WESTERN POWER DISTRIBUTION
INNOVATION

NEXT GENERATION NETWORKS

Voltage Reduction Analysis
Results overview
June 2016

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Glossary

Abbreviation	Term
AVC	Automatic Voltage Control
BSP	Bulk Supply point
CLASS	Customer Load Active System Services
DNO	Distribution Network Operator
ENW	Electricity North West
GC OC	Grid Code Operating Code
IFI	Innovation Funding Incentive
LCNF	Low Carbon Networks Fund
LVNT	Low Voltage Network Templates
NIA	Network innovation Allowance
SWVRA	South Wales Voltage Reduction Analysis
UoB	University of Bath
VRA	Voltage Reduction Analysis
WPD	Western Power Distribution

1 Executive Summary

Following the Low Voltage Network Templates (LVNT) tier 2 Low Carbon Networks Fund (LCNF) trial, Western Power Distribution (WPD) reduced its Automatic Voltage Control (AVC) settings in the East Wales, Cardiff and Swansea areas from 11.4kV (±200V) to 11.3kV (±165V). The Voltage Reduction Analysis (VRA) project looked to assess the effects of this change through the analysis of over 200 million data points by the University of Bath (UoB).

Through rigorous statistical testing of weather corrected and sense checked data it was found that the reduction in voltage caused a statistically significant reduction in average and maximum real power demands as well as average reactive demand at the monitored substations. This compared to non-significant changes in substations without the settings changes. Furthermore, statistical change point models were run on the data which accurately identified the date of setting changes in most substations.

The 0.88% reduction in voltage settings caused a 1.16% reduction in average demand (equivalent to consumption) over the year. If scaled to the whole of South Wales the reduction in consumption would equate to a yearly decrease of 131.9 GWh, based on the total consumption of 11374.2 GWh. This equates to a saving of £14.9m of customer bills over a year and a reduction in CO2 of ca. 70,000 tonnes.

A 1.14% reduction in maximum demand was also found which could release capacity on the network.

The effect of the time of year were successfully identified for all these values, however detailed analysis into substation types and customer make up were limited by small sample sizes causing non-significant results.

Voltage profiles from both substations and feeder ends were also analysed. Following the change in settings, voltages still sit at the higher end of the allowable spectrum with scope for further reductions. The change of setting has reduced the already low number of voltage excursions as the increase in under voltage excursion is easily offset by the reduction in over voltage excursions. This would suggest there is scope for further reduction however this must be weighed up against the potential operational costs of rectifying individual issues.

Investigations into National Grids operation juniper were also run, confirming the low response from substations in South Wales to the GC OC6 trial call. This was due to a combination of time of implementation but also a smaller than expected reduction in voltage seen at the distribution substations.

The University of Bath’s full report on the analysis is available on request.

2 Introduction

This report summarizes the learning from the VRA Network Innovation Allowance (NIA) project. This includes the background of the project, the data analysed, the results of voltage changes on demand, the effects on voltage profiles and the correlations with National Grid's "Operation Juniper".

3 Project Background

LV voltages must be kept within the statutory limits of 230V + 10% or - 6% (253.3V-216.2V). With minimal active voltage control beyond 33/11kV transformers and designs based on demand dominated networks, LV voltages are generally set as high as possible to allow for voltage drop along the network and ensure that voltages never drop below the limits.

However reducing network voltage can have significant benefits, particularly where there is a large concentration of resistive loads. For these types of loads reducing the voltage will reduce the maximum demand requirements and, depending on the control mechanism, can also reduce the consumption. The effect of voltage reduction on a substation depends on the specific make-up of the local load. As this is generally unknown, estimates of the benefits of voltage reduction vary drastically, ranging from consumption dropping by the square of the reduction to no drop at all.

Within such uncertainty the VRA project aims to quantify the reaction of consumption, maximum demand and voltage profiles to voltage drop on real monitored networks. This could then ease the implementation of voltage reduction across network licensees and derive benefits to customers.

Initial analysis of voltage profiles in South Wales was conducted as part of the LVNT Tier 2 LCNF project. This showed that voltages at both substations and feeder ends sat at the higher end of the allowable range, with very few (only 0.015%) measurements below the statutory limits. As such a program of voltage reduction was carried out in the area covered, altering the AVC settings at the 33/11kV transformers. These were shifted from a target of 11.4kV (±200V) to 11.3kV (±165V), approximately 0.88%. The majority of the voltage changes occurred in November and December of 2014.

Following this reduction the South Wales Voltage Reduction Analysis (SWVRA) Innovation Funding Incentive (IFI) project was run to assess the effect of this change. Using the data captured by the LVNT monitoring equipment a statistically significant change was detected on the corresponding dates and it was seen that the reduction in voltage had caused a 1.5% reduction in consumption.

Whilst this showed that small voltage reductions can have a significant effect on consumption, the analysis was limited by the data available at the time, approximately 1 month following the reduction. As such questions about the effects of time and seasonality couldn't be answered. Furthermore the effect of substation make up was not addressed nor the effect of the change on Maximum demand.

The VRA project seeks to follow up this promising IFI work with analysis on a more complete data set. The analysis work was conducted by the UoB in late 2015 and early 2016. Their full report is available on the WPD innovation website with full electronic appendices available on request.

It should be noted that this project investigates one option of exploiting voltage foot-room in distribution networks, and must be balanced against the benefits of utilising dynamic voltage reduction to provide services to National Grid as demonstrated in Electricity North West's (ENW) Customer Load Active System Services (CLASS) project.

4 Data analysed

The analysis carried out used data collected by the LNVT monitoring equipment from 2014 and 2015. Substations monitored voltage, current, real power delivered and reactive power delivered at 10 minute averages, the feeder end monitors measured only voltage at the same time intervals. As of 31/12/2015, measurements were available from 753 substations and 2810 voltage monitors. The number of substations available and suitable for analysis varied for different months and years. Figure 1 shows a schematic of the available data from substations in January 2014.

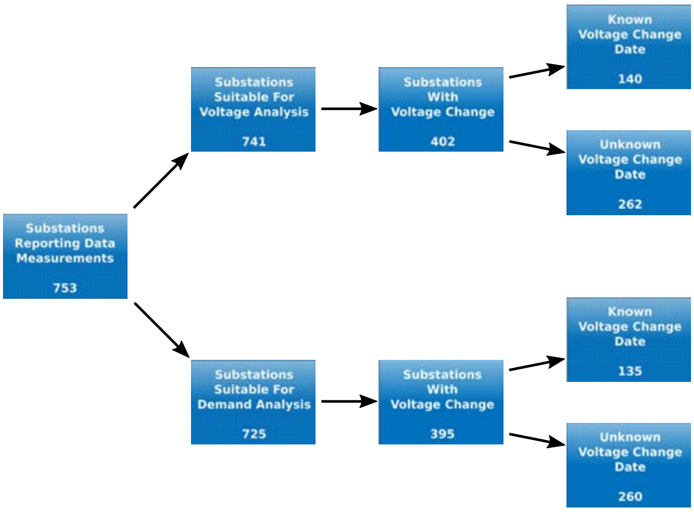

Figure 1: Substation data available in January 2014

Many substations did not have a change in voltage due to practical reasons at the relevant primaries. This was, in pragmatic terms, random and provided a control group. The location of the substations can be seen in Figure 2 in which the locations of substations that had voltage changes are shown by red dots and those that did not change by blue dots.

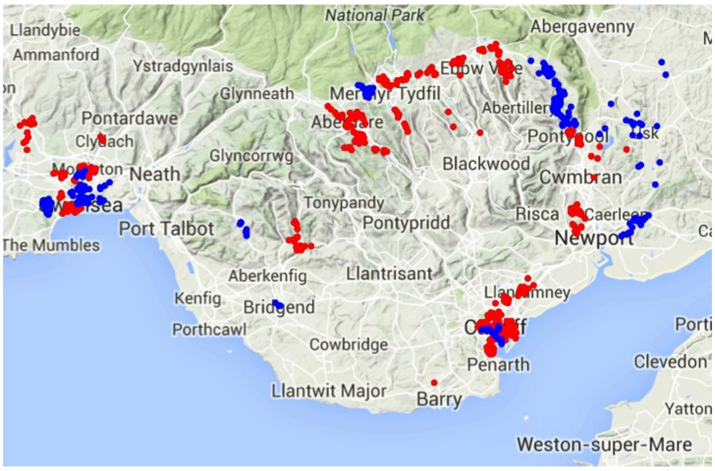

Figure 2 Locations of substations providing data for the analysis

Table 1 displays the number of substations providing suitable demand data for analysis for every month in 2014 and 2015. As can be seen in Table 1, there is a period of time between February and April 2015 where data was not collected. This was due to technical issues; as such March has been omitted from most of the following analysis.

Table 1: Data available for analysis

Month	2014			2015		
	No. Days supplied	subs with a change	Subs with a known change date	No. Days supplied	subs with a change	Subs with a known change date
January	31	395	135	31	400	136
February	28	395	135	17	399	136
March	31	394	135	0	0	0
April	30	392	134	18	369	131
May	26	247	80	30	369	131
June	30	251	81	30	366	131
July	31	256	82	31	390	131
August	31	257	84	31	391	132
September	30	259	85	30	388	131
October	31	259	84	31	368	117
November	30	261	86	30	368	117
December	31	398	135	31	362	116

The number of voltage monitors available and suitable for analysis also varied for different months and years. Figure 3 shows a schematic of the available data from feeder end monitors in January 2014.

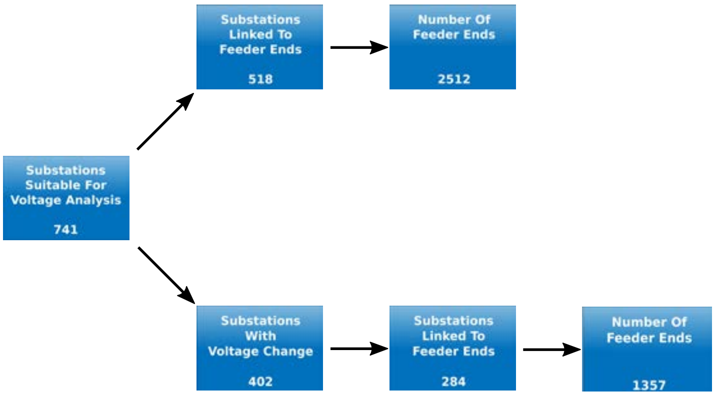

Figure 3: Feeder end voltage monitor data available in January 2014

5 Demand Analysis

The aim of the analysis of demand data was to determine whether there were any discernible changes in both average and maximum demands associated with the 11kV AVC settings changes.

In order to ensure that demands were comparable between years, they were adjusted for weather. Weather corrections were available from WPDs charging team in the form of uncorrected consumption values for each half hour for the entire South Wales area together with the weather corrected version. From these, correction ratios were calculated which were then applied to the demand data.

Sense checking was also performed on the data to ensure that large external factors, such as the loss/gain of customers on a substation did not affect the results. The sense checking consisted of two stages: comparing between daily average demands and comparing aggregated monthly average demands. This removed any changes that were too large to be attributed to voltage change. The default cut off used was 20kW in order to allow a reasonable inherent variability in demands to propagate through the analyses whilst excluding very large differences. Sensitivity to the choice of cut-off was assessed by repeating the analyses for a range of values. Results proved to be insensitive to the exact cut-off points, except in the extreme cases of no sense-checking where decreases were noticeably greater.

For January 2015, 609 substations were deemed suitable for analysis. Data was extracted and daily average and maximum demands calculated for each substation for each year using measurements from the 144 ten minute periods. As mentioned previously no data was recorded in March 2015 due to technical issues and so a comparison based on that month is not possible.

5.1 Changes in average demand

The first section of the analysis focussed on changes in average demand, which can be directly correlated to consumption. Testing consisted of detecting differences between demands for each month e.g. January 2015 vs. January 2014. The testing established the differences for each substation which were then combined into a single summary of the difference, together with an assessment of the statistical significance of any change. Figure 4 shows an example of average daily demands measured at a substation for two months (January and July) for both 2015 and 2014. A decrease can be seen in both cases, with the decrease in the average demand being greater in January.

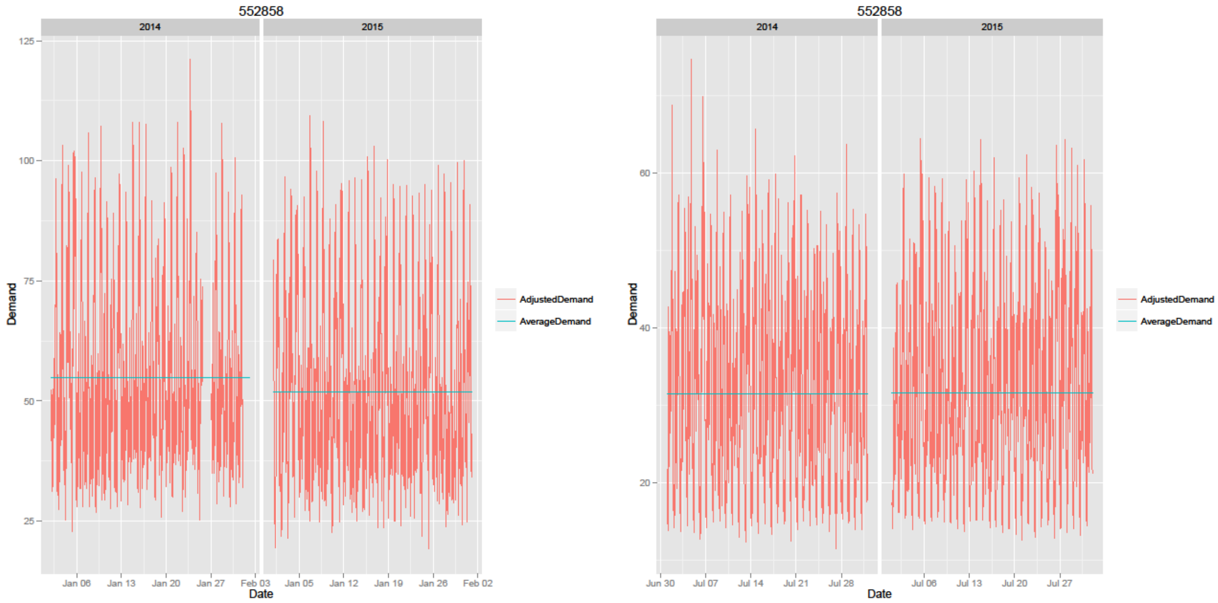

Figure 4: Comparison of average daily demand data for substation 552858 in January and July

Table 2 shows the summary results for each month.

Table 2: Differences in monthly average demand for 2014 and 2015

Month	Mean 2014 (kW)	Mean 2015 (kW)	Mean difference (kW)	Percentage difference	p-value
January	95.83	94.49	1.34	1.40	0.00
February	94.53	93.61	0.92	0.97	0.00
April	57.62	56.74	0.88	1.53	0.01
May	60.45	60.37	0.08	0.13	0.39
June	59.17	58.30	0.87	1.48	0.00
July	58.82	58.41	0.41	0.70	0.08
August	59.15	58.48	0.67	1.13	0.01
Septembe	62.44	61.87	0.57	0.91	0.04
October	70.39	67.74	2.65	3.77	0.00
November	77.19	75.97	1.22	1.58	0.00
December	82.52	81.12	1.40	1.70	0.00

Reductions were found in each month, with values being greater in the winter months than in the summer. In all months except for May and July, these reductions were statistically significant ($p < 0.05$). Analysis was also conducted on substations without a voltage change and the same patterns were not observed. Instead insignificant decreases and increases were observed.
Also noticeable in Table 2 is the very high decrease observed for October. An extensive examination of the data of historical October data showed that the measurements for 2015 were significantly lower than might be expected. This decrease appeared to last through the month of October and into the first week of November. This period was unseasonably warm and this led to a detailed examination of the unadjusted (for weather) data and the ratios between the unadjusted and adjusted demands for October 2014 and 2015. The ratios were very similar for both years, which indicate that the weather correction had not compensated sufficiently for the

mildness of 2015. This may be due to the softer element of customer demand profiles where demand can be quite different on identical days depending on whether customers have gone into “winter mode” and turned on heating systems.

Statistical smoothing techniques can be used to estimate values where no data is available. Figure 5 shows the effect of fitting a *lowess smoother* to the results obtained from each month and shows a smooth pattern over the year, with the decreases in the summer months being smaller than those in the winter period.

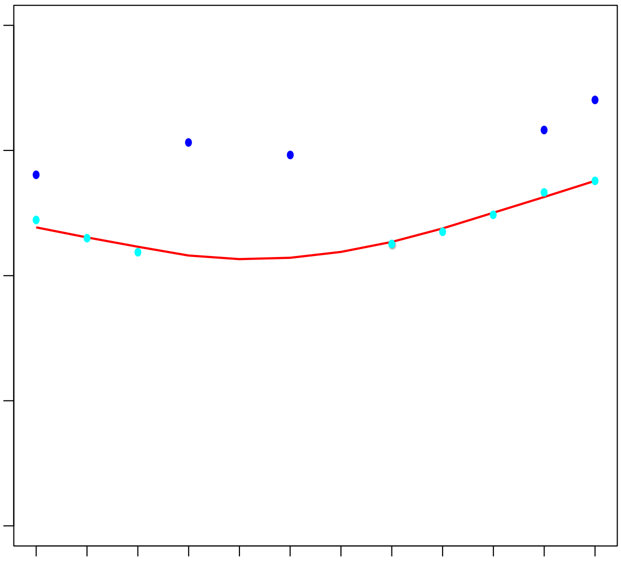

Figure 5: Estimates of average demand reduction between 2014 and 2015

The value for March was estimated using this smoothing model, as was the value for October, which was treated as missing and estimated in the same way. This estimated values of 1.09% and 1.24%, respectively. Using either direct averaging or smoothed estimates, as shown in Figure 5, gives an overall average decrease in average demand of 1.16%. This methodology was also run ignoring the highly non-significant result in May. This provided and estimate for the overall reduction on 1.24%. Both these values compare favourably against the maximum theoretical reduction of 1.75%.

Using the same methodology as LVNT and SWVRA, and the lower value of a 1.16% reduction, this equates to a yearly decrease of 131.9 GWh across South Wales, based on the total consumption of 11374.2 GWh. This equates to a saving of £14.9m over a year and a reduction in CO2 of ca. 70,000 tonnes.

5.2 Average demand changes by category

Further analysis was carried out to investigate the effects of different parameters such as time of week or substations characteristics on the response achieved from a reduction in voltage.

Table 3 shows the results of the split by week day and week end. As the subsets of data are smaller they are less stable and there are more non-significant results, this makes it much harder to discern any underlying patterns. Even amongst the significant results there are no clear patterns of either higher or lower response depending on the type of day.

Table 3: differences between monthly averages for weekdays and weekends

Month	Overall results		Weekdays		Weekend Days	
	Percentage difference	p-value	Percentage difference	p-value	Percentage difference	p-value
January	1.40	0.00	0.88	0.01	1.13	0.00
February	0.97	0.00	0.67	0.05	0.38	0.18
April	1.53	0.01	1.21	0.02	2.56	0.00
May	0.13	0.39	0.03	0.48	-0.04	0.53
June	1.48	0.00	1.44	0.00	1.01	0.03
July	0.70	0.08	0.44	0.20	1.45	0.00
August	1.13	0.01	0.73	0.10	0.66	0.10
September	0.91	0.04	0.56	0.17	1.06	0.03
October	3.77	0.00	3.78	0.00	3.32	0.00
November	1.58	0.00	1.62	0.00	0.67	0.09
December	1.70	0.00	1.78	0.00	1.37	0.00

Divisions based on transformer ratings, percentage of Industrial and Commercial (I&C) customers, Low Voltage Network Templates, or time of day were also assessed but did not show clear patterns in the estimated reductions.

5.3 Changes in Maximum Demand

Alongside the analysis of average demand a similar paired analysis was performed on substation maximum demands (defined as the 99.9th percentile). Table 4 shows the results for maximum quarterly demands (excluding the last week of July and October due to issues with the data). In both cases, the results shown follow the pattern seen in the average demand analysis, with higher decreases seen in the winter months compared with summer ones.

Table 4: differences in quarterly maximum demand

	Mean of substation maxima 2014 (kW)	Mean of substation maxima 2015 (kW)	Mean of difference (kW)	p-value	Percentage drop
Dec, Jan, Feb	161.00	159.20	1.83	0.00	1.13
Apr, May	100.30	99.86	0.43	0.13	0.43
Jun, Jul, Aug	98.04	97.37	0.67	0.03	0.68
Sep, Oct, Nov	119.20	117.50	1.65	0.00	1.38

Whereas a change in average demand equates to a reduction in consumption, a reduction in maximum demand could release additional capacity onto the network. The amount of capacity released is highly dependent on network conditions and the constraints on the particular local network studied. Where thermal overload is the constraining factor then the capacity released is directly related to the demand reduction at peak times, potentially 1.13% in the case trialled. However on voltage constrained networks the increase in voltage due to reduced load will be offset by the reduction needed to cause it.

5.4 Change point detection

As part of the project, statistical change-point models were assessed to see if underlying changes in demand could be detected with no information on voltage change dates. This was used to confirm changes in the underlying demand data from a purely mathematical perspective as well as determine the change dates when they weren't known.

Three separate sets of analysis are considered:

- Cases where there has been a change and the exact date is known.
- Cases where there has been a change and the exact date is not known.
- Cases where there has been no change.

The first step in the analysis was to de-seasonalise the data. This was done by fitting a smoothed curve through the time-series data, which represents the underlying pattern. The residuals between the data and this curve provide the de-seasonalised series. The smoothed curve was then fit using *penalised splines*, which are a form of polynomial regression.

The analysis initially used a period of 4 months (01/10/2014-16/02/2015) centred on the period in which the changes were made (or should have been made in the case where the exact date is not known. The analysis was then repeated for a selection of earlier time points with longer periods giving more data on which to base the underlying mean values. The method was then applied to the three cases listed above.

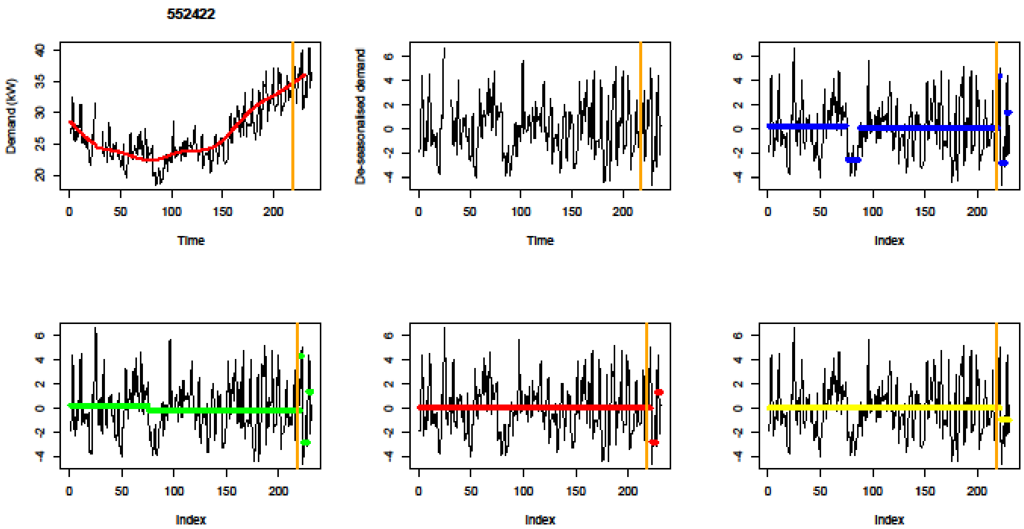

Figure 6: Results of change point model for substation 552422

Figure 6 shows an example of the first case, where the date of change is known. In the top left panel the original (weather corrected) series of demand data is shown together with the smoothed line representing seasonal patterns. In the top middle panel, the de-seasonalised series is shown. Figure 6 also contains the results of applying change point models with different constraints on the number of changes that are allowed. In this case, the maximum number of changes shown are four, three, two and one. If the model is able to detect a difference that might be driven by the change in voltage settings, then a single change in the underlying demand would be permitted and it would be detected at the point of the vertical orange line which shows, in this example, when the change was made. In the last panel in Figure 6, there is an indication that a change has occurred on the 4th December, which is the date of the actual change, as shown by the vertical orange line.

Of the substations that had enough suitable data, change-points within a week of the specified dates were identified in ca. 75% of cases. Of the substations when the change data was recorded, data was available for 128. Performance was similar to that when dates were unknown with changes detected in November or December for ca. 65% of the substations. In the third case, where there was no change to voltage settings, data was available for 204 substations. The change-point model indicated a potential change in the underlying mean in ca. 15% (false positive rate) of cases. Many of these may be due to underlying seasonal effects not being picked up in the standard approach, used when dealing with a large number of substations. Further investigation, with more bespoke modelling of the underlying trends indicated that the false positive rate could be reduced to ca. 10%.

5.5 Effect on reactive power delivered

As well as investigating the changes in real power, the effect of the voltage reduction on reactive power was also investigated. A similar methodology to average real power analysis was used. The same weather correction factors were used and sense checking was applied. Again various levels of sense checking were assessed, as results were relatively robust within those levels. The data shown below has been sense checked based on changes in realistic changes in real power.

Table 5: Effects on reactive power per month

Month	Mean 2014 (kVAr)	Mean 2015 (kVAr)	Mean Difference (kVAr)	Percentage difference	p-value
January	14.96	13.67	1.29	8.62	0.00
February	13.80	12.63	1.16	8.44	0.00
April	10.05	9.48	0.56	5.60	0.04
May	10.66	9.77	0.89	8.35	0.00
June	12.61	11.45	1.16	9.20	0.00
July	13.52	12.36	1.16	8.59	0.00
August	11.70	10.89	0.81	6.95	0.00
September	12.35	11.18	1.17	9.48	0.00
October	13.26	12.39	0.86	6.52	0.00
November	12.83	12.06	0.77	6.02	0.00
December	12.73	12.23	0.49	3.89	0.00

As can be seen in Table 5, there are stable and significant reduction in reactive power due to the drop in voltages. This reduction is of a similar absolute magnitude as the reduction in real power. As the base level of reactive power is significantly lower than the real power, the percentage reduction is much higher. There are no clear seasonal patterns with the results.
As with the real power, investigations were also run on some of the possible influencing characteristics. No clear patterns emerged for the weekday/weekend split however, as shown in

Table 6 and Table 7, there is a much stronger response for smaller, less industrial sites.

Table 6: Effects of I&C split on reactive power reduction

Month	% I&C ≤ 80%		% I&C > 80%	
	(%) Difference	p-value	(%) Difference	p-value
January	11.61	0.00	3.47	0.00
February	10.60	0.00	5.31	0.00
April	7.14	0.00	-5.74	0.90
May	10.13	0.00	2.91	0.10
June	10.94	0.00	3.25	0.06
July	9.66	0.00	6.80	0.01
August	9.05	0.00	2.76	0.06
September	12.02	0.00	5.50	0.01
October	10.01	0.00	2.39	0.07
November	8.24	0.00	3.02	0.03
December	6.56	0.00	0.04	0.49

Table 7: Effects of transformer rating on reactive power reduction

Month	Transformer rating < 500		Transformer rating ≥ 500	
	(%) Difference	p-value	(%) Difference	p-value
January	11.15	0.00	7.90	0.00
February	10.31	0.00	7.89	0.00
April	6.75	0.00	0.10	0.49
May	8.41	0.00	7.47	0.00
June	9.58	0.00	7.95	0.00
July	9.03	0.00	8.38	0.00
August	8.17	0.00	6.38	0.00
September	11.93	0.00	8.48	0.00
October	9.78	0.00	5.29	0.00
November	7.37	0.00	5.48	0.00
December	6.12	0.00	2.83	0.02

6 Voltage Analysis

There are 3 key elements to the investigation of voltages in this project: determining what voltage reduction was actually seen at the distribution substations, highlighting any issues caused by the reduction, and then identifying the scope for further reduction.

6.1 Voltage reduction

The first element of the analysis is to determine the effects of the drop in settings on LV voltages. This conceptually simple question is made more complicated by the fact that the reductions were introduced through 11kV AVC schemes. These are set with dead-bands; as such the reduction is not between 2 set positions, but between 2 different ranges, from 11.4kV (±200V) to 11.3kV (±165V). Furthermore the voltage out along the 11kV and LV networks will be influenced by the loads around them and any generation. As such a change in settings at the primary will not guarantee the same drop across the whole network.
No suitable weather correction could be found for the voltage measurements, as such there will be variability introduced due to the differing conditions.

For the analysis, data from 2014 and 2015 was compared from each individual substation and feeder end monitor using a paired t-test. These were then combined into a summary monthly number just like the demand analysis. This is equivalent to taking the mean of each individual change rather than the difference of the overall mean values. Data was selected for inclusion following some basic sense checking. This compared the mean voltages and ensured they were between 150V and 300V. In addition to this, any voltage measurement of 2V or less was treated as a missing value. The results of this analysis are shown in Table 8 and Table 9.

Table 8: Voltage information for substations monitors

	With Change				Without Change			
Month	Mean 2014	Mean 2015	Percentage difference	p-value	Mean 2014	Mean 2015	Percentage difference	p-value
January	242.10	240.80	0.53	0.00	243.10	242.80	0.13	0.00
February	241.70	240.60	0.44	0.00	243.00	242.40	0.25	0.00
April	244.20	243.30	0.35	0.00	243.20	243.10	0.01	0.38
May	244.40	243.30	0.42	0.00	243.20	243.00	0.08	0.02
June	244.40	243.80	0.28	0.00	243.20	243.10	0.03	0.34
July	244.40	243.70	0.30	0.00	242.40	243.10	-0.30	1.00
August	244.40	243.80	0.25	0.00	242.40	242.90	-0.19	0.96
September	244.30	243.80	0.20	0.00	242.50	242.70	-0.09	0.77
October	243.60	243.60	0.03	0.29	242.40	242.70	-0.12	0.87
November	243.00	243.10	-0.01	0.58	242.80	242.70	0.04	0.32
December	242.70	243.00	-0.15	1.00	243.00	242.60	0.18	0.00

Table 9: Voltage information for feeder end monitors

	With change				Without change			
Month	Mean 2014	Mean 2015	Percentage difference	p-value	Mean 2014	Mean 2015	Percentage difference	p-value
January	241.70	240.40	0.54	0.00	241.90	241.50	0.16	0.00
February	241.50	240.50	0.42	0.00	242.00	241.20	0.32	0.00
April	242.70	242.00	0.27	0.00	242.20	242.30	-0.08	0.99
May	243.30	241.90	0.58	0.00	242.10	242.20	-0.02	0.69
June	243.40	242.60	0.32	0.00	242.10	242.40	-0.12	1.00
July	243.40	242.60	0.34	0.00	241.20	242.40	-0.51	1.00
August	243.30	242.50	0.31	0.00	241.10	242.10	-0.40	1.00
September	243.20	242.50	0.29	0.00	241.50	241.90	-0.18	0.99
October	242.50	242.40	0.04	0.14	241.20	241.70	-0.24	1.00
November	241.70	241.70	0.00	0.46	241.60	241.60	0.02	0.33
December	241.10	241.50	-0.17	1.00	241.70	241.50	0.09	0.00

The results show a statistically significant (p value ≤0.05) reduction for substations and feeder ends with the voltage change. In general the changes are not significant for monitors that did not have the change.

As the changes happened from October 2014, a drop in the significance for the substations with a change can be seen in November and December. This is caused by a static classification within the groups, some of the monitors will have already been subject to the change by November 2014.

The results show that the reduction in settings has caused a reduction in system voltage. However this is lower in magnitude than the change in settings.

It should be noted that these values are the product of multiple averages. As such they will attenuate the individual substation values. When dealing with a non-linear relationship such as the one between demand and voltage, using such values to determine the associated demand drop would significantly underestimate results.

Figure 7 presents the distribution of voltages for all substations in January and July of 2014 and 2015. Figure 8 presents the equivalents for feeder ends.

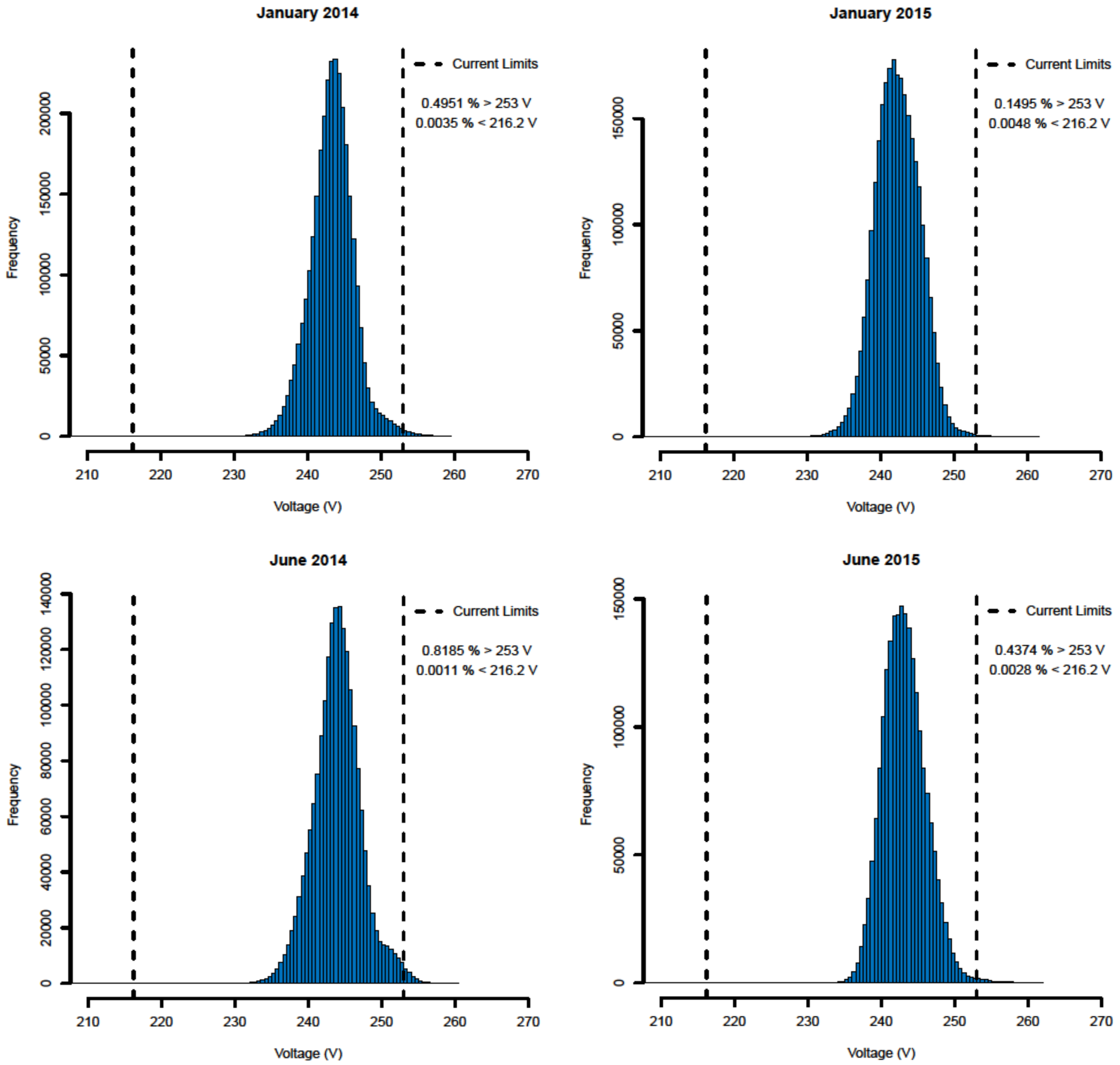

Figure 7: Substation voltage distributions

As presented in the LVNT project, the voltages sit at the higher end of the spectrum with the substation voltages higher and less spread than the feeder ends. Also, as expected, the voltages are higher in the summer than the winter. The voltage reduction program shifts the distributions down the voltage spectrum between 2014 and 2015, however even after the changes, the voltages sit at the higher end of the allowable voltage window.

It should be noted that networks were designed to provide voltages within limits to customers at the end of feeders under abnormal running conditions. This would allow networks to be back-fed whilst still providing sufficient voltages to customers. Such conditions will be rare and will only affect a small proportion of LV networks along a feeder; as such these conditions will be lost in the lower tails of the distributions. The ability of a network to keep these tails within limits will increase the ability to back-feed customers under outage conditions without the need for supporting generation, enabling quicker and more efficient restoration times.

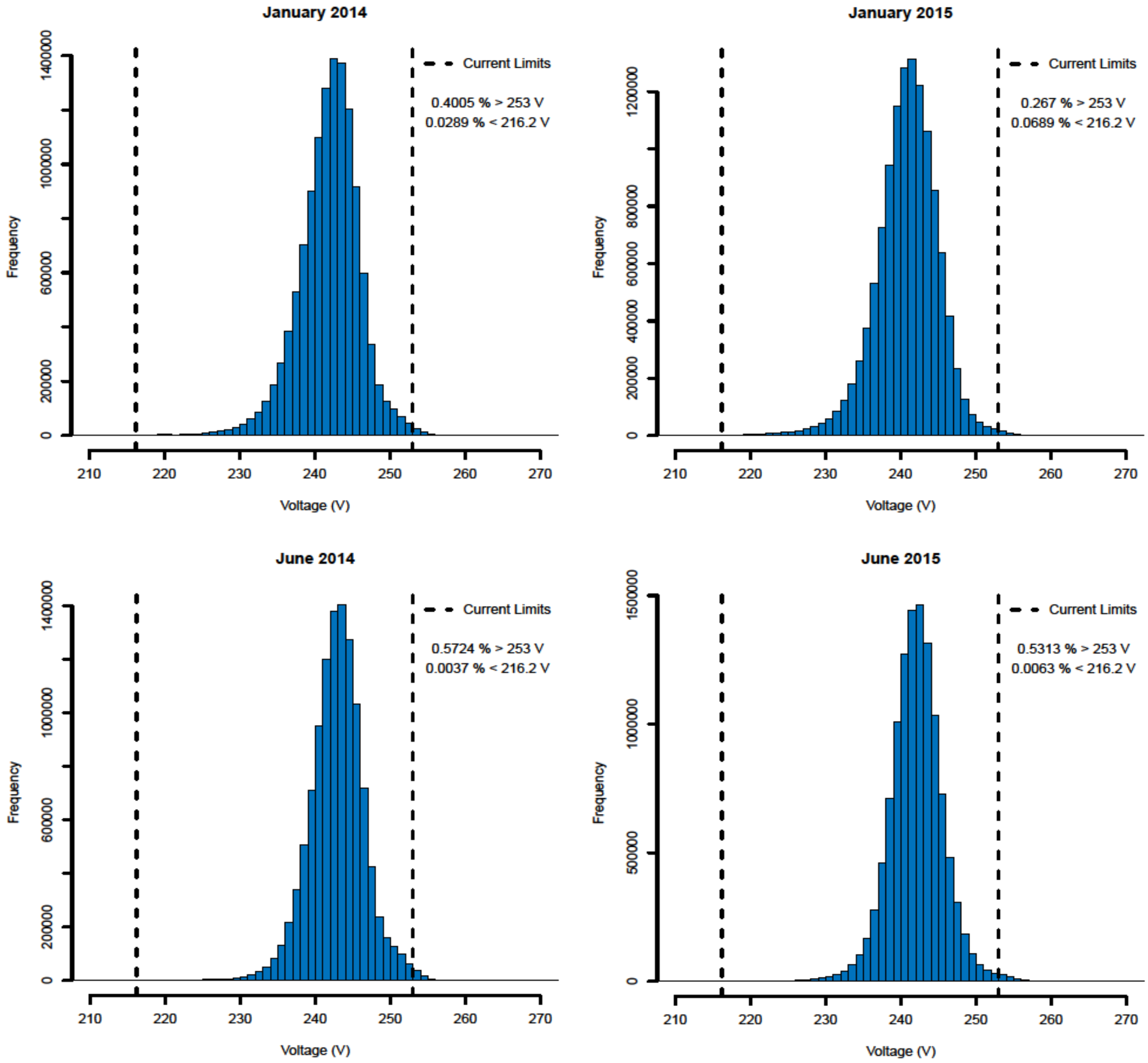

Figure 8: Feeder end voltage distributions

6.2 Effects on excursions

Figure 9 and Figure 10 plot the profiles of substations with excursions in January 2015. These highlight several interesting points:

- The majority of substation under voltages are not true issues. These are a mix of outages or spurious data points (sharp dips below 200V)
- The substation overvoltage data presents a more realistic picture with small excursions over the limits.
- Apart from a few spurious over voltage measurements, the feeder end data is consistent and shows a much larger spread. This ties into expectations, as the extra impedance between the substation and feeder end allows for this wider spread.
- Some monitors register both over and under voltage excursions.

It should be noted that all networks identified as having significant levels of excursions as part of this trial have been assessed for remedial work.

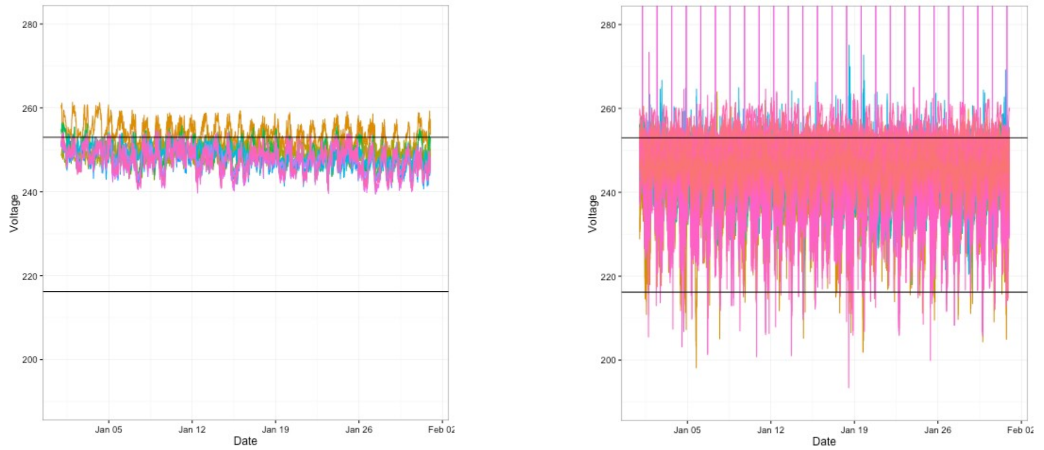

Figure 9: Voltage plots for all substations (left) and feeder ends (right) with at least one over voltage excursion

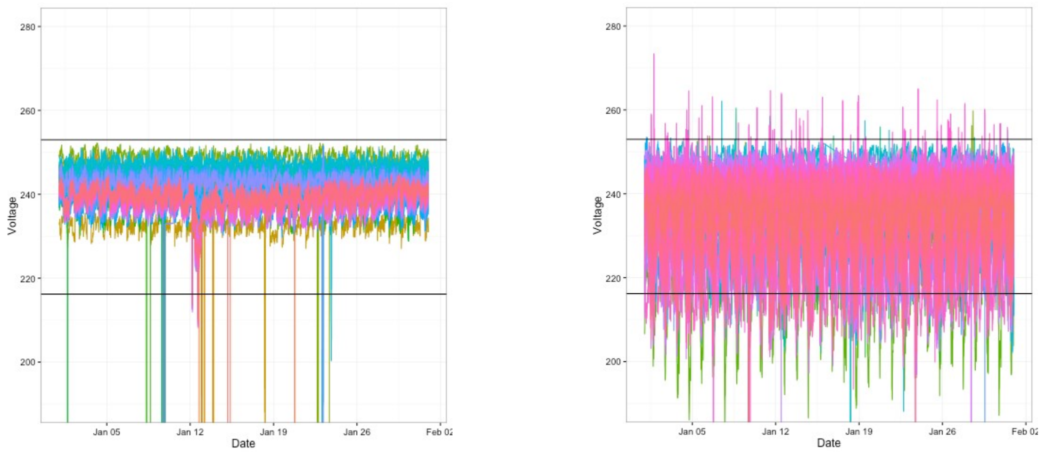

Figure 10: Voltage plots for all substations (left) and feeder ends (right) with at least one under voltage excursion

The total number of voltage excursions monitored on the network is very low, just 0.33% of measurements at feeder ends were over voltage and 0.004% were under. The results of the full analysis are presented in Table 10 and Table 11.

Table 10: overview of substation excursions

Month	% of Ten-Minutes Over 253 V				% of Ten-Minutes Under 216.2 V			
	No Voltage Change		Voltage Change		No Voltage Change		Voltage Change	
	2014	2015	2014	2015	2014	2015	2014	2015
January	0.27	0.04	0.31	0.20	0.0019	0.0049	0.0023	0.0048
February	0.25	0.00	0.24	0.20	0.0036	0.0002	0.0040	0.0013
March	0.23		0.39		0.0030		0.0012	
April	0.13	0.00	0.72	0.32	0.0011	0.0624	0.0020	0.0001
May	0.17	0.00	1.16	0.50	0.0044	0.0008	0.0135	0.0007
June	0.26	0.03	1.25	0.67	0.0008	0.0058	0.0014	0.0012
July	0.36	0.00	1.16	0.50	0.0062	0.0021	0.0014	0.0003
August	0.26	0.00	0.99	0.65	0.0087	0.0022	0.0021	0.0001
September	0.32	0.00	0.65	0.50	0.0011	0.0013	0.0009	0.0008
October	0.17	0.00	0.40	0.69	0.0035	0.0031	0.0100	0.0008
November	0.10	0.00	0.26	0.58	0.0068	0.0006	0.0009	0.0056
December	0.12	0.00	0.27	0.60	0.0020	0.0034	0.0003	0.0009

Table 11: overview of feeder end excursions

Month	% of Ten-Minutes Over 253 V				% of Ten-Minutes Under 216.2 V			
	No Voltage Change		Voltage Change		No Voltage Change		Voltage Change	
	2014	2015	2014	2015	2014	2015	2014	2015
January	0.47	0.11	0.20	0.10	0.0019	0.0073	0.0441	0.0890
February	0.44	0.00	0.17	0.07	0.0117	0.0082	0.0522	0.0624
March	0.42	0.00	0.26	0.06	0.0215	0.0048	0.0224	0.0326
April	0.36	0.01	0.32	0.07	0.0013	0.0317	0.0060	0.0072
May	0.50	0.01	0.36	0.31	0.0006	0.0067	0.0045	0.0048
June	0.72	0.02	0.40	0.41	0.0123	0.0099	0.0014	0.0008
July	0.80	0.01	0.38	0.37	0.0225	0.0124	0.0012	0.0024
August	0.78	0.01	0.32	0.56	0.0099	0.0090	0.0034	0.0024
September	0.75	0.01	0.23	0.37	0.0034	0.0046	0.0029	0.0045
October	0.48	0.01	0.09	0.53	0.0043	0.0049	0.0241	0.0088
November	0.46	0.00	0.10	0.46	0.0050	0.0105	0.0643	0.0314
December	0.29	0.00	0.15	0.43	0.0108	0.0061	0.0789	0.0363

As expected, in 2014 the total number of excursions is dominated by over voltages. These are worse at substations, during the summer, during the night. The under voltages are an order of magnitude smaller than the over voltages and are worse at feeder ends, during the winter and during the evening peaks. An example of the excursions over 3 days is shown in Figure 11

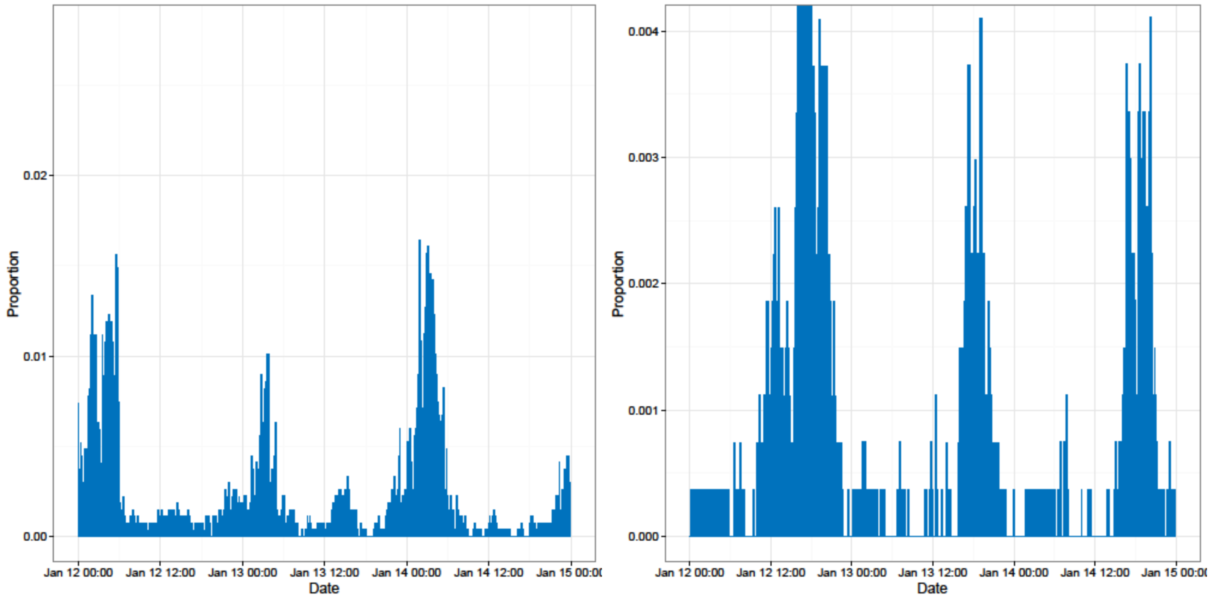

Figure 11: Number of over (left) and under (right) excursions on the 12th, 13th and 14th of January

The shift in voltage has a noticeable impact on voltage excursions, reducing the overall number. Whilst the number of under voltage excursions increased, the number of over voltages decreased by significantly more. This is to be expected considering the distribution of voltages.

It should be noted that Table 10 and Table 11 show large drops in excursions for both substations with and without the voltage change. However the excursions for the substations without the change come from very few monitors making the changes statistically non-significant.

Table 12 and Table 13 highlight the changes of substation excursion statuses, used to track the changes in substations. This shows that most of the changes associated with the change in voltage settings. Also all the substations that no longer have excursions are amongst the substations affected by the voltage change.

Table 12: Changes in substation excursions in January

2014	2015	No. of Substations	
		Substations without a Voltage Change	Substations with a Voltage Change
Over-excursions	Over-excursions	2	4
Over-excursions	No over-excursions	0	12
No over- excursions	Over-excursions	1	4
Under-excursions	Under-excursions	3	0
Under-excursions	No under-excursions	2	21
No under-excursions	Under-excursions	15	50

Table 13: Changes in feeder end excursions in January

2014	2015	No. of Feeder Ends: Feeder Ends without a Voltage Change	No. of Feeder Ends: Feeder Ends with a Voltage Change
Over-excursions	Over-excursions	25	18
Over-excursions	No over-excursions	1	58
No over-excursions	Over-excursions	3	14
Under-excursions	Under-excursions	3	19
Under-excursions	No under-excursions	3	19
No under-excursions	Under-excursions	9	25

Correlations between substation and feeder end excursions were also investigated to try and determine the root cause of the excursions. It was observed that most substation over voltage excursions (between 50% and 70%) were accompanied by excursions of the associated feeder end monitors. This highlights the knock on effect of the substation voltage on the whole feeder. Inversely between 30-80% of feeder end over-excursions were associated with substation excursions. This implies that a voltage rise and generation have caused the remaining feeder excursions.

The number of under excursions is far more limited and so the high correlation (over 90%) between substation under voltages and feeder end that are in limit is probably due to spurious reading at substations mentioned previously. In contrast the high association between feeder end under voltages and substations within limits shows the expected voltage drops along networks.

It was also shown that the majority of excursions are focussed on a few key substations. This is particularly true for under voltage excursions. As such, targeting of these specific issues could allow for a further reduction in overall voltages

6.3 Scope for further work

As mentioned previously the voltages observed still sit at the higher end of the limits. As such it appears that there is scope for further reduction and benefits to customers.

Based on the distributions shown earlier, a further 1.2% reduction could be accommodated to optimise the voltage to minimise excursions (based on January).

However there are limitations to this simplistic approach.

As mentioned earlier, networks need to be able to maintain voltages in abnormal running to allow for quick and efficient restoration of supplies during outages. These infrequent occurrences will be masked by the normal running conditions and are not obviously visible on the distributions.

Furthermore, the capacity of the 11kV network to accept reduced voltages is limited. In certain situations, mainly long rural feeders, the 11kV network will see voltage issues before the LV network, especially with the tighter restrictions of ±6%. As well as limits on the network, primary transformer tap changers have limited ranges. As such physically implementing reductions may not be possible with upgrading tap changers.

The implementation of voltage reduction via 11kV AVC schemes is also very broad brush, covering all customers fed from each primary substation. These broad reductions will require DNO's to manually tap up distribution tap changers to resolve issues at network extremities, requiring outages. However as highlighted earlier, these can be highly targeted and if well-coordinated could allow for further reductions.

It should also be noted that there are multiple different design philosophies across DNO's for LV voltage design. These reflect the historic differences in ownership, different designers as well as the different geographies. As such different networks have different starting points. Should a network already be running lower voltages, for historic reasons, or even to accommodate additional generation, there will not be the same scope for reduction.

The development of other methods of exploiting voltage foot room must also be considered. ENW, through their CLASS project have identified the significant value of ancillary services a DNO could offer to National Grid through dynamic voltage reduction. This could not be offered to the same extent if voltages were reduced on a permanent basis. As such both options should be compared to establish how to present the best value to customers.

There is also an ENA task force looking at Statutory Voltage Limits on the LV network, specifically the widening of limits to ±10% in line with many other European countries. Should such a change be implemented it would allow for further use of this foot room.

7 Operation Juniper

Under GC OC6, DNOs have a requirement to provide demand reduction to the System Operator during system operation problems. At the time of the trial it was expected that the first 10% of the reduction would be achieved through 2 steps of voltage reduction, each of 3%.
In an attempt to test and quantify the response, National Grid ran Operation Juniper across the licence areas in October 2013. This called for a reduction of 3% with the effects closely monitored. In South Wales the demand reduction was carried out between 10:00am-12:00pmon on October 15th.
The trial found that the demand reduction delivered via a 3% voltage reduction varied considerably. Results ranged from 0% to 2.7%, with an average reduction in demand of 1.5% and the reduction seen in South Wales of 0.2%. This is much lower than the expected 5%. Following the trial GC OC6 was amended to expect a 1.5% reduction in demand following a 2-4% reduction in voltage.

The aim of this analysis is to observe the effects of Operation Juniper on the LVNT monitored network. The main analysis comprises of a comparison of voltage and demand before, during and after the period of the Operation Juniper trial.

7.1 Reductions observed

Figure 12 shows an example of the voltage profile measured at a substation for the 15th October 2013. The period of the Operation Juniper trial can clearly be seen with a marked drop in voltage between 10am and 12pm. Similar shapes can be seen for the other substations and the feeder end monitors.

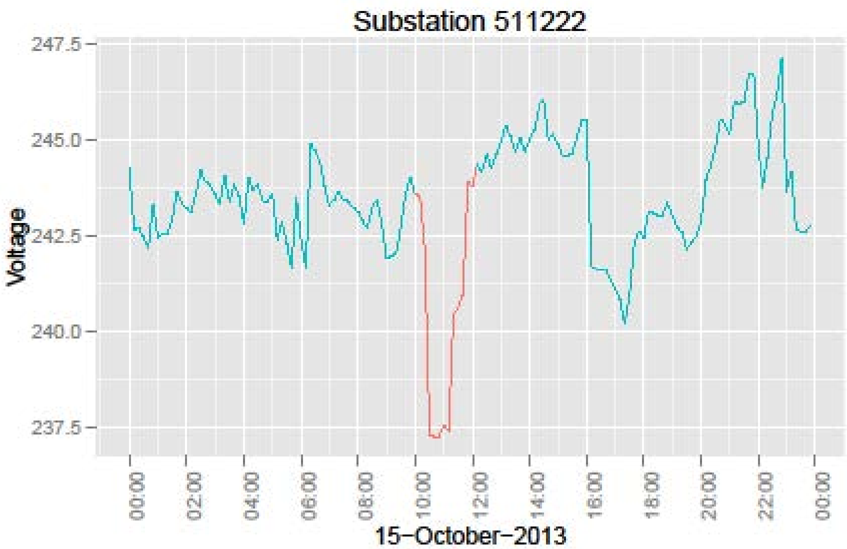

Figure 12: Voltage profile for substation 511222

The corresponding demand profile can be seen in Figure 13 in which an associated, albeit less marked, decrease in demand can be seen. The corresponding plots for all substations and voltage monitors at feeder ends are available upon request in digital format.

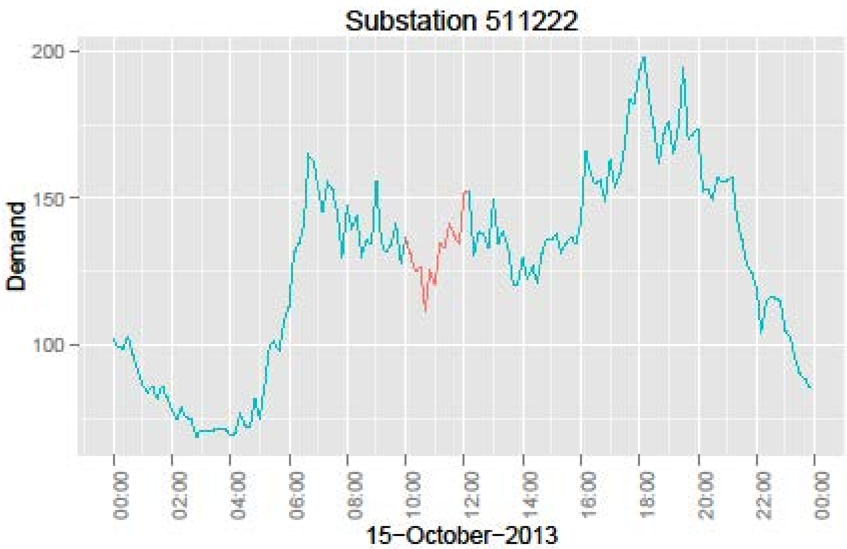

Figure 13: demand profile for substation 511222

The level of voltage drop can be determined in several different ways. By comparing the voltage during the trial period with average voltage in the 2 hours previous, 2 hour following or both, reductions of 0.75%, 0.9% and 0.8% can be found, all with very high significance. Similar, statistically significant, reductions of voltage was measured at feeder ends with results of 0.7%, 1.0% and 0.9% respectively.

These reductions are significantly lower than the requested 3% drops applied at the higher voltage levels. The reduction in voltage then has knock on effects on the demand drops found.

A detailed assessment highlighted 3 contributing factor:

- Operational faults on certain tap changers. WPD has since worked to rectify these issues
- 2 Networks in South Wales are fed at EHV rather than 132kV. The OC6 call in South Wales is operated at BSP level and hence did not affect those networks
- At certain sites the reduction of voltages at the BSP was not reflected at primary level. This may be due to embedded generation.

Directly comparing demand during and around the trial time gave non-significant results due to the more variable nature of demand profiles. For this reason, an alternative method was developed in which the measurements made during the trial period are treated as missing data and then estimated based on a model for the underlying demand profile. Multiple approaches were used to estimate the measurements during the trial period as if the reduction in voltage hadn't occurred. These include linear interpolation between the periods before and after the trial, smoothing splines and trending based on historical data.

An example can be seen in Figure 14 for substation 512443 where the black is the actual profile; green is the result of linear interpolation and red the result of smoothing splines. There are pros and cons with each prediction method, however all produced similar results: a significant reduction of 0.6% was observed using linear interpolation ($p = 0.017$) and 0.5% using splines (non–significant). This drop in demand is far lower than the 5% traditionally expected.

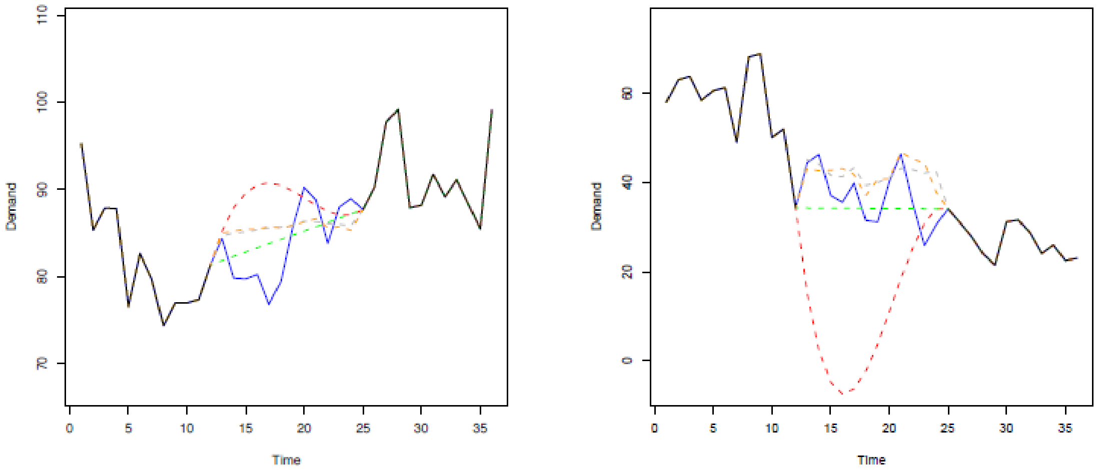

Figure 14: example of demand predictions during operation juniper.

However acknowledging the reduced voltage drop it does tie into previous project findings. The expected response to a 0.88% drop in demand was found to be approximately 0.77% for the period between 10 and 12 in September (chosen due to the issues with the data in October). With the minimal drop in voltage actually seen at distribution substations, approximately 0.8%, then we would only expect to see a reduction of 0.7%.

7.2 Predicted effects for other months

Operation Juniper reduced the voltage for ten minutes over a two-hour period, mid-morning on a Tuesday in October 2013. As described above, this resulted in a significant reduction of 0.6% during the trial period. The average reductions in demand, given in Section 2, can be used to estimate the effect of the same action performed at a different time of the year. For example, the measured average demand reduction for December is 1.7%, compared to 1.13% in August. From this, it can be assumed that if Operation Juniper had been performed in December, its effect would be greater than if it had been performed in August. Taking the ratio of the average demand reduction for a given month, relative to the baseline, October, gives a factor which can be used to estimate the effect of performing Operation Juniper at other times of the year. This factor multiplied by the reduction of 0.6%, gives a predicted reduction for performing Operation Juniper for every month. Table 4.3 presents the predicted reductions using the smoothed values of the monthly average demand reduction.

Table 14: The estimated drops of OC6 calls in other months

Month	Average Reduction (Smoothed) (%)	Reduction Relative to Baseline (Oct)	Predicted Reduction due to Juniper (%)
January	1.22	0.98	0.59
February	1.15	0.92	0.55
March	1.09	0.88	0.53
April	1.05	0.85	0.51
May	1.04	0.84	0.50
June	1.05	0.84	0.50
July	1.07	0.86	0.52
August	1.12	0.91	0.55
September	1.17	0.94	0.56
October	1.24	1.00	0.60
November	1.33	1.07	0.64
December	1.38	1.11	0.67

8 Conclusions

The analysis carried out as part of the VRA project has presented some clear learning.
The permanent reduction in voltage at 11kV AVCs can deliver a significant benefit to customers. This is mainly in the form on a reduction in consumption. The 0.88% reduction trialled showed an average demand consumption drop of 1.16%, worth approximately £14.9 million annually in South Wales. There are also network benefits to be found due to the reduction in maximum demand, helping release additional capacity. The effect of voltage reduction on demand is seasonal, however further characterisation was not possible. There is also a significant reduction reactive power consumed by the networks associated with the voltage changes which must be accounted for.
A detailed investigation of the voltage profiles highlighted the effects of reduction and it’s ability to reduce voltage excursions on the network. This also highlights the scope for further reduction in the monitored network. By dropping the voltage the extra 1.2%, and optimising the distribution to minimise excursions, an extra £15.41 million could be saved off customer bills. However these benefits must be weighed up against the other potential uses of foot-room and the additional costs incurred resolving individual under voltage issues caused by the widespread changes as well as the operational restrictions this might bring.
The investigation into operation juniper highlighted the effects of a dynamic drop in voltage. This response was however muted by the time of the call and the issues actually implanting the drop on the distribution network.