WESTERN POWER DISTRIBUTION
INNOVATION

NEXT GENERATION NETWORKS

VOLTAGE REDUCTION ANALYSIS

CLOSEDOWN REPORT

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Contents

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
SO	System Operator
SWVRA	South Wales Voltage Reduction Analysis
UoB	University of Bath
VRA	Voltage Reduction Analysis

Executive Summary

Following the Low Voltage Network Templates project, WPD reduced the voltage settings across its East Wales, Cardiff and Swansea areas. This project looked to assess the effects of this change on both demand and voltage to help inform any future changes to network voltages.

The University of Bath, conducted extensive statistical analysis on over 200 million data points to identify any changes caused by the modified settings. The analysis found that the reduction in voltage caused a statistically significant reduction in both average and maximum demands as well as average reactive demand at the monitored substations. No reductions were identified where settings hadn't been altered.

The 0.88% average reduction in voltage settings caused a 1.16% reduction in average demand over the year and a 1.13% reduction in maximum demand. If scaled to the whole of South Wales, the reduction in average demand would equate to a yearly decrease of 131.9 GWh, worth approximately £14.9m on customer bills over a year. This would also save ca. 70,000 tonnes of CO_2 per year. In addition the reduction in maximum demand would release capacity on thermally constrained LV networks.

Voltage profiles were also analysed as part of the project. Following the change in settings, voltages still sit at the higher end of the allowable spectrum with scope for further reductions. The change of settings also reduced the already low number of voltage excursions. A small increase in under-voltage excursions was offset by a much larger reduction in over-voltage excursions.

Building on this improved understanding of the benefits and effects of voltage reduction, WPD will be reducing 11kV voltage settings across its network. This will enable further reductions in demand and further savings.

Investigations into National Grid's operation juniper were also carried out, confirming the low responses mentioned. This was due to a combination of time of implementation but also a smaller than expected reduction in voltage seen at the distribution substations.

1 Project Background

LV voltages must be kept within the statutory limits of 230V + 10%/- 6% (253.3V-216.2V). With minimal active voltage control beyond the 33/11kV transformers and designs based on demand dominated networks, the voltages were generally set as high as possible to account 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 magnitude of the reaction to the reduction depends on the specific make-up of the network load. As this is generally unknown there are various wide ranging estimates, going from consumption dropping by the square of the reduction to no drop at all.

With such uncertainty it is important to quantify the reactions of consumption, maximum demand and voltage profiles to reduction in voltage. This will allow network licensees to understand the effects of dropping voltage and make informed decisions on any changes in voltage setting policy.

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 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%

Following this reduction the SWVRA 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 shows that a small voltage reduction can have a significant effect on consumption, the analysis was limited by the data available at the time and lead to many additional questions. The analysis only covered approximately 1 month following the reduction, January 2015, and so 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.

As such this project looked to follow up the promising IFI project with a much fuller analysis on a more complete data set. The analysis work was conducted by the University of Bath. Their full report is available on the WPD innovation website:

www.westernpowerinnovation.co.uk/Projects/Closed-Projects/Voltage -Reduction-Analysis.aspx with full electronic appendices available on request.

2 Scope and Objectives

This project had no operational elements as the monitoring equipment was already in place from the LVNT project. The University of Bath analysed the large database of voltage current and power measurements for the area. This included a whole year of data following the voltage change.

The detailed areas assessed were:

- The effect of seasonality on consumption reduction
- The effect of customer make up on consumption reduction
- The effect of seasonality on demand reduction
- The effect of customer make up on demand reduction
- The effect of the 11kV voltage reduction on LV voltage profiles
- The effect of temporary voltage reduction on demand and consumption (investigate the effects of National Grid's operation Juniper on our monitored network).

The objective of this project was to refine our estimates on the effects of voltage reduction on consumption, demand and voltage profiles.

By understanding the effects of key parameters current predictions can be improved and the benefits better understood. The assessment of existing profiles should also indicate the available scope for further reduction.

3 Success Criteria

The project had four success criteria:

- Quantifying the effect of seasonality, time and substation type on consumption reduction
- Quantifying the effect of seasonality, time and substation type on Maximum demand reduction
- Quantifying the effect of 11kV voltage reduction on LV substation and feeder end voltage distributions
- Refined estimate of the benefits of voltage reduction as well as the scope for further reduction

4 Details of the Work Carried Out

There were three main strands of work carried out:

- Investigation into the effects of the settings change on demand
- Investigation into the effects of the settings change on voltages
- Investigations into the effect of National Grid's operation Juniper on the LVNT monitored area.

4.1 Demand Analysis

The aim of the demand data analysis 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 WPD's 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 of comparing 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. No data was recorded in March 2015 due to technical issues and so a comparison based on that month is not possible.

4.1.1 Analysis of 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.

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. This used a similar method on different subsets.

4.1.2 Analysis of Maximum Demand

Alongside the analysis of average demand a similar paired analysis was performed on substation maximum demands (defined as the 99.9th percentile). This was used to assess the network capacity released by the drop in voltage. The sensitivity to the different time frames of the maximum values was also investigated.

4.1.3 Change Point Models

As part of the project, statistical change-point models were also 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 were 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 where the smoothness of the line is chosen to guard against over-fitting the data.

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.

4.1.4 Analysis of 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 the 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.

4.2 Voltage Analysis

There were 2 key elements to the voltage investigations in this project

- Determining what voltage reduction was actually seen at the distribution substations;
- Highlighting any issues caused by the reduction.

4.2.1 Voltage Reduction

The first element of the analysis was 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.

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. 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.

4.2.2 Effects on Excursions

Alongside the analysis of network voltage profiles, a comprehensive investigation into the effects of the settings change on voltage excursions was carried out. During this work the frequency, timing and location of excursions was investigated for substation and feeder ends. The interactions of both ends of the networks was also investigated.

4.3 Operation Juniper Assessment

The aim of this analysis was to compare National Grid's findings from Operation Juniper to those observed within the LVNT monitored network. Operation Juniper aimed to test the capability of DNOs to respond to a GC OC6 call for demand reduction via voltage reduction. This was done by requesting a 3% drop in voltage for 1 hour on the 13th of October 2013. The main analysis comprised of a comparison of voltage and demand before, during and after the period of the Operation Juniper trial.

Predictions of for the application in other months were also made.

5 The Outcomes of the Project

The following section outlines the learning and outcomes of the project.

5.1 Demand Analysis

5.1.1 Analysis of Average Demand

Figure 1 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.

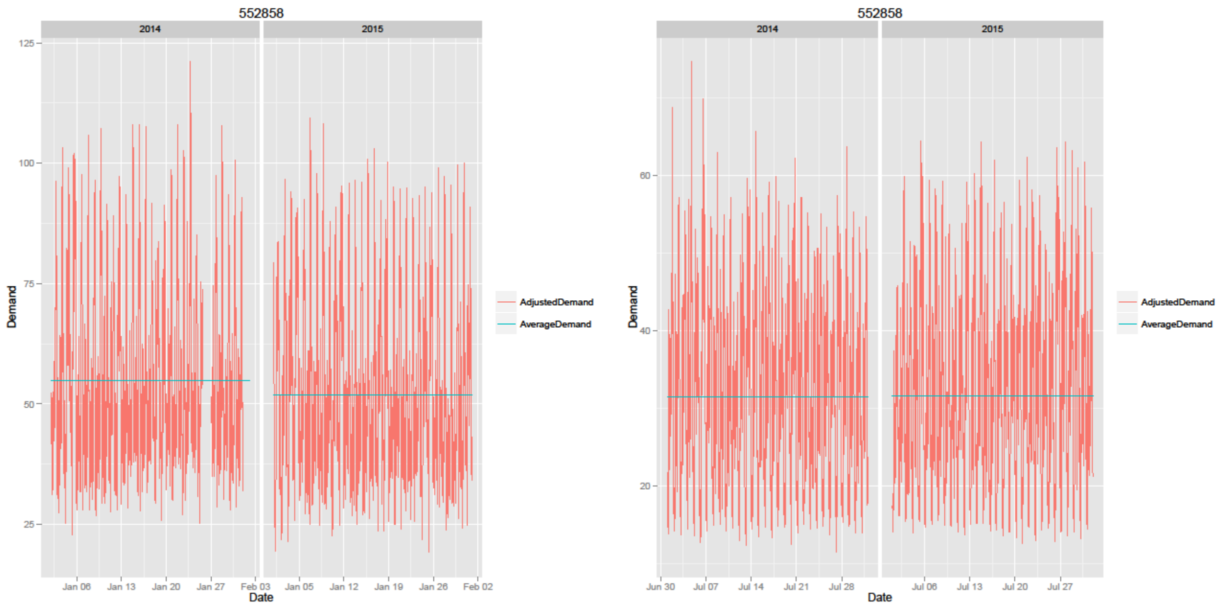

Figure 1: Comparison of average daily demand data for substation 552858 in January and July

Table 1 shows the combined results for all the relevant substations for each month.

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
September	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

Table 1: Differences in monthly average demand for 2014 and 2015

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 1 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 sufficiently compensated for the mildness of 2015. This may be due to the softer element of customer behaviour. Different demand requirements will be seen on climatically 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 2 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.

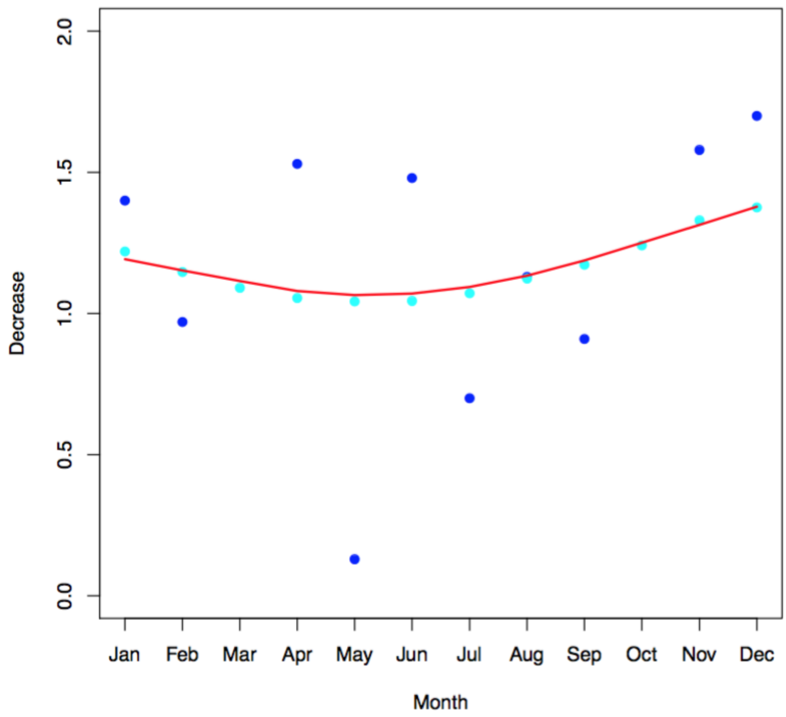

Figure 2: Estimates of average demand reduction between 2014 and 2015

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 2, 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.

Table 2 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.

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

Table 2: differences between monthly averages for weekdays and weekends

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.

5.1.2 Analysis of maximum demand

Table 3 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.

	Mean of Substation Maxima 2014 (kW)	Mean of Substation Maxima 2015 (kW)	Mean of	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

Table 3: differences in quarterly maximum demand

Whereas a change in average demand equates to a reduction in consumption, a reduction in maximum demand would 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 more than offset by the reduction needed to cause it.

5.1.3 Change Point Models

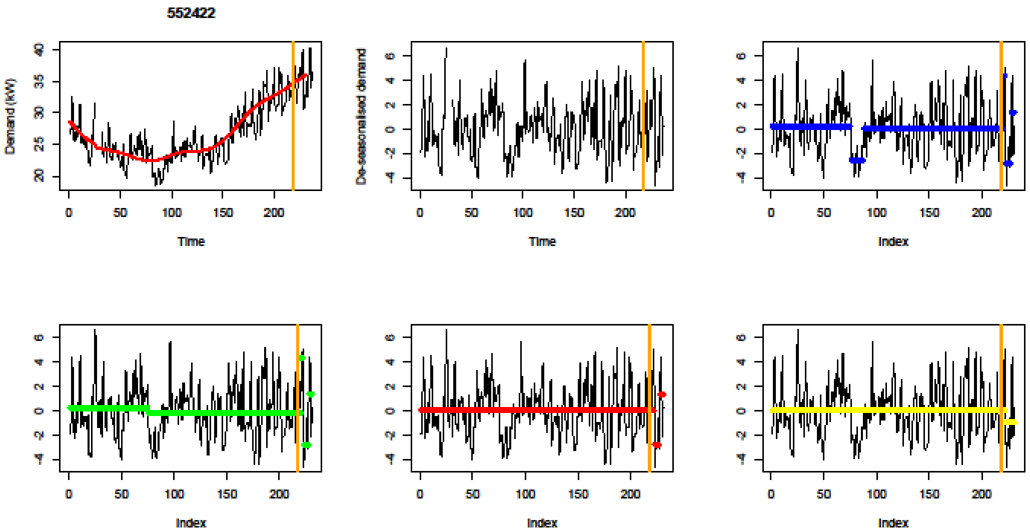

Figure 3: Results of change point model for substation 552422

In the top left panel of Figure 3 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 3 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 3, 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 weren't known 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%.

5.1.4 Analysis of Reactive Power Delivered

As can be seen in Table 4, there is a stable and significant reduction in reactive power due to the drop in voltage. 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.

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

Table 4: Effects on reactive power per month

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

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 5: Effects of I&C split 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

Table 6: Effects of transformer rating on reactive power reduction

5.2 Voltage Analysis

5.2.1 Voltage Reduction

The results of this analysis are shown in Table 7 and Table 8.

Month	Transformer rating <500				Without Change			
	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 7: Voltage information for substations monitors

With change	Without change				With change			
Month	Mean 2014	Month	Mean 2014	Month	Mean 2014	Month	Mean 2014	Month
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

Table 8: Voltage information for feeder end monitors

The results show a statistically significant (p value ≤ 0.05) reduction for substations and feeder ends with the voltage change. As the changes happened from October 2014, a drop in the significance 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.

In general the changes are not significant for monitors that did not have the change.

This shows that the reduction in settings has caused a reduction in system voltages. 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 4 presents the distribution of voltages for all substations in January and July of 2014 and 2015. Figure 5 presents the equivalents for feeder ends.

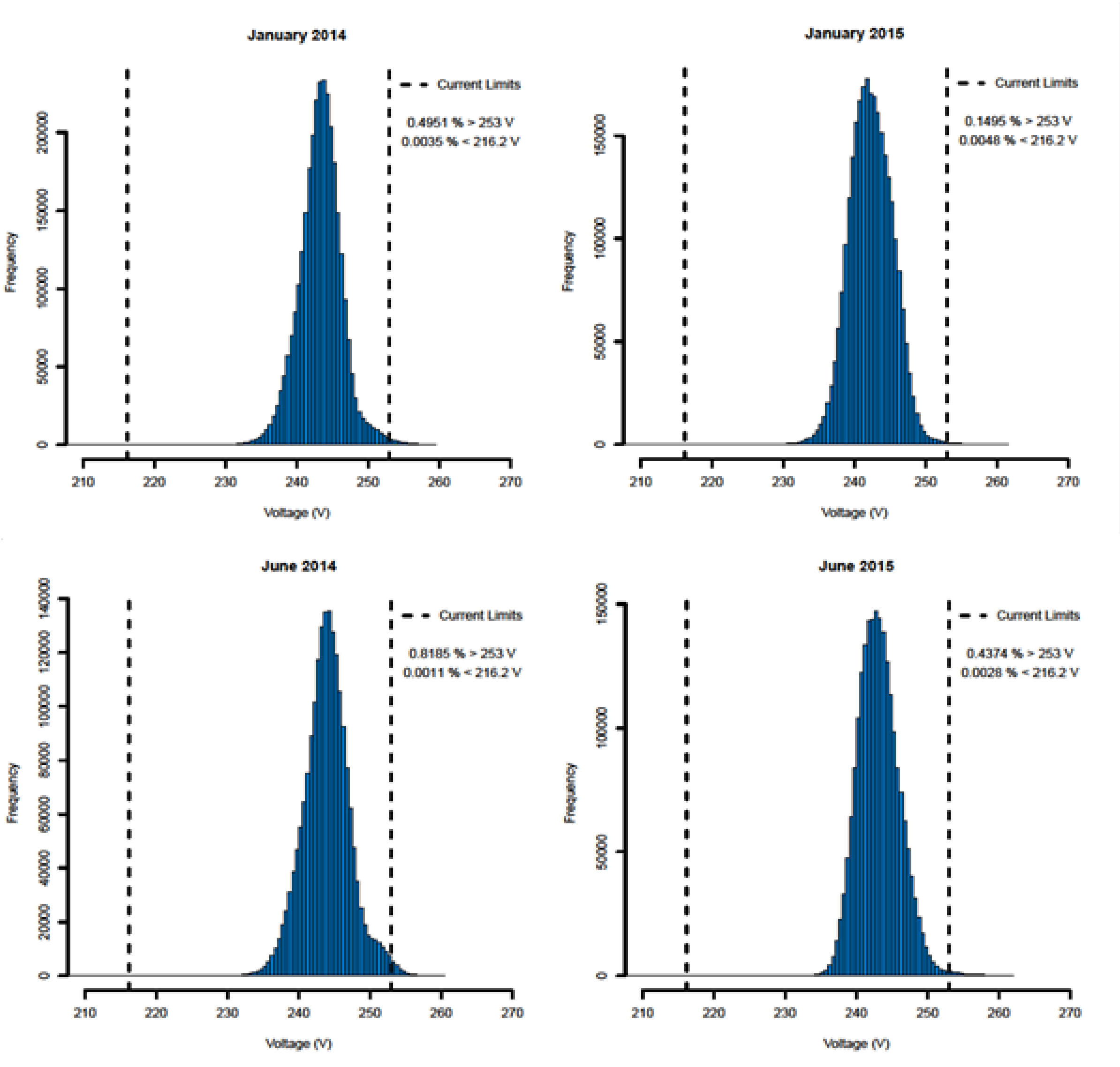

Figure 4: Substation voltage distributions

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. This is a feature designed into the network to allow voltages to remain within limits during abnormal running conditions such as back feeds.

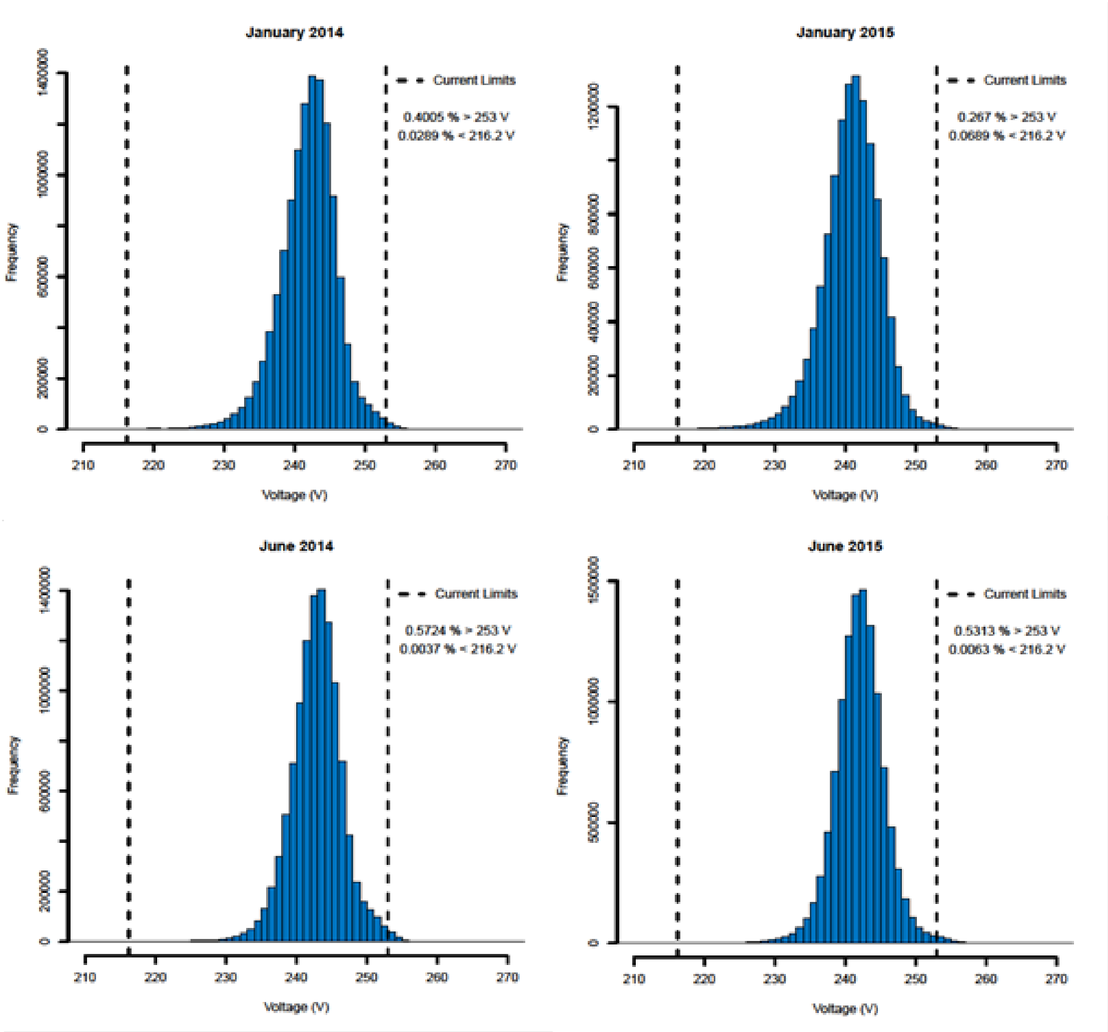

Figure 5: Feeder end voltage distributions

5.2.2 Effects on Excursions

Figure 6 and Figure 7 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.

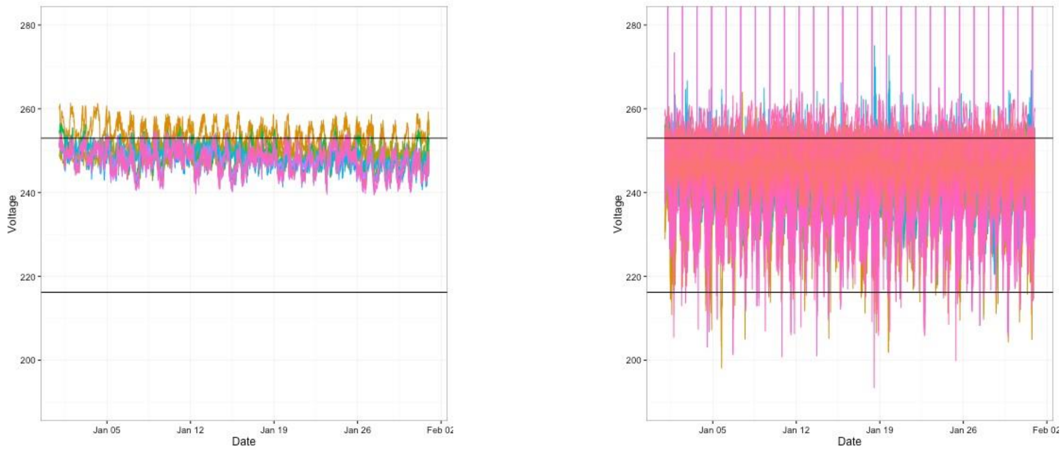

Figure 6: Voltage plots for all substations (left) and feeder ends (right) with at least one over voltage excursion

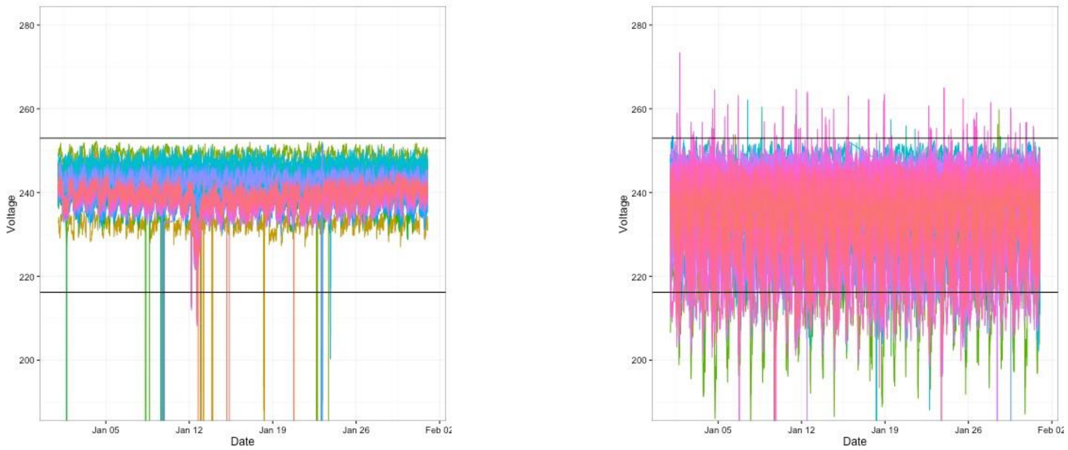

Figure 7: Voltage plots for all substations (left) and feeder ends (right) with at least one under voltage excursion

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 analysis are presented in Table 9 and Table 10.

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 9: 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	0.47	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

Table 10: overview of feeder end excursions

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 8

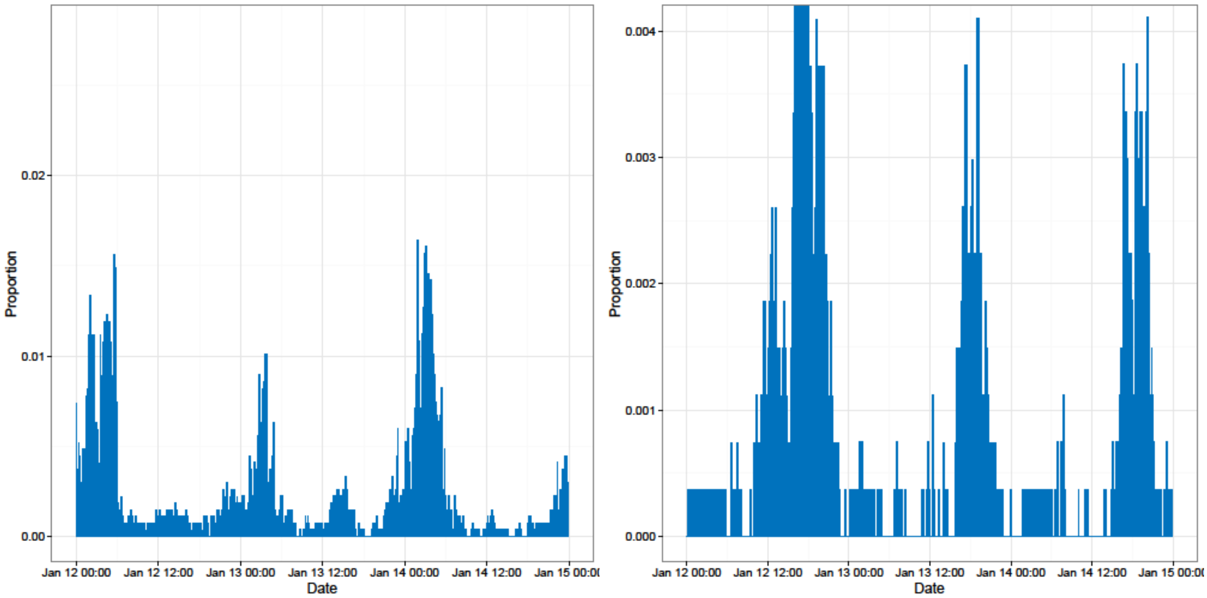

Figure 8: Number of over (left) and under (right) excursions on the 12th, 13th and 14th of January

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 9 and Table 10 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 11 and Table 12 highlight the changes of substation excursion statuses. This shows that most of the changes amongst substations are 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.

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 11: Changes in substation excursions in January

2014	2015	No. of Feeder Ends	
		Feeder Ends without a Voltage Change	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

Table 12: Changes in feeder end excursions in January

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. Conversely 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 so the correlations are much less meaningful.

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 these individual cases could be rectified by manually tapping the distribution transformer. Selectively targeting these substations could allow for greater drops of the main 11kV AVC settings. Whilst 11kV AVC settings can be changed without disturbance on the network, the tapping of distribution transformers must be done off load. As such there are significant costs associated with tapping distribution transformers

5.3 Operation Juniper Assessment

Figure 9 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 feeder end monitors.

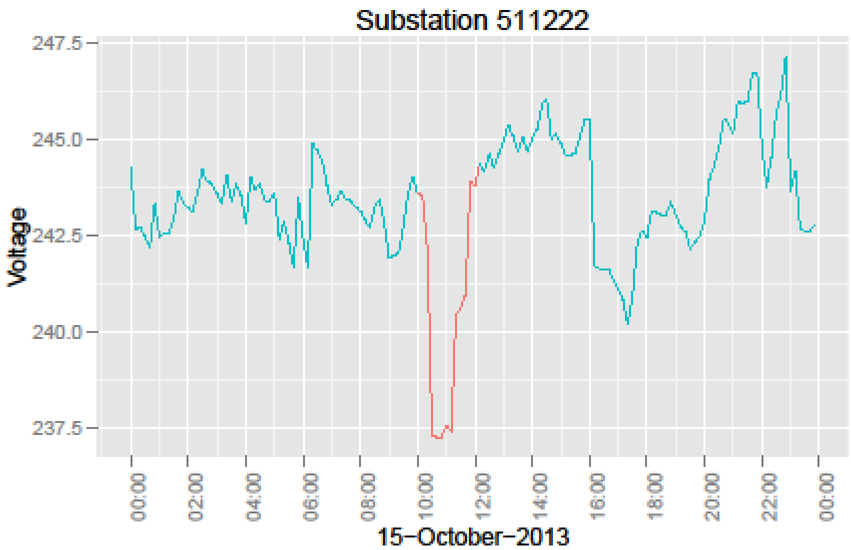

Figure 9: Voltage profile for substation 511222

The corresponding demand profile can be seen in Figure 10 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.

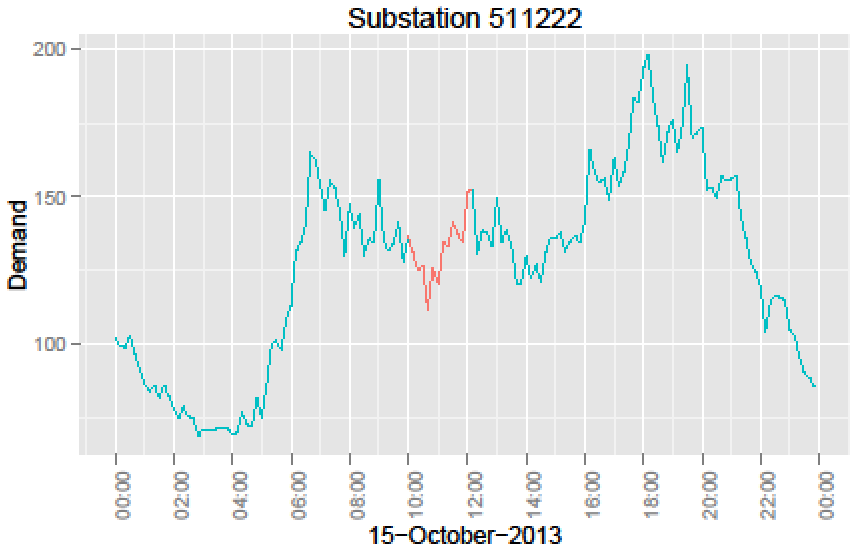

Figure 10: demand profile for substation 511222

The level of voltage drop can be determined in many different ways. By comparing the voltage during the trial with average voltage in the 2 hours previous, 2 hour following and 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 far lower than the instructed 3% drops applied at the higher voltage levels. Further study of the actual event raised several key reasons for this reduced drop.

In WPD's South Wales network an OC6 call is implemented at BSP level with taps at the associated primaries locked to pass through the reduction. Whilst this allows for a quicker implementation of the command it increases the effect of any failures. Several failures were identified after the call, affecting a wide area including most of Cardiff. WPD has since worked to rectify these failures. A further intricacy of the South Wales network is the supply of 2 primary networks directly from National Grid. At these networks, there are no WPD controlled BSP level AVC schemes and hence no response to a GC OC6 call. Some of the substations monitored were in these networks. It was also identified that at certain sites the reduction at BSP level was not translated down to primary level, this may be attributable to the connected generation, but will require further investigation

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 11 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.

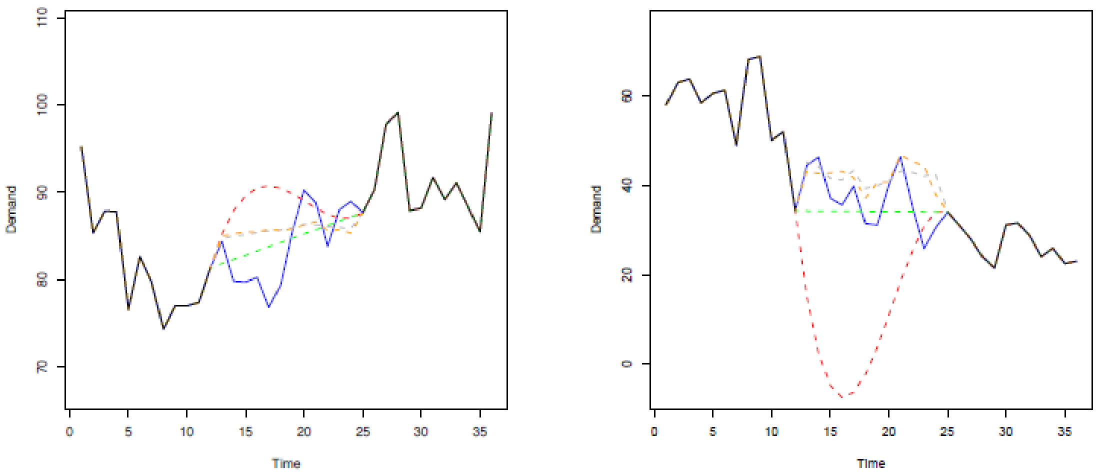

Figure 11: example of demand predictions during operation juniper.

However acknowledging the reduced voltage drop the drop in demand does tie into earlier 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%, a reduction of 0.7% would be expected.

6 Performance Compared to the Original Project Aims and Objectives

The aim of the project was to better understand and quantify the effects of the change in voltage settings in South Wales. The analysis conducted as part of the trial fulfilled these ambitions.

Success criteria 3 and 4 were fully met. Criteria 1 and 2 were only partially met as no statistically significant results were found for the effects of time and substation type. This is due in part to the reduced data sets required for the investigation of time and substation type.

Additional learning, such as the analysis of reactive power, was derived to fulfil the overall objective.

7 Required Modifications to the Planned Approach During the Course of the Project

There were several minor changes to the planned approach during the course of the project. These generally revolved around extending the analysis to resolve queries that arose from the original analysis. These were covered within the original budget and timescales.

The main additions were:

- Further investigation into the weather correction factors to explain unexpected values in October
- Investigations into the effects of reactive power
- Addition of paired analysis for voltages

8 Significant Variance in Expected Costs

There were no significant variances in expected costs. The existing relationships with, and experience of the suppliers in this project enabled it to be delivered on time and on budget.

Funding	Value
NIA Funding Request	£ 150,570
WPD DNO Contribution	£ 16,730
Total Budget	£ 167,300
Total Actual Spend	£ 155,931
Variance to budget	**-7%**

Item	Budget	Actual
WPD Project Management	£ 22,000	£ 18,331
Analysis carried out by Bath University	£ 77,500	£ 77,500
Extension to GE SMOS	£ 60,100	£ 60,100
Contingency	£ 7,700	£ -
Total	**£ 167,300**	**£ 155,931**

9 Lessons Learnt for future Innovation Projects

This project helped develop WPD's understanding of the effects of long term voltage reduction on LV networks. Using a large, statistically significant sample, great confidence can be taken in the replicability of the learning. As discussed in more detail in section 10 the method will be rolled out across the majority of WPD's network. The learning will also be shared for other network licensees to follow suit.

The project showed the value of large datasets to enable the capture of statistically robust data. However even with over 600 substation monitors if categorisation is required even larger sample sizes are required. This may be possible following the roll out of smart meters. The availability of additional data in a similar format allowed for the delivery of significantly more learning with minimal additional resource. Following some basic sense checking the reactive power data could be fed into the same algorithms as the real power. The investigations into operation juniper also showed that the same datasets can be used and interrogated in many different ways for multiple reasons. There is significant value in these data set often far beyond the original purpose.

Whilst there is significant value in these data sets the method of collection and storage must be carefully planned. As shown by the missing month of data, the supervision and maintenance of data collection systems in important. This can be especially challenging in the times between innovation projects. In addition the method of transferring data must be well developed. The original method for sending data established in the LVNT project was still in used for the VRA project. Whilst this was effective for the LVNT project when the dataset was smaller, with larger datasets the process was challenging. As such it is prudent to develop processes that can scale effectively.

Finally the management and contracting of the project benefited significantly from the existing relationships developed as part of the LVNT project. By using existing experienced partners, the investigations could easily build on previous work rather than start afresh.

10 Planned Implementation

Building on the learning from the VRA project WPD will lower the operating voltage of it's 11kV network across the company. This will be implemented through a new standard technique ST which is in draft.

This will require the reduction of 11kV AVC setting by 100V across most of WPD's primary substations.

This will be rolled out over the course of the 3 year maintenance cycles of 11kV AVC schemes. Levels of voltage complaints will be closely monitored and provisions made for potential feeder end substations that need manual tapping up.

This project has also fed into the ENA Statutory Voltage Limits task force. A recommendation of the task force is for the widening of LV voltage limits to ±10%. Such a reduction could give further scope for voltage reduction.

11 Facilitate Replication

This project has provided a much greater understanding of the operation of LV networks and the potential for voltage reduction. The learning will be shared with all network licensees. In depth details of analysis processes and data are available on request.

Tests as to the relevance of the monitored network for the wider GB network were conducted as part of the LVNT project and so the knowledge should be transferable.

All analysis was conducted using well established statistical techniques and software. The default NIA IPR position was applied for the project and WPD own all IPR developed as part of the project.

12 Contact details

Further details on replicating the project can be made available from the following point of contact:

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website: www.westernpowerinnovation.co.uk

Appendices

A. University of Bath Report

https://www.westernpowerinnovation.co.uk/Document-library/2016/VRA_Report_1-5.aspx

B. Project Registration Form

https://www.westernpowerinnovation.co.uk/Document-library/2016/Registration-Forms/Voltage-Reduction-Analysis-Project-Registratio-(1).aspx