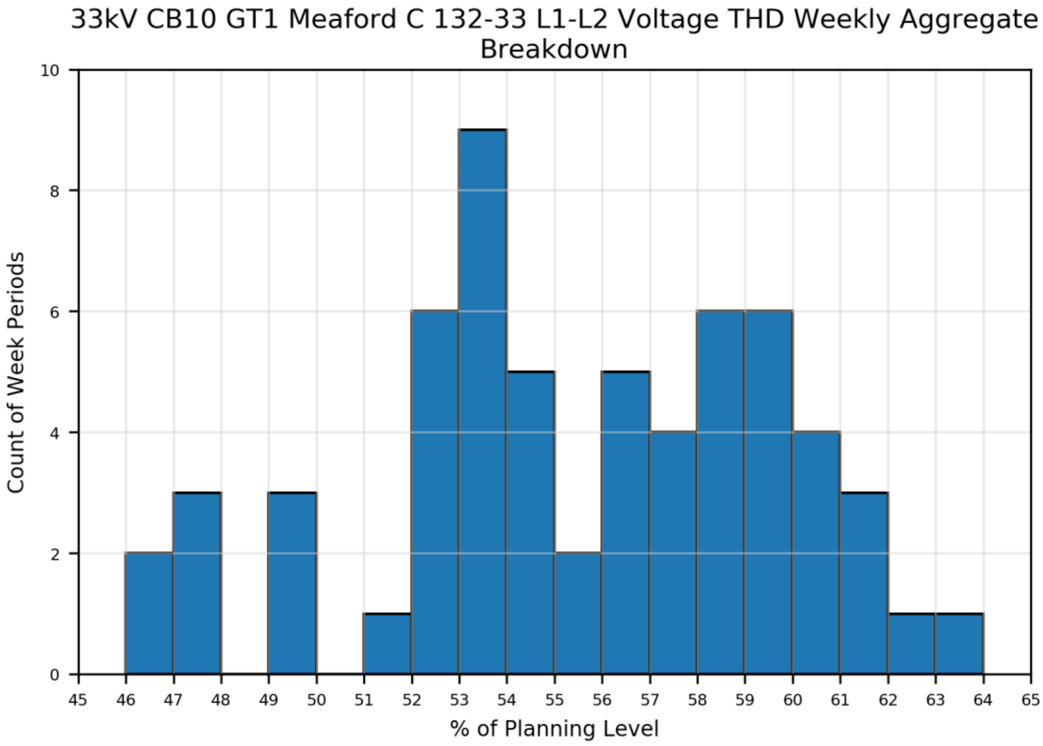

Figure 5-51: Histogram of weekly aggregate values for voltage THD (L1-L2) at Meaford C 33 kV BSP

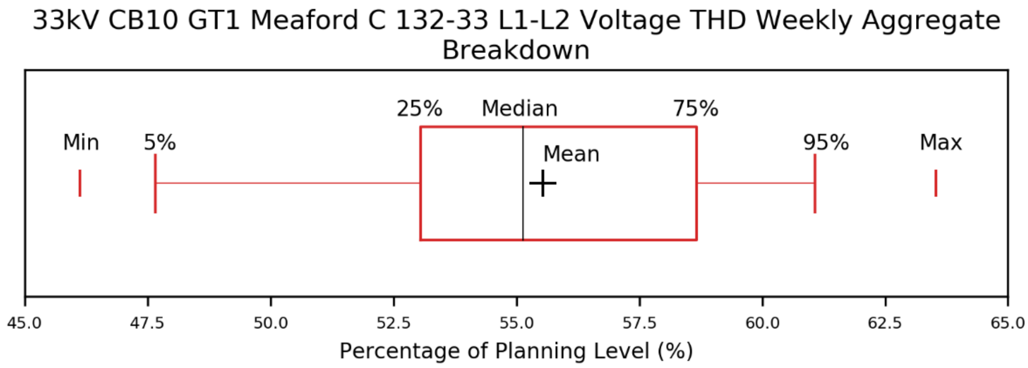

Figure 5-52: Annotated box plot showing distribution of weekly aggregate voltage THD values (L1-L2) at Meaford C 33 kV BSP

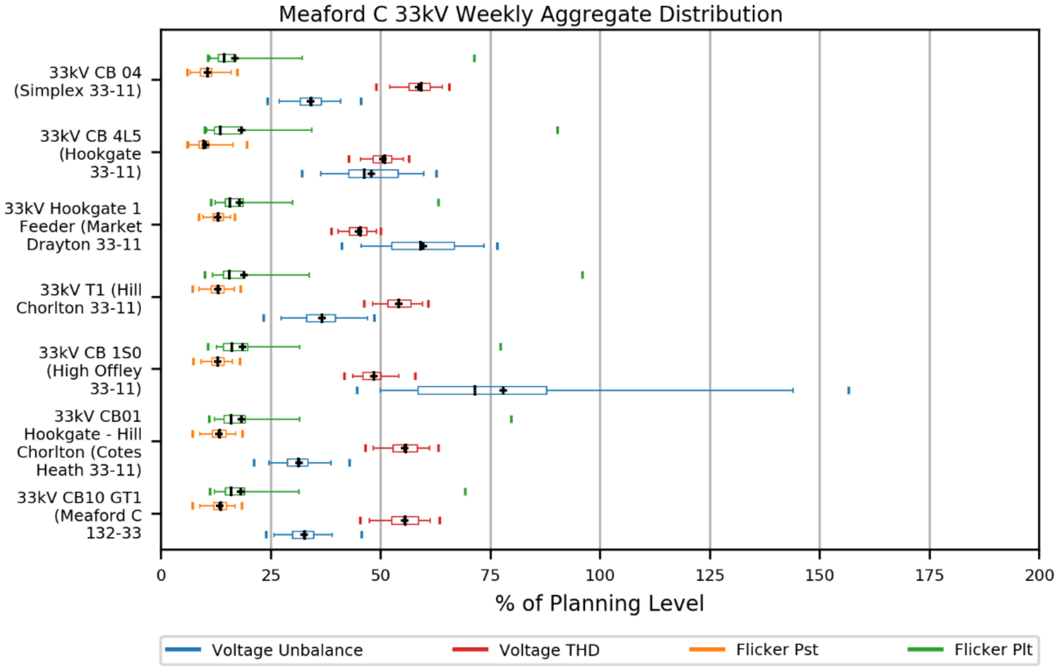

Figure 5-53: Range of non-harmonic PQ measurand weekly aggregates for Meaford C 33 kV sites

At some sites there were large variations in the weekly aggregates for particular measurands. For instance, as can be seen in the box plot of the distribution of non-harmonic PQ measurands for the Meaford C 33 kV sites Figure 5-53, at High Offley the difference in voltage unbalance between the week with the minimum aggregate value and the week with the maximum was 111.90% relative to the planning level. Voltage harmonics at the 5th and 7th harmonic orders were observed to be those that vary most at every site, and at Garreg Lwyd Wind the weekly aggregate values of the 5th harmonic varied by up to 50.90% relative to the planning level. Similarly large variations were seen at other sites and for other measurands. Whilst these large variations appear when looking at the extreme values, there are still substantial variations if the extremes are discounted, which highlights the importance of monitoring for periods longer than one week in order to obtain representative data.

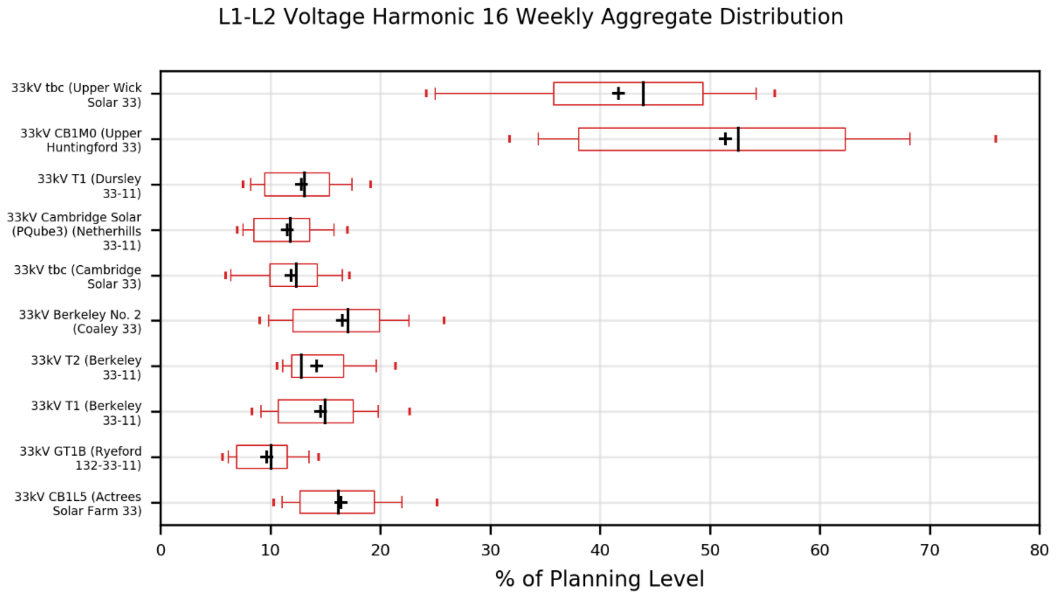

Figure 5-54: Box plot showing the distribution of 16th voltage harmonic weekly aggregates for the Ryeford 33 kV GT1B sites

The range of variation in weekly aggregates differs from site to site, even within a network area. For example, as shown in Figure 5-54 for the Ryeford GT1B area, the weekly aggregates of the 16th harmonic in particular have been found to vary by up to 44.22% of the planning level (at Upper Huntingford Solar), but at the BSP this variation is only 8.73%, whilst most of the remaining sites have weekly aggregates with value ranges slightly above that at the BSP. The data presented in Figure 5-54 also reinforces a point made in answering Question 1: none of the weekly aggregates at two of the sites (Upper Wick and Upper Huntingford) lie within the same range of values as at the other sites; therefore, the weekly aggregates for those two sites are not representative of conditions at sites elsewhere in the same network area, and vice-versa.

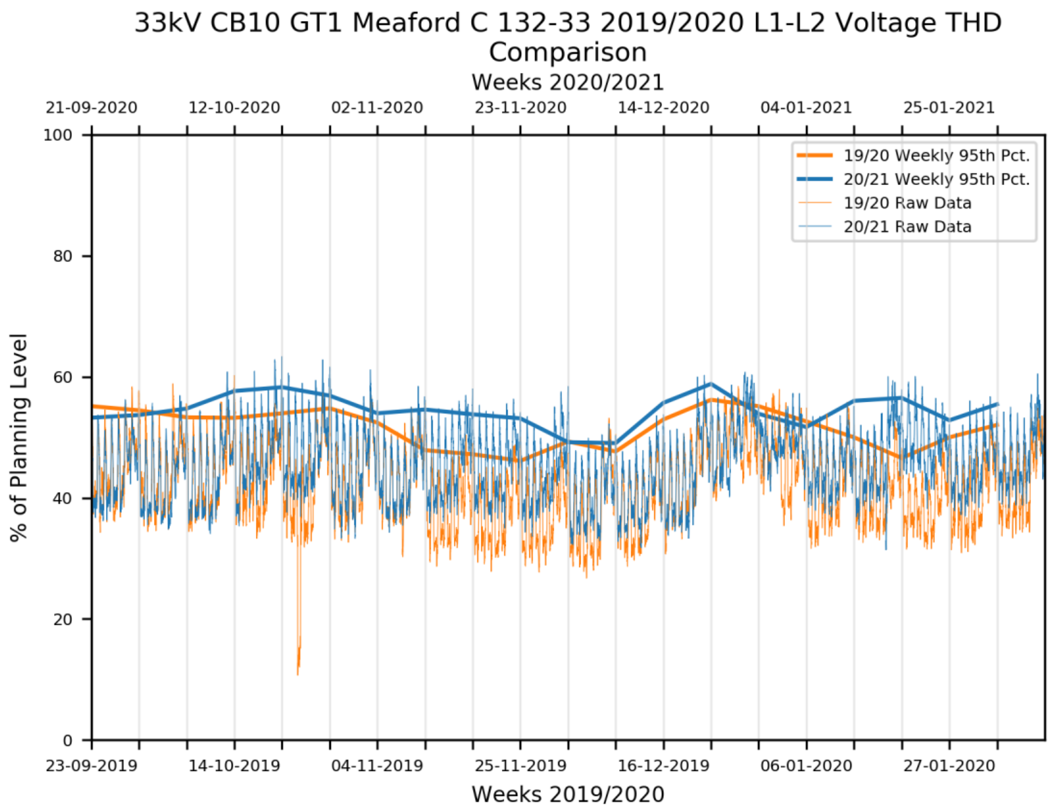

Figure 5-55: Year-on-year comparison of voltage THD for Meaford C 33 kV substation (GT1)

Data taken a year apart at several sites was analysed to understand any year-on-year changes in voltage THD. Some limited increases in weekly aggregate voltage THD values were observed when comparing data from October 2019 to January 2020 against data from October 2020 to January 2021. Figure 5-55 is an example of this for voltage THD at Meaford C 33 kV BSP. Further analysis suggests that COVID-19 response had some effects on PQ and therefore some of the year-on-year changes and some of the large variation in weekly PQ aggregates may be due to shifts in demand patterns due to the COVID-19 response. Figure 5-56 is an example of how changes in demand due to the COVID-19 response (in this case, power demand through Meaford C BSP reduces significantly through March 2020, before slowly recovering throughout the year) coincides with a change in PQ (in this case, an increase in voltage THD that reduces later in the year).

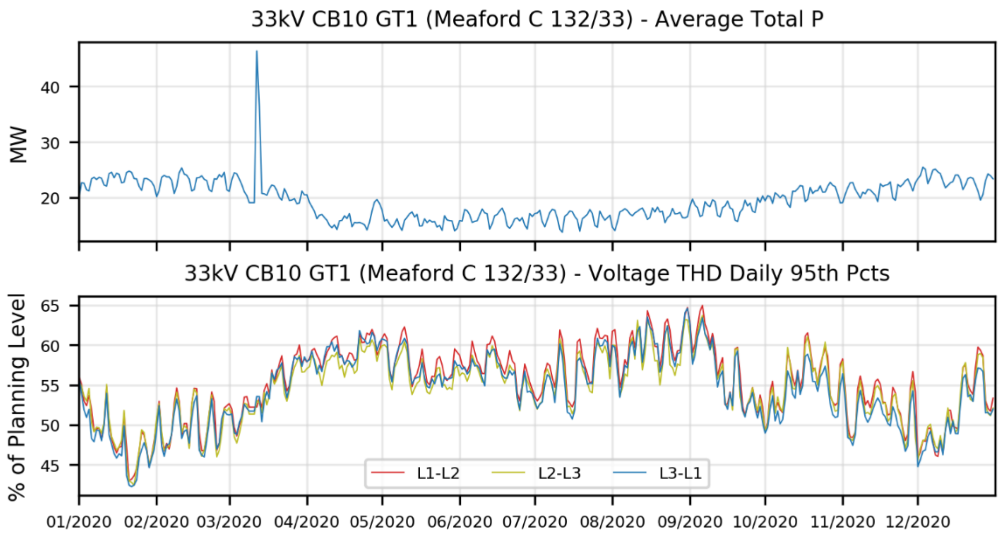

Figure 5-56: Daily average power and 95th percentile voltage THD values at Meaford C 33 kV BSP during 2020

5.4.4. Question 3: Do multiple monitors in a network area deliver useful extra visibility?

In summary, PQ data from the PNPQA trials shows that PQ measurements can vary substantially between sites in the same network area, meaning measurements taken at the BSP, for example, are not representative of the conditions at remote ends of the network. Therefore, PQ monitoring within a network area can delivery useful extra visibility, revealing issues that may have gone unnoticed and also providing more accurate background data for connection studies.

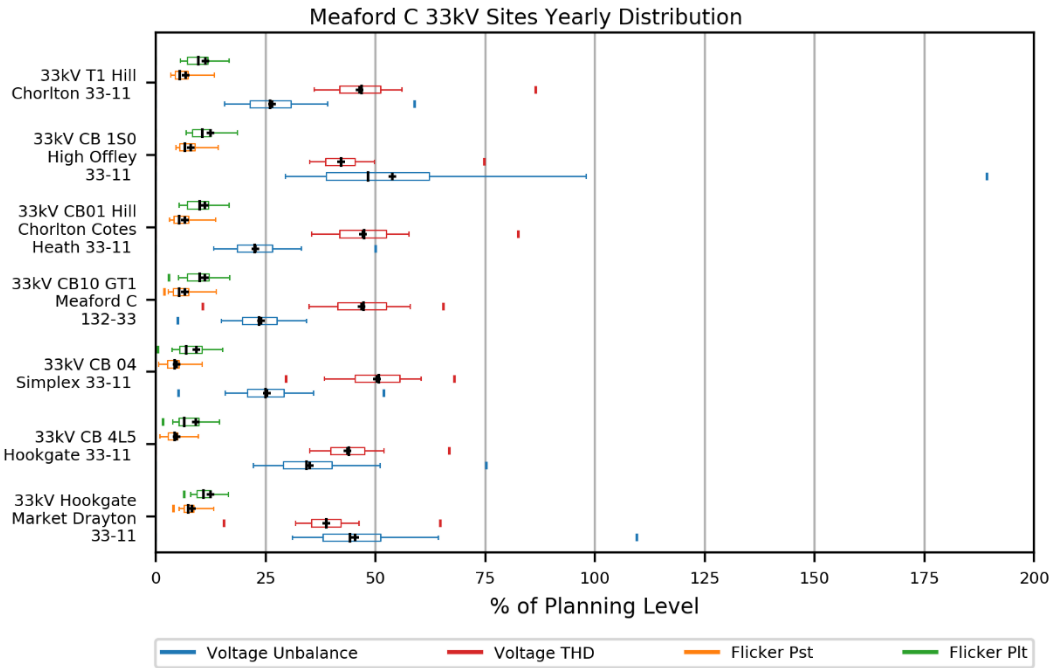

Figure 5-57: Box plot showing distribution of all non-harmonic PQ measurements for Meaford C 33 kV sites

Figure 5-57 is an example of how non-harmonic PQ measurands can vary across a network area. The figure is a box plot of the distribution of measurements taken at the 33 kV Meaford C sites over the course of the monitoring period, for several PQ measurands. The figure shows, for example, that the 95th percentile value of voltage unbalance varies by up to 64.83% of the planning level between sites, being 33.19% at Hill Chorlton and 98.02% at High Offley.

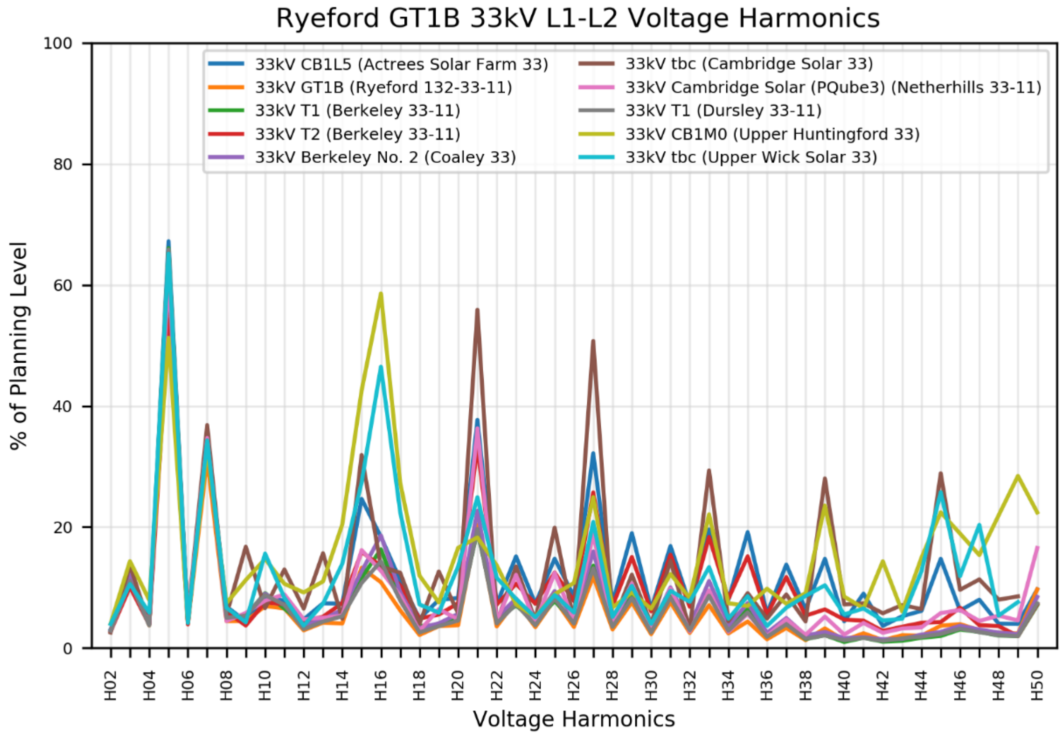

Figure 5-58: Overall voltage harmonic aggregates (95th percentile) for Ryeford 33 kV GT1B group sites

Voltage harmonics were also seen to vary substantially across a network area. Figure 5-58 is an example of this and is a plot of the 95th percentile aggregates for each voltage harmonic at each 33 kV site in the Ryeford GT1B network area, using all available measurements from the monitoring period. Several voltage harmonic orders show substantial variations between the sites, such as the 15th, 16th, 21st, and the 27th. The 16th harmonic order, for example, varies by as much as 47.68% of the planning level across the network, being 58.57% at Upper Huntingford solar farm and 10.89% at the BSP. The 5th and 7th harmonic orders – which are the dominant harmonics in terms of magnitudes across all the sites monitored – have also been observed to vary by 10% or more across a network area.

In addition to overall PQ aggregates varying substantially across network areas, the analysis of weekly aggregates shows that the range of weekly aggregates can also vary substantially in a similar fashion. For example, in the Ryeford GT1B area, the weekly aggregates of the 16th voltage harmonic – in addition to having higher values than the rest of the network – were found to vary by up to 44.22% of the planning level, but at the BSP this variation was only 8.73%. Furthermore, there were several instances where the range of weekly aggregates at one or more sites did not overlap with the range of values at the remaining sites; in other words, measurements from one site (e.g. a BSP) would not be representative of the conditions at another site (e.g. a remote end). This is the case for the data presented in Figure 5-54.

The implication of the findings from the analyses of the overall and weekly PQ aggregates is that monitoring at a single site with a network area – such as a BSP – is not guaranteed to yield PQ measurements that are representative of conditions elsewhere in the network area. Therefore, monitoring at several sites is recommended, such as the infeeding substation and remote ends as a minimum. This finding holds for areas with and without strong LCT penetrations but was particularly noticeable in areas with LCTs.

5.4.5. Question 4: How do the different PQ monitors compare?

In summary, the PQ monitors trialled during PNPQA all have similar performance in terms of the essential continuous PQ measurands. However, their capabilities for event capture varied significantly, with the a-eberle PQI-DA smart being the most capable, the PSL PQube3 being slightly less capable, and the Siemens SICAM Q200 being much less capable than the other two. The PQube3 was the most straightforward to interface with.

The PNPQA project trialled PQ monitors from three different manufactuers: the a-eberle PQI-DA smart, the PSL PQube3, and the Siemens SICAM Q200. Each monitor type was integrated into the monitoring system and their performance was assessed throughout the trial period.

For capturing basic continuous PQ measurements – such as voltage harmonics aggregated every 10 minutes – the different monitors performed very similarly in terms of the values obtained. However, there were some differences: 1) each monitor calculated a different variation of current THD, 2) occasional data drop outs in 10 s frequency measurements occurred when a-eberle PQI-DA smart units were heavily loaded, and 3) spurious value spikes were recorded by Siemens SICAM Q200 monitors every 10 minutes in the 10 s frequency measurements.

Significantly different methods for accessing the data off the monitors was required, and it was found that file-based transfer of data on a regular but non-continuous basis (such as every day) was more robust, simpler to implement, and less resource intensive than data transfer that was based on continuously polling for new values.

The a-eberle PQI-DA smart had the most capable event recording functions, in terms of the type of triggers supported and the waveform and RMS recording length. The PSL PQube3 lacked some of the more important triggers (e.g. RoCoF, vector shift) and had relatively limited event recording lengths. The Siemens SICAM Q200 was much less capable than the other two devices and did not have a comparable RMS recorder and did not support several important triggers.

All three monitor types had some sort of hardware or software issue affecting one or more of the devices used during the project. The most severe of these was partial failure of the voltage inputs to a-eberle PQI-DA monitors, which affected 4 out of the 10 units used for the project.

5.4.6. Dissemination of Findings

The project's findings have been disseminated through technical papers, webinars, and reports:

- CIRED conference 2019 (held in Madrid, 3rd-6th June 2019) – technical paper and presentation:
    - V. Peesapati, R. Gardner, J. King, S. Jupe, J. Berry, "Understanding the harmonic performance of voltage transformers for distribution system power quality monitoring" (Paper 1168)
- ENA Power Quality & Electromagnetic Compatibility Working Group – presentation on 7th October 2020

- CIGRE UK webinar on project findings (4th November 2020)
- CIRED conference 2021 (to be held virtually, 20th-23rd September 2021) – technical papers and presentations:
    - P. Davis, P. Wright, J. King, S. Jupe, S. Pinkerton-Clark, "Voltage transformer harmonic characteristics for distribution power quality monitoring" (Paper 0369)
    - J. King, A. Forster, S. Jupe, S. Pinkerton-Clark, "A view of 2020 power quality within GB distribution networks" (Paper 0370)
    - J. King, D. Wiley, S. Hoda, S. Jupe, S. Pinkerton-Clark, "An integrated platform for power quality monitoring" (Paper 0372)

Data gathered by the PNPQA project was shared with members of the Investigation & Modelling of Fast Frequency Phenomena ("F2P") project[1] from National Grid and Brunel University. Of particular interest to the F2P team were the continuously monitored frequency data (at 10 s time resolution) and half-cycle RMS event recordings captured by the PNPQA PQ monitors.

[1] https://www.smarternetworks.org/project/nia_ngso0007

6. Performance Compared to Original Aims, Objectives and Success Criteria

6.1. Aims and Objectives

The project achieved the following in fulfilment of the originally stated objectives:

Aims & Objective	Status
Understand the power quality / harmonics impact of LCTs throughout primary networks in a systematic way.	**Complete -** Over a year of PQ data was obtained for most of the monitored sites (LCT and non-LCT). The data obtained was analysed to reveal insights regarding the PQ impacts of LCTs and the PQ characteristics of Primary Networks more generally
Understand the behaviour of PQ monitoring transducers in a systematic way	**Complete** - Laboratory testing of VTs to validate their performance for capturing PQ measurements was performed by the University of Manchester (UoM) and at National Physical Laboratory (NPL).
Automate power quality / harmonics data retrieval and analysis processes.	**Complete** - Software to automate PQ data retrieval and analysis tasks was specified, developed, deployed, and demonstrated. The software was designed to be PQ monitor vendor agnostic and was used to retrieve and analyse data from all the communicating PQ monitors installed as part of the project
Develop a decision support tool for modelling and forecasting harmonic / PQ effects	**Complete** - The PQ analysis automation software included a tool to automate performing an ER G5/5 Stage 2C assessment, which is required for some classes of connection application

6.2. Success Criteria

The project achieved the following in fulfilment of the originally stated success criteria:

Success Criteria	Status
Impact of LCTs on power quality and harmonics within primary networks better understood	**Complete** - All PQ monitors for the wide scale trial of communicating PQ monitors were installed. These monitors provided detailed data on the power quality within primary networks including the impact of LCTs.
Power quality monitors installed at trial locations and remote retrieval of data successfully demonstrated	**Complete** - All 46 PQ monitors for the project's trial were installed, data was successfully remotely retrieved from all installed PQ monitors
Tools for automating power quality data retrieval and analysis demonstrated	**Complete** - Six main features of the PQ analysis automation software were specified, developed, and deployed to the project's data server. Two additional reporting features (an EN 50160 compliance report and an ER G5/5 background report) were specified, developed, and deployed also.
Policies created to implement project outputs in WPD's business	**Compete** - Standard Techniques on PQ monitoring installs and PQ data analysis have been drafted.

7. Required Modifications to the Planned Approach during the Course of the Project

Some minor modifications to the project approach were made that enhanced the learning obtained:

1. Three different PQ monitor types were trialled rather than two types as originally planned. This allowed for more learning to be obtained regarding the performance and differences between PQ monitors. This was achieved at no extra cost as the integration work for the third monitor was provided as a contribution by the main project partner (Nortech).
2. The number of 11 kV sites monitored was increased from the originally planned number of 1-2 distribution substations per trial area due to several reasons and as the project budget would allow it. In the Meaford C area, 9 distribution substations were monitored at 11 kV: some provided PQ measurements at or Primary substations were 33 kV monitoring was not possible, whilst others provided baseline PQ measurements for 11 kV feeders with no identified LCTs. In the Ryeford area, 3 distribution substations were monitored at 11 kV, to provide PQ measurements for specific LCTs and for the length of one feeder that had an LCT (a solar PV farm) in the middle. Additionally, two 11 kV sites outside the main trial areas were monitored: one was a battery energy storage unit, and the other a rapid EV charge station.

8. Project Costs

Table 8.1 summarises the details of the final costs that have been made with respect to the project budget.

Table 8-1: Project Spend

Spend Area	Budget (£k)	Expected Spend to Date (£k)	Actual Spend to Date (£k)	Variance to expected (£k)	Variance to expected %
Nortech Contract	£635,400	£635,400	£635,400	£0	£0.0%
WPD Project Management	£45,679	£45,679	£76,333	£30,654*	67.1%
Hardware & Software Requirements	£553,825	£553,825	£550,150	(£3,675)	-0.7%
Network Services Costs	£0	£0	£3,253	£3,253*	N/A
Contingency	£123,490	N/A	£33,907 was used and is included in the costs above.	N/A	N/A
TOTAL	**£1,358,394**	**£1,234,904**	**£1,265,136**	**£30,232**	**2.4%**

WPD Project Management – increase in costs due to change over of project managers after the project had begun, extra days spent for new project manager to familiarise themselves with the project, more project management days were required than anticipated, utilised contingency to cover these additional costs.

Hardware & Software Requirements – variance due to slight discounts on equipment when ordering high volumes, slightly less spend required as a result

Network Services Costs – We utilised contingency budget to cover these additional costs as some sites required Network services teams and 3rd party contractors to install.

Contingency – *£33,907 of contingency used to cover additional costs for project management and to cover the extra costs incurred by network services.

9. Lessons Learnt for Future Projects

Table 9-1 summarises the learning that has been generated through the project that are useful for future projects.

Table 9-1: Lessons learnt

Area	Learning Generated
Primary Network PQ	The standard way of assessing PQ is to use the 95th percentile aggregates of data taken over a week-long measurement period. However, the year or more of monitoring data gathered by the project has revealed that the 95th percentile aggregates can vary significantly from week to week, so basing PQ assessments on a single week of measurements may over- or under-represent existing PQ issues.
Primary Network PQ	Monitoring every site within a 33 kV network has revealed that PQ can vary significantly across the sites, meaning that PQ data gathered at a single site may not be representative of the conditions at other sites. Therefore, monitoring should ideally be located at the network infeed and the remote ends as a minimum to achieve broader PQ visibility and capture more representative data.
LCT PQ impacts	Comparing PQ during LCT operation and during outages is a very straightforward way to understand the PQ impact of a specific LCT, but realistically this can only be achieved through constant monitoring.
LCT PQ impacts	The influence of LV connected LCTs, such as heat pumps and electrics vehicles, on higher voltage networks (e.g. Primary Networks at 33 kV) is still uncertain, and could be a major source of PQ issues as the uptake of LV-connected LCTs accelerates.
PQ monitor features	Market research revealed at least 20 manufacturers of PQ monitors that met the basic requirements expected for the project. However, none had identical interfaces meaning bespoke work was needed for each to enable remote communications with the monitors.
PQ monitor features	Whilst the 3 different PQ monitor models trialled during the project allowed the same aggregated continuous PQ monitoring data to be obtained (typically aggregated every 10 minutes), they varied significantly in their event triggering and recording capabilities. The ability to record high-resolution waveform data and RMS data – typically at half-cycle resolution, ideally for 10 s or more – were both found to be useful. Triggers for rapid voltage change (RVC) were useful at capturing data during network faults, even at sites that did not see the fault current. Triggers for rate of change of frequency (RoCoF) were only available for one of the monitors but are useful for capturing RoCoF events that can lead to distribution generation tripping such as the low frequency event of 9th August 2019.
PQ data transfer	Communications surveys during the pre-installation site surveys revealed that no single mobile network provider could provide coverage at all sites, particularly for 4G. Therefore, roaming SIM cards were used so the communications hub could use whatever providers are available at each site.

Area	Learning Generated
PQ data transfer	Two different monitors were interfaced with using IEC 61850. Testing of these monitors revealed differences in their implementation of IEC 61850, in particular the file transfer mechanism, which prevented a single "standard" interface from being used for both monitors.
PQ data transfer	One of the monitors interfaced using IEC 61850 required constant polling in order to obtain the most recent measurements. This approach occasionally led to small amounts of data being lost as the monitor was sometime unable to reply to all requests. Furthermore, if communication between the monitor and communication hub was lost for a period, almost all monitoring data for the period cannot be subsequently retrieved using the IEC 61850 protocol as implemented on the monitor. As the PQ monitoring data does not need to be transmitted continuously, transfer of the data via file transfer is preferred as it can be carried out asynchronously, is more robust to temporary communications loss, and is less resource intensive.
PQ data transfer	Generally, file-based transfer of monitoring data from the remote sites into the central data analysis server was found to be very robust, even when faced with very poor signal strength and communication outages of a week or more. Generally, the data for a single day of monitoring could be compressed into a few MB, so many months – or even years – of data could be stored locally prior to upload.
Remote reconfiguration	PQ monitors that use files for configuration and firmware updates allowed remote reconfiguration and updates to be achieved, which was used effectively in the project to avoid site visits to achieve the same outcome. This was not possible for the monitors that needed a direct connection to the vendor's software for updates due to: 1) IT rules preventing the software being installed and used on the central monitoring server, 2) network routing preventing direct traffic between the central monitoring server to the PQ monitors, and 3) the potential for poor signal strength to slow or stop communications between the central software and remote PQ monitors. Furthermore, file based transfers could be automated, removing the need for manual intervention to reconfigure or update PQ monitors in the field.
Time synchronisation	Time synchronisation using NTP over the 2G/4G network was observed to deliver adequate performance for general PQ monitoring, with generally <1 s difference in clocks between sites. Adding GPS-based high resolution time synchronisation would have added some cost of the PQ monitoring equipment and complicated the installation process as an external antenna must be fitted to access the GPS signals.
PQ monitor installations	Occasional instability of one PQ monitor was observed, so a method of remotely triggering a power cycle was developed using a non-latching relay to interrupt the power supply, driven by the communications hub. This was used a few times and avoided needing to visit site to reset the units.
PQ monitor installations	The project trialled semi-permanent "plug & play" PQ monitor installations, which used PQ monitors in small enclosures that could be placed inside existing cabinets – or on the top or side using magnetic mounting feet – with voltage test lead and current (clamp CT) inputs. The "plug & play" monitors could be installed with 1-2 hours with 1-2 personnel, including sourcing

Area	Learning Generated
	power and post-install checks, and did not require any outages. There was no significant time saving if current monitoring is skipped.
PQ monitor installations	The “plug & play” PQ monitor installations were sped up by pre-configuring and pre-commissioning the monitors (using secondary injection) and communications hubs prior to going to site. This reduced the complexity of install checks on site to a simple single A4-sized checklist.
PQ monitor installations	One downside of the “plug & play” installations was that the power supplies used were not backed up, so if a network fault occurred the power supply to the PQ monitors could be lost along with the monitoring data up to the point of the outage. This could be solved by attaching the monitors to the substation batteries (if spare capacity is available) or by integrating a small uninterruptable power supply (with battery) alongside the PQ monitors.
PQ data analysis	Most PQ monitoring is based on average measurements taken every 10 minutes. However, having some measurands (e.g. voltages and currents) also available at higher sampling intervals and with minimum and maximum aggregates was found to be useful in understanding device behaviour (e.g. short term variations in solar PV power output) and for observing network faults (e.g. by looking for short-term spikes in current and dips in voltage).
PQ data analysis	For offline analysis of large PQ datasets, using the hierarchical data format (HDF) rather than CSV or spreadsheets allowed for much more efficient storage and retrieval of data, and easy integration in to automated analysis scripts.
VTs for harmonic monitoring	33 kV and 11 kV VTs pass through signals at the harmonic frequencies typically measured (up to the 50^{th}) but introduce attenuation in the output magnitude at higher frequencies.
VTs for harmonic monitoring	Close attention must be paid to the frequency response of the measurement system in addition to the VT under test, as this can influence the results. Calibration of the equipment at harmonic frequencies is vital in addition to calibration at the fundamental frequency.
VTs for harmonic monitoring	The ability of 3-phase VTs to transfer triplens harmonics – which typically are in phase – varies significantly depending on the construction of the VTs.

10. The Outcomes of the Project

Technical Papers

- V. Peesapati, R. Gardner, J. King, S. Jupe, J. Berry: "Understanding the harmonic performance of voltage transformers for distribution system power quality monitoring", 25th International Conference and Exhibition on Electricity Distribution (CIRED), Madrid, June 2019

- P. Davis, P. Wright, J. King, S. Jupe, S. Pinkerton-Clark: "Voltage Transformer Harmonic Characteristics for Distribution Power Quality Monitoring", 26th International Conference and Exhibition on Electricity Distribution (CIRED), 2021 (accepted for presentation)

- J. King, A. Forster, S. Jupe, S. Pinkerton-Clark: "A View of 2020 Power Quality within GB Distribution Networks", 26th International Conference and Exhibition on Electricity Distribution (CIRED), 2021 (accepted for presentation)

- J. King, D. Wiley, S. Hoda, S. Jupe, S. Pinkerton-Clark: "An Integrated Platform for Power Quality Monitoring", 26th International Conference and Exhibition on Electricity Distribution (CIRED), 2021 (accepted for publication)

Reports

- **PQM Market Research Report:**
This report summarises the findings from a market research exercise on power quality monitors (PQMs) that was undertaken to inform the selection of PQMs for the PNPQA project. The research exercise comprised of identifying vendors of PQMs and examining their products to determine the key features of different PQM devices.

- **Power Quality Monitor Remote Communications Initial Feasibility Assessment**:
A report of early work done in the project; this consisted of assessing the feasibility of interfacing with several PQMs that were in use by WPD or that had been identified for potential future use by WPD, so that PQ data can be communicated remotely.

- **Envoy/PQube3 Interface Factory Acceptance Tests:**
This report is both a test specification and a test record for the Factory Acceptance Test of the Envoy firmware modifications to interface with PSL PQube3 PQ monitor.

- **Envoy/a-eberle PQI-DA smart Interface Factory Acceptance Tests:**
This report is both a test specification and a test record for the Factory Acceptance Test of the Envoy firmware modifications to interface with a-eberle PQI-DA smart PQ monitor.

- **Envoy/Siemens SICAM Q200 Interface Factory Acceptance Tests:**
This report is both a test specification and a test record for the Factory Acceptance Test of the Envoy firmware modifications to interface with Siemens SICAM Q200 PQ monitor.

- **Power Quality Monitor Pilot Trial Analysis:**
Prior to the widescale trial of communicating PQ monitors, a pilot trial with a single monitor took place to help guide the preparations and reduce uncertainties. The monitor and a communication hub were installed at Meaford C Bulk Supply Point (BSP) in June 2018 and data from the 6 weeks after installation was analysed and the findings presented in this report.

- **Trial Area and Site Selection:**
  This report describes the development and application of a methodology for the selection of trial areas and sites for the widescale power quality monitoring trial within the project.

- **Proposal for Additional 11 kV Sites:**
  This report described and applied a methodology for identifying and selecting additional 11 kV sites to be monitored as part of the PNPQA project, which was developed as the project budget allowed for additional monitoring to be installed.

- **PQ Trial Data Analysis Scope:**
  This report outlined the scope for PQ trials data analysis. As the project would generate around 1.5 billion measurements, having a clearly defined scope for the analysis of that amount of data was vital.

- **PQ Trial Data Analysis Report:**
  This report contains the analysis and key findings from the remote PQ monitoring trial.

- **Power System Analysis Tools Review:**
  This report is a review of several power system analysis tools in order to recommend which tool would be used for the future-looking power quality studies as part of the PNPQA project. Requirements for the tool were developed and used to compare 20 different tools that were available at the time, including those is use in WPD.

- **PQ Study Objectives & Methods**:
  This report outlined objectives and methods for the future-looking power systems studies as part of project.

- **PQ Study Results**:
  This report presents the implementation, results, and key findings from the future-looking power system studies of the potential impacts of increased penetrations of LCTs.

- **Six monthly project progress reports:**
  These are standard project progress reports that are produced every 6 months.

- **Project close down report:**
  The project close down report as required under the NIA process.

Documents

- Draft Standard Technique Relating to the Installation, Configuration, and Commissioning of Power Quality Monitoring Using the PSL PQube3

- Draft Standard Technique Relating to the Retrieval, Monitoring, and Analysis of Power Quality Data using iHost

Systems

- Automated software for vendor-agnostic retrieval and analysis of PQ data from remote monitors, integrated in to Nortech's iHost platform

Processes

- Process for installing and commissioning PQ monitors as defined by the Standard Technique.

- Process for analysing PQ monitors data as defined by the Standard Technique.

Presentations & Dissemination Events

- CIGRE UK webinar on project findings
- Presentation at ENA Power Quality & EMC Working Group

11. Data Access Details

To request access to project data, please visit: www.westernpower.co.uk/Innovation/Contact-us-and-more/Project-Data.aspx

12. Foreground IPR

New foreground IPR was generated by the project in the following areas:

Title	Description	Ownership	Access Location
Methodology and results of VT harmonic response testing.	Relevant Foreground	Nortech/WPD	www.westernpower.co.uk/Innovation/Contact-us-and-more/Project-Data.aspx
Development and application of a methodology for trial area and site selection	Relevant Foreground	Nortech/WPD	www.westernpower.co.uk/Innovation/Contact-us-and-more/Project-Data.aspx
Implementation of interfaces for retrieving PQ data off PQ monitors.	Relevant Foreground	Nortech/WPD	www.westernpower.co.uk/Innovation/Contact-us-and-more/Project-Data.aspx
Requirements and designs for PQ analysis automation software	Relevant Foreground	Nortech/WPD	www.westernpower.co.uk/Innovation/Contact-us-and-more/Project-Data.aspx
Implementation of PQ analysis automation software	Relevant Foreground	Nortech/WPD	www.westernpower.co.uk/Innovation/Contact-us-and-more/Project-Data.aspx

13. Planned Implementation

The communicating PQ monitoring system and software for automating PQ data retrieval and analysis is actively being transitioned to BaU . Documentation has been drafted on PQ monitor installations and PQ data analysis based on the outcomes of the project. Deployment of PQ monitoring using the systems developed through the project are being planned for the remainder of RIIO-ED1 and throughout RIIO-ED2.

In addition, another Network Licensee – UK Power Networks – is adopting the automated PQ data retrieval and analysis tool developed through the PNPQA project for BaU use. The result of this is the Method developed through the project will be rolled out to half of the distribution license areas in GB.

14. Contact

Further details on this project can be made available from the following points of contact:

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15. Glossary

Abbreviation	Term
BaU	Business-as-Usual
BEIS	Department of Business, Energy & Industrial Strategy
BSP	Bulk Supply Point
CSV	Comma Separated Values
CT	Current Transformer
DAQ	Data Acquisition
DECC	Department for Energy and Climate Change (defunct; now part of BEIS)
DFES	Distribution Future Energy Scenarios
DG	Distributed Generation
EV	Electric Vehicle
FES	Future Energy Scenarios
GIS	Geographic Information Systems
HDF	Hierarchical Data Format
HV	High Voltage
IPR	Intellectual Property Rights
JSON	JavaScript Object Notation
LCT	Low Carbon Technology
LV	Low Voltage
NIA	Network Innovation Allowance
NPL	National Physical Laboratory
PNPQA	Primary Networks Power Quality Analysis
PSD	Primary System Design
RMS	Root Mean Squared
RoCoF	Rate of Change of Frequency
UoM	University of Manchester
VT	Voltage Transformer
WPD	Western Power Distribution

16. Appendices

There are no appendices in this report, all supporting information and reports are detailed in section 12 of this report.

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