# VOLTAGE REDUCTION ANALYSIS

Gavin Shaddick, Amelia Jobling,
Ellen Murphy, Daniel Simpson

Department of Mathematical Sciences &
Institute of Mathematical Innovation

University of Bath

# Contents

# Executive summary

This report presents the analyses of whether changes in 11kV AVC settings in South Wales had an effect on electrical demand, consumption and feeder voltage. It updates and extends the analyses presented in 'South Wales voltage reduction analysis'[1], presenting results for all of the data that is currently available. The changes were from 11.4 kV ± 200V to 11.3 kV ± 165V and were made in a selection of substations in the South Wales area in the latter part of 2014. Data is used from a selection of the monitoring network established as part of the Low Voltage Network Templates project (LVNT). In addition, voltage data monitored at substations and feeder ends was assessed with reference to the statutory limits of 230V +10%, -6%.

**Summary of findings**:

- Demand analysis was performed on over 50m data points from over 750 substations. Voltage analysis used over 50m data points from substations and over 100m from voltage monitors.
- Overall, a statistically significant reduction in demand was associated with substations that had changes in 11kV AVC settings with significant differences being observed for many individual months. No significant change was found in substations that did not have changes in settings.
- The overall average decrease was estimated to be 1.16%, with a greater reduction in winter months and a lower reduction in summer months. Reductions were found to be robust to changes in the temporal resolution used for the analysis.
- Using the methodology established in the LVNT project[2], an average reduction of 1.16% in demand would equate to an estimated reduction of 132 GWh for a year, worth £14.9 million if all substations in South Wales were changed.
- The proportion of voltage measurements outside the statutory limits was very small; over all months in 2015 only 0.33% of ten–minute measurements at feeder ends were above 253V and 0.004% were below 216.2V.

[1] www.westernpowerinnovation.co.uk

[2] Low Voltage Templates Closedown Report, Appendix B: South Wales Voltage Reduction

# Section 1

# Introduction

The aim of this piece of work is to determine whether the change in 11kV AVC settings in South Wales has had an effect on electrical demand, consumption and feeder voltage. Changes were from 11.4 kV ± 200V to 11.3 kV ± 165V and were made in a selection of substations in the South Wales area in the latter part of 2014.

This report contains a number of analyses of the potential effects of these changes at both substations and feeder ends. Data is used from the monitoring network established as part of the Low Voltage Network Templates project. Section 1 of this report gives details of the available measurement data and the creation of a working dataset for analyses. In Section 2, demands at substation level are considered in relation to the change in voltages. Details of weather corrections, which allow comparisons between years, followed by a comparison of demands before and after the changes in voltages take place. There are two main strands to the detection of potential changes: (i) a comparison of demand data for substations with a voltage reduction between similar time periods over the years of study and (ii) an analysis of whether a (significant) change can be detected without knowing the actual dates of change. In the former, after weather correction, demands for every month in 2015 (after voltage changes) are compared to their corresponding month in 2014 (before voltage changes). A statistical analysis of changes in demands at both a monthly and daily level allows an assessment of whether any reductions associated with the changes in voltages are statistically significant allowing for overall patterns in demand over this period of time. In the second approach, the exact dates of the voltage changes are not know and *change-point* models are used to try to assess when there might be a fundamental change in the underlying levels of demand.

In addition to the analyses of demand and the possible changes associated with the reduction in the 11kV AVC settings, in Section 3 there is an analysis of voltage profiles at both substation and feeder ends. Voltages are examined over time and compared to statutory limits. Section 4 presents analysis comparing the findings of Operation Juniper, a voltage reduction trial, to those observed after the change in voltage settings within the Low Voltage Network Templates monitoring network.

## 1.1 Monitoring in the Low Voltage Network Templates project

The Low Voltage Network Templates (LVNT) project was an Ofgem funded Tier 2 project run by Western Power Distribution. Full details of the LVNT project can be found at http://www.westernpowerinnovation.co.uk. The aim of the LNVT project was to see whether there was a simple method, outside of costly widespread monitoring, that could assist in providing the visibility needed in order to effectively design, plan and operate the LV distribution network. Taking daily patterns from substations as the object of interest, the aim was to create clusters of substations within which daily patterns are more similar than those in other clusters. Statistical clustering as performed on demands measured every ten minutes at ca. 800 substations located throughout South Wales. The result of the project was ten distinct LV Templates being identified which classified demand at the substation level according to daily load patterns.

The study area was South Wales. The rationale for choosing this area was to collect and analyse data on areas of WPDs network that had similar characteristics to that of the other DNOs. The study area from which data was gathered includes geographical locations ranging from inner-city, urban, suburban, and rural to industrial sites. Additionally the monitored substations cover a wide range of customer mixes; from those highly dominated by residential customers, to those exclusively industrial and commercial. The data comprised of measurements made on 10 minute intervals of voltage, current, real power delivered (kW) and power received at LV substations and voltages at remote feeders-ends.

Since May 2012 the data delivery was fully automated, via WPD to a dedicated secure server at the University of Bath. At the end of the LNVT project there were over 1/2 billion substation and in excess of 101 million feeder-end data points for analyses, a subset of which is analysed in this report. Since the official end of the LVNT project, monitoring has continued together with data delivery to the University of Bath and subsequent analysis. The analysis performed within this project and reported here uses these data for the period of 2014-2015. The analysis presented here updates and extends that contained in the previous report on this subject, 'South Wales voltage reduction analysis'.

## 1.2 The state of the monitoring data

This analysis of the effects of the reduction in voltages at substations uses data from the LNVT monitoring equipment for the period 2014-2015. The analysis in this report uses a selection of the monitors installed as part of the LVNT project. As of 31/12/2015, measurements were available from 753 substations and 2810 voltage monitors. It is noted that during this period these totals include those monitors that may not have consistently provided data throughout the entire period. Figure 1.1 shows a schematic of the available data from substations.

The number of substations available and suitable for analysis varies for different months and years. For example, in January 2014, after sense-checking the data, 741 were deemed suitable for voltage analysis and 725 for demand analysis. Of these 741, 402 had a change in voltage for which the date of the change was known for 140 substations and unknown (at the time of writing) for 262. The choice of which substations had the change in voltage settings was not based on any pre-specified criteria but was, in pragmatic terms, random. Tables 1.1 and 1.2 display the number of substations providing suitable demand data for analysis for every month in 2014 and 2015, respectively. The tables also give information on the number of days' worth of data received per month and the number of substations with voltage changes.

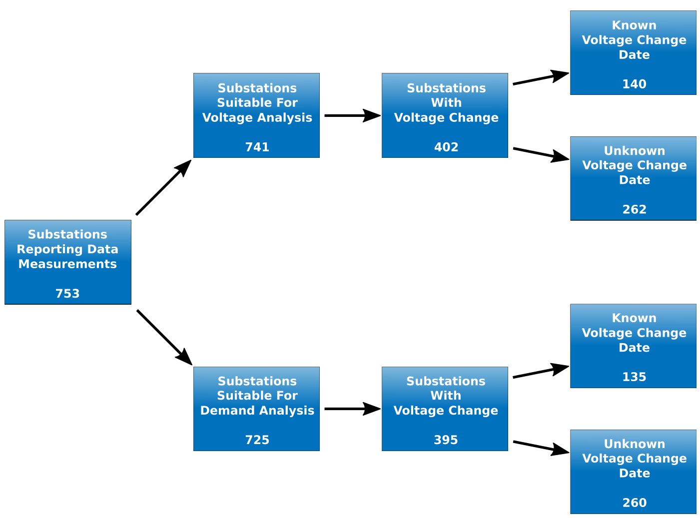



Figure 1.1: Schematic showing the number of substation monitors providing data for analysis for January 2014.

The location of the substations can be seen in Figure 1.2 in which the locations of substations that had voltage changes are shown by red dots and those that did not change by blue dots.

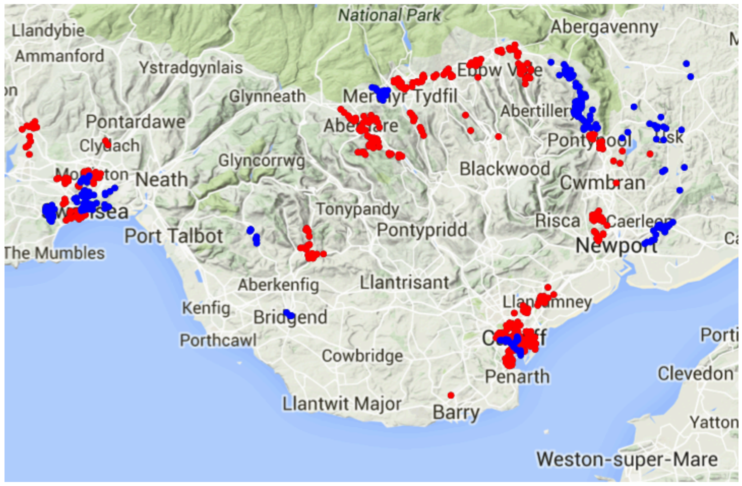



Figure 1.2: Locations of substations providing data for the analysis. Substations that had changes in 11kV AVC settings are denoted by red dots and those with no change by red dots.

Figure 1.3 shows a schematic of data availability at feeder end monitors. For January 2014, suitable voltage data was available from 2806 feeder end monitors. Of the 741 substations providing suitable data at the time of the project, 518 could be linked to at least one voltage monitor at feeder ends. The total number of feeder end voltage monitors that could be linked to substations providing data was 2512 (for January 2014, other months may vary slightly). For the 402 substations that had their voltage changed, 284 had associated voltage monitors at feeder ends resulting in 1357 feeder end monitors in total (again, for January 2014 only, other months may vary slightly).

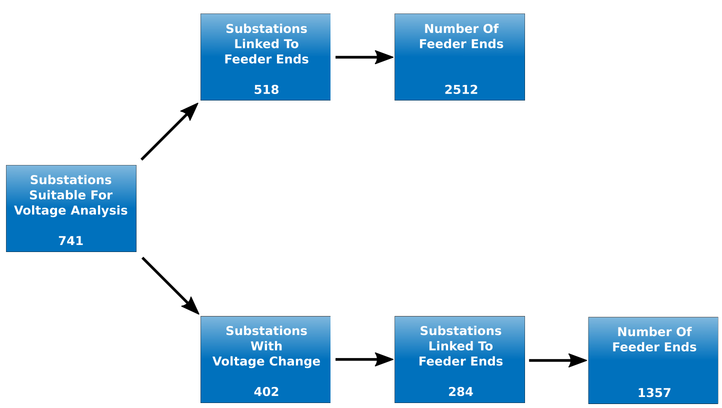



Figure 1.3: Schematic showing the number of voltage monitors at feeder ends providing data for analysis for January 2014.

Table 1.1 provides a summary of the state of the data for 2014. The number of substations provided suitable data is given, along with the number of days of data supplied per month. The same information for 2015 is given in Table 1.2.

| Month | No. Days Supplied | No. Providing Suitable Data | No. With Voltage Change | No. Voltage Change Known |
|---|---|---|---|---|
| January | 31 | 725 | 395 | 135 |
| February | 28 | 651 | 395 | 135 |
| March | 31 | 643 | 394 | 135 |
| April | 30 | 641 | 392 | 134 |
| May | 26 | 436 | 247 | 80 |
| June | 30 | 448 | 251 | 81 |
| July | 31 | 453 | 256 | 82 |
| August | 31 | 456 | 257 | 84 |
| September | 30 | 455 | 259 | 85 |
| October | 31 | 455 | 259 | 84 |
| November | 30 | 451 | 261 | 86 |
| December | 31 | 607 | 398 | 135 |

Table 1.1: Information on the number of substations, per month in 2014, providing suitable demand data for analysis, including the number of days' worth of data, and the number of substations with voltage changes.

| Month | No. Days Supplied | No. Providing Suitable Data | No. With Voltage Change | No. Voltage Change Known |
|---|---|---|---|---|
| January | 31 | 609 | 400 | 136 |
| February | 17 | 601 | 399 | 136 |
| March | 0 | 0 | 0 | 0 |
| April | 18 | 556 | 369 | 131 |
| May | 30 | 563 | 369 | 131 |
| June | 30 | 549 | 366 | 131 |
| July | 31 | 594 | 390 | 131 |
| August | 31 | 598 | 391 | 132 |
| September | 30 | 593 | 388 | 131 |
| October | 31 | 569 | 368 | 117 |
| November | 30 | 569 | 368 | 117 |
| December | 31 | 552 | 362 | 116 |

Table 1.2: Information on the number of substations, per month in 2015, providing suitable demand data for analysis, including the number of days' worth of data, and the number of substations with voltage changes.

# Section 2

# Demand analysis

The aim of the analyses of demand data is to ascertain whether there are any discernible changes that are associated with the change in 11kV AVC settings. The majority of the voltage changes occurred in November and December of 2014 and the primary analysis is a comparison of demands before and after this period.

The analysis presented here updates and extends that contained in the previous report on this subject, 'South Wales voltage reduction analysis', hereafter referred to as SWVRA. At the time of writing SWVRA, demand data was only available up to the end of January 2015 and comparisons before and after the changes were made were therefore limited to a comparison of demands from January 2015 and January 2014. Secondary analyses also investigated patterns from January 2013 and the following two years.

Demand is high in January and it may be that the decreases previously observed may not be representative of what might be expected over the entire year. In this report we report findings using data from the whole of 2015, enabling comparisons to be made on a month-by-month basis and assessment of whether there are differences in any observed decreases that might be attributable to the time of year.

For this, daily demand data monitored from 753 substations was considered. From these, 725 substations were deemed to have suitable data, which was extracted for each month in 2014 and 2015 from the database described in Sections 1.1 and 1.2. Of these 725 substations, 395 had the change in voltage settings and 200 did not. As described in Section 1.2, the number of substations reporting data varied by month, with a gradual falling off over time giving, for example, data from 552 substations being available in December 2015 (369 with the change, 183 without). As described in Section 1.2, no data was recorded in March 2015 and so a comparison based on that month is not possible. An estimate for the effect in March 2015 is given in Section 2.2, based on the patterns seen throughout the year, together with a description of the methodology used. The same methodology was used to a produce 'stable' estimates for cases where there appeared to be idiosyncrasies in the data or where sample sizes, i.e. number of days within a month for which data were available, were too small to produce stable estimates.

The primary statistical analysis of these data uses a *paired* approach in which demand data for each substation is matched across years. This allows for the dependence that might be expected within measurements from the same substation to be acknowledged and correctly incorporated into the assessment of whether observed changes are statistically significant. The requirement for measurements to be available for a particular substation *in each period* means that the number of substations contributing to the tests in different month will vary.

A comparison between two years could be performed using a *paired t-test* or non-parametric equivalent, the *Wilcoxon rank sum test*. These consider the differences between the average monthly demands for each individual substation and offer an initial assessment of whether there have been changes over the period in which the settings were changed.

A more complex, though equivalent, approach is to used formal statistical modelling techniques with random effects. These allow for the dependence (or correlation) that is present in demands from the same substations but offer greater flexibility than the aforementioned tests when appraising the potential influence of other factors, such as overall longer-term patterns in demand when assessing the effects of any changes. *Random effects models* were used for both monthly averages (for each substation by year) and also for daily measurements of demand. The increase in complexity when using daily data may be offset by the ability to work with a large sample size and the ability to investigate changes at a higher temporal resolution. For example, possible sub–month patterns may be masked when using monthly averages.

In addition to the overall testing of whether average demand changed before and after the changes in voltage, sub-analyses are performed for selections of substations based on their characteristics. For example, categorising the substations by transformer rating or by the customers they serve, i. e., the proportion of industrial and commercial customers.

Analysis is also presented of changes in maximum demand over the same time period. Following the analysis of average demands, monthly maximums recorded for each substation in 2015 are compared with the maximum from the corresponding month in 2014 together with an analysis of changes in maximum demands by quarters.

A further set of analyses aims to detect whether changes in the voltage settings can be detected without prior knowledge of the times at which those changes occurred. *Change–point models* attempt to detect underlying changes in the data generating mechanism which would manifest in changes in the observed data. At the time of writing SWVRA, time-series of daily average demands were only available up to the 20th December which meant that a full evaluation was not possible as the many (ca. 60%) of the (known) changes in voltage settings were made in that month and so there was not enough data post-change in many cases.

Here, time-series of daily average demands are used for 2014 (Jan 1st – Dec 20th) with the aim of assessing whether changes can be detected and, if so, checked to see whether they coincide with known dates of changes in the voltage settings. This approach can also be applied to cases where the exact date at which the settings were changed is not known, as information on when the change may have occurred is not used in the modelling procedure.

## 2.1 Data

For the analyses of demands over the specified time period, data from the substations was sense-checked before being used. For January 2015, 609 were deemed suitable for analysis. As previously mentioned, this is the maximum number available for any of the monthly comparisons, with a drop-off to 552 for December 2015. Data was extracted and daily average and maximum demands calculated for each substation for each year using measurements from the 144 ten minute periods.

### 2.1.1 Weather corrections

In order to ensure that demands were comparable across years, the recorded values were adjusted for weather. To do this, correction ratios were calculated by comparing the uncorrected consumption values, for each half hour for the entire South Wales, to weather-corrected values. The correction ratios were then applied to the demand data to produce a weather adjusted value. Figure 2.1 shows the weather corrections for January 2013, 2014 and 2015, that were applied to the demand data in this analysis.

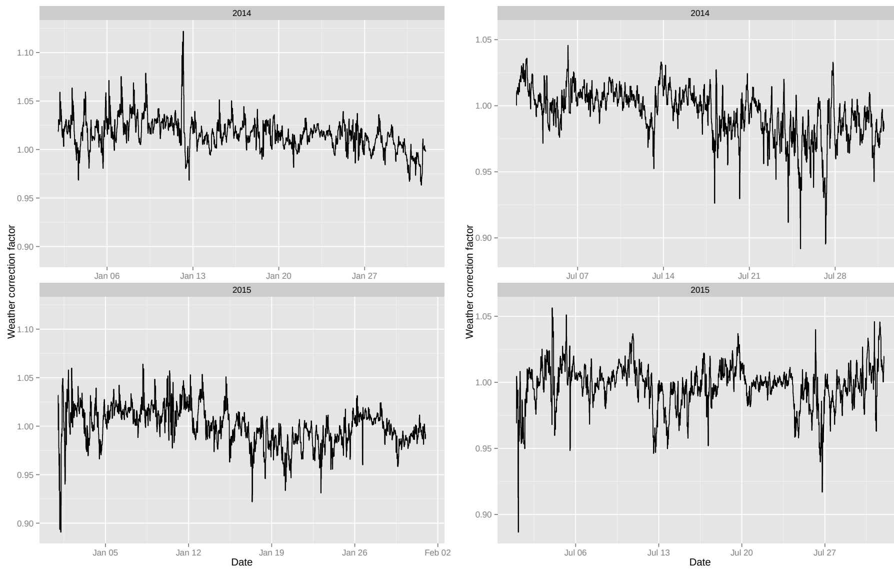



Figure 2.1: Weather correction factors for January 2014 and 2015 (left hand panel) and July 2014 and 2015 (right hand panel).

## 2.2 Changes in average demand

Testing comprised of detecting differences between demands for each month; e.g. January 2015 vs. January 2014, ..., December 2015 vs. December 2014. The testing was based on the differences observed for each substation which were then combined to result in a single summary of the difference, together with an assessment of the statistical significance of any change. Figure 2.2 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, after the changes in voltage settings had been made, with the decrease in the average demand being greater in January. Corresponding plots for the other substations are available in digital format.

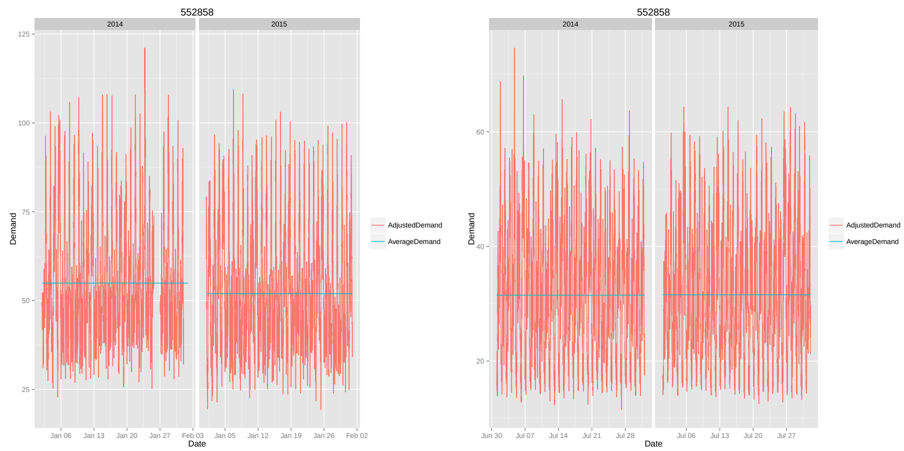



Figure 2.2: Weather corrected ten minute demand data for substation 552858. Daily average demand is shown for for January 2014 and January 2015 (left hand panel) and July 2014 and July 2015. The horizontal lines show the average demand for each of the months.

In SWVRA, a comparison between the monthly averages by substation for January 2014 and January 2015 (before and after the changes to voltage settings) showed a significant decrease in demands for those substations that had changes in settings but not in those that did not have the change. In each month, for a number of substations, the differences between the monthly averages between years were larger than could be attributed to changes in voltage. Sense–checking the data included excluding differences that are likely to be due to data anomalies and other factors. Sense checking was performed at two stages; (i) comparison of difference between daily (weather adjusted) demands and (ii) comparison between aggregated monthly demands. The former (daily comparison sense-checking) is more stringent than the latter (monthly comparison) and might place too much emphasis on the weather adjustments being able to correct demands. The default setting for both the daily and monthly comparison 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, and for extremely fine values of the daily comparison cut-offs.

Results for comparisons of all months can be seen in Table 2.1. Reductions were observed in all months, with values being greater in the winter months, e.g. January 1.40%, 1.34 kW, from a baseline in January 2014 of 95.83; December 1.70%, 1.4 kW, from a baseline of 82.52 in December 2014, than in the summer, e.g. July 0.68%, 0.4 kW, from a baseline of 58.8 in July 2014. In all months except for May and July, these reductions were statistically significant ($p < 0.05$) using both the paired t-test and the non parametric wilcoxon test, with July being of borderline significance for both tests. Note that in Table 2.1 and all other tables in this section, the figures given are for the t-test. In substations that did not experience the change in voltage settings the same pattern of decreases was not observed, with a mixture of non-significant increases and decreases, seen in the percentage differences.

| Month | Mean 2014 | Mean 2015 | Mean difference | 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 2.1: Differences between monthly averages for years 2014 and 2015 based on a sense checking of (i) no more than 20kW difference between daily (weather adjusted) demands and (ii) no more than 20kW difference between aggregated monthly demands. Due to a marked contrast to those observed in the other weeks of July, the last week of July data was removed.

The result for July is likely due to a smaller sample size, i. e., number of days, than for other months. Detailed checking of the daily data by individual substations for the last week of that month showed patterns that were in marked contrast to those observed in the other weeks of July and other months. Including the data from the last week of July resulted in an overall increase in demand between the years. Also noticeable in Table 2.1 is the very high decrease observed for October. This was the subject of a great detail of forensic examination, details of which can be seen in the Appendix.

Where there is no data available for estimating the effects associated with the voltage reduction, for example in March where the monitoring network was not functioning correctly, or where the results are considered unstable, e.g. October, statistical smoothing techniques can be used to estimate missing values and to produce more reasonable estimates than are provided when using the data directly. Figure 2.3 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. 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. The estimated values for March and October are 1.09 and 1.24, respectively. Inserting the set of results shown in Table 2.1 gives monthly estimates of 1.40, 0.97, 1.09, 1.53, 0.13, 1.48, 0.70, 1.13, 0.91, 1.24, 1.58 and 1.70 for January to December, giving an average decrease of 1.16%. Using smoothed estimates, as shown in Figure 2.3 also gives an overall average decrease of 1.16%.

| Month | Percentage difference (Measured) | Percentage difference (Smoothed) | Percentage difference (Smoothed excl. May) |
|---|---|---|---|
| January | 1.40 | 1.22 | 1.31 |
| February | 0.97 | 1.15 | 1.26 |
| March | – | 1.09 | 1.22 |
| April | 1.53 | 1.05 | 1.20 |
| May | 0.13 | 1.04 | 1.18 |
| June | 1.48 | 1.05 | 1.18 |
| July | 0.70 | 1.07 | 1.18 |
| August | 1.13 | 1.12 | 1.19 |
| September | 0.91 | 1.17 | 1.21 |
| October | – | 1.24 | 1.25 |
| November | 1.58 | 1.33 | 1.32 |
| December | 1.70 | 1.38 | 1.37 |

Table 2.2: The percentage differences by month. The first column shows the monthly estimates as in Table 2.1. Column two shows the results of fitting a lowess smoother to the monthly estimates, and column three shows the same but with the estimate for May excluded.

It can be seen in the figures given above, that the monthly estimate for May, 0.13%, is small in comparison to the other estimates. Detailed examination of the data for May showed no evidence to suggest it should be omitted and estimated in the same manner as October. Excluding May, and fitting a smoothing function to the remaining monthly estimates results in an overall average decrease of 1.24%, with the estimates for the winter months remaining much as before but the estimates for the summer months increasing. A comparison of the percentage differences for each month given by the smoothing function, with and without the May estimate, is shown in Table 2.2. In the absence of underlying information to exclude May, the average decrease over the year remains estimated at 1.16%.

This equates to a decrease of 131.9 GWh, based on the total consumption in South Wales being 11374.2 GWh. With an average unit cost of 11.26p per kWh, this equates to a saving of £14.9m over a year and a reduction in $CO_2$ of ca. 70,000 tonnes.

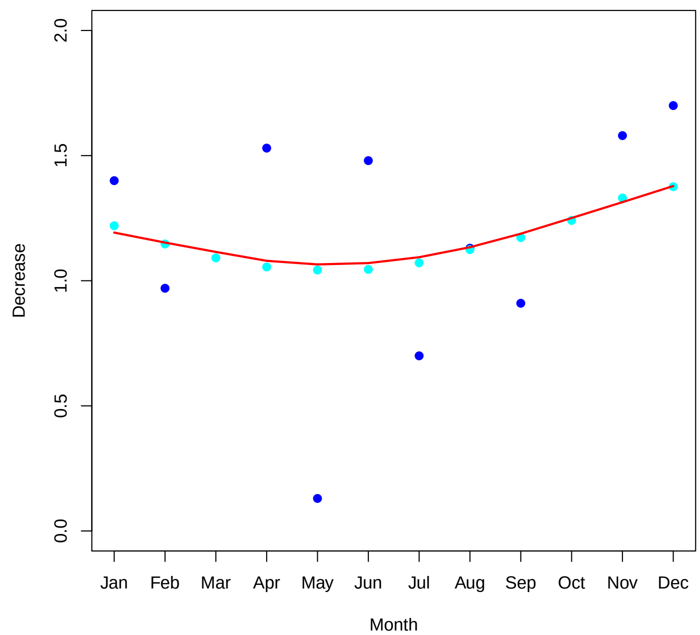



Figure 2.3: Estimates of the percentage decrease in average demand, by month. Comparisons are between 2014 and 2015. The dark blue dots indicate the estimates from a paired comparison by substation and the light blue dots a set of 'smoothed' estimates based on a lowess smoother (red line).

### 2.2.1 Changes in demand within categories

Further investigation was performed into whether the observed patterns in reductions associated with the changes in voltage settings varied according to time of week and substation characteristics. Table 2.3 shows the equivalent to Table 2.1 for both weekdays and weekends.

Table 2.3 shows that for weekdays, similar reductions were observed in all months, with values being greater in the winter months, e.g. December 1.78%, 1.49 kW, from a baseline in December 2014 of 84.04, than in the summer, e.g. July 0.44%, 0.27 kW, from a baseline of 59.93 in July 2014. The months of August and September joined May and July in becoming insignificant, while the remaining months' reductions were highly statistically significant ($p < 0.05$).

Sub-dividing into weekend days meant that there were smaller numbers

| Month | Weekdays | | Weekend Days | |
|---|---|---|---|---|
| | Percentage difference | p-value | Percentage difference | p-value |
| January | 0.88 | 0.01 | 1.13 | 0.00 |
| February | 0.67 | 0.05 | 0.38 | 0.18 |
| April | 1.21 | 0.02 | 2.56 | 0.00 |
| May | 0.03 | 0.48 | -0.04 | 0.53 |
| June | 1.44 | 0.00 | 1.01 | 0.03 |
| July | 0.44 | 0.20 | 1.45 | 0.00 |
| August | 0.73 | 0.10 | 0.66 | 0.10 |
| September | 0.56 | 0.17 | 1.06 | 0.03 |
| October | 3.78 | 0.00 | 3.32 | 0.00 |
| November | 1.62 | 0.00 | 0.67 | 0.09 |
| December | 1.78 | 0.00 | 1.37 | 0.00 |

Table 2.3: Differences between monthly averages for weekdays and weekend days of the years 2014 and 2015, based on a sense checking of (i) no more than 20kW difference between daily (weather adjusted) demands and (ii) no more than 20kW difference between aggregated monthly demands. Due to a marked contrast to those observed in the other weeks of July, the last week of July data was removed.

in categories making the results less stable, enhancing the likelihood of non-significant results. This is evident in Table 2.3 where values in winter months are similar to those seen in the summer, e.g. December; 1.37%, 1.10 kW, from a baseline in December 2014 of 80.19, vs. July; 0.44%, 0.27 kW from a baseline of 59.93 in July 2014.

Division of the data based on transformer ratings, percentage of Industrial and Commercial (I&C) customers), Low Voltage Network Templates, or time of day did not show clear patterns in the estimated reductions, see the Appendix for detailed tables. This is likely to be due the sub division of the data resulting in even smaller sample sizes, giving less stable results and non statistical differences.

## 2.3 Changes in maximum demand

In the previous section, comparisons were made between average demand before and after the change in voltage setting. In this section, a similar paired analysis is performed, with comparisons between substations of the monthly average of the daily maximum demands. Table 2.4 shows the maximum (defined as the 99.9th percentile) recorded demands for each month for the years 2014 and 2015.. The fourth and fifth columns of the table show the average of the maximums recorded at each substation, and the difference is calculated as the average of the differences between maximums at each substation.

| | Max. 2014 | Max. 2015 | Mean (Sub. Maxs) 2014 | Mean (Sub. Maxs) 2015 | Mean of difference | p-value |
|---|---|---|---|---|---|---|
| Jan | 660.60 | 637.60 | 161.80 | 159.60 | 2.15 | 0.00 |
| Feb | 654.20 | 658.80 | 156.40 | 155.60 | 0.81 | 0.07 |
| Apr | 381.80 | 388.20 | 96.75 | 96.63 | 0.12 | 0.39 |
| May | 419.90 | 423.20 | 98.29 | 97.97 | 0.32 | 0.22 |
| Jun | 401.00 | 401.10 | 96.39 | 95.40 | 0.99 | 0.02 |
| Jul | 412.00 | 393.70 | 92.16 | 91.76 | 0.40 | 0.13 |
| Aug | 413.00 | 395.70 | 96.88 | 95.73 | 1.14 | 0.00 |
| Sep | 437.70 | 432.60 | 106.50 | 105.20 | 1.35 | 0.00 |
| Oct | 492.30 | 472.70 | 120.80 | 117.30 | 3.52 | 0.00 |
| Nov | 535.00 | 519.40 | 133.10 | 130.80 | 2.29 | 0.00 |
| Dec | 557.00 | 534.30 | 139.30 | 136.50 | 2.84 | 0.00 |

Table 2.4: Differences between monthly maximums for years 2014 and 2015. The fourth and fifth columns of the table show the average of the maximums recorded at each substation, and the difference is calculated as the average of the differences between maximums at each substation.

The result of analysis of patterns for higher level of temporal aggregation can be seen in Table 2.5 which shows the results for quarters (December-February, April-May, June-August and September-November, noting as previously described that data was not available for March) and Table 2.6 which shows the equivalent results excluding the last week of July and October due to issues with the data in those periods. In both cases, the results shown follow the pattern seen in the individual month analysis, with higher decreases seen in the winter months compared with summer ones.

| | Max. 2014 | Max. 2015 | Mean 2014 (Sub. Maxs) | Mean 2015 (Sub. Maxs) | Mean difference | p-value |
|---|---|---|---|---|---|---|
| I | 645.80 | 635.20 | 161.00 | 159.20 | 1.83 | 0.00 |
| II | 424.30 | 426.10 | 100.30 | 99.86 | 0.43 | 0.13 |
| III | 408.50 | 397.70 | 98.04 | 97.37 | 0.67 | 0.03 |
| IV | 489.70 | 475.70 | 118.40 | 116.20 | 2.20 | 0.00 |

Table 2.5: Differences between quarterly maximums for years 2014 and 2015. The groupings in column one are: I) December, January, February; II) April, May; III) June, July, August; and IV) September, October and November. The fourth and fifth columns of the table show the average of the maximums recorded at each substation, and the difference is calculated as the average of the differences between maximums at each substation.

| | Max. 2014 | Max. 2015 | Mean 2014 (Sub. Maxs) | Mean 2015 (Sub. Maxs) | Mean difference | p-value |
|---|---|---|---|---|---|---|
| I | 645.80 | 635.20 | 161.00 | 159.20 | 1.83 | 0.00 |
| II | 424.30 | 426.10 | 100.30 | 99.86 | 0.43 | 0.13 |
| III | 408.50 | 397.70 | 98.04 | 97.37 | 0.67 | 0.03 |
| IV | 487.30 | 477.10 | 119.20 | 117.50 | 1.65 | 0.00 |

Table 2.6: Differences between quarterly maximums for years 2014 and 2015. The groupings in column one are: I) December, January, February; II) April, May; III) June, July, August; and IV) September, October and November. The fourth and fifth columns of the table show the average of the maximums recorded at each substation, and the difference is calculated as the average of the differences between maximums at each substation. Results are shown excluding data from the last week of July and October due to issues with data during those periods.

## 2.4 Detecting changes

In this secondary analysis we assess whether statistical change-point models can be used to detect underlying changes in demand where no information is supplied as to when changes to voltage settings may have occurred. Three separate sets of analysis are considered:

(i) Cases where there has been a change and the exact date is known.

(ii) Cases where the has been a change and the exact date is not known.

(iii) Cases where there has been no change.

In the first case, it is good for the proportion of cases where the method detects a potential change-point, known as *false positives*, to be low and correspondingly, for the latter two cases, it is good for the proportion in which a change-point is detected, *true positives*, to be as high as possible.

Applying the models directly to the demand data would result in detecting changes due to seasonal patterns rather than any change in voltage settings and so, the first step in the analysis is to de-seasonalise the data. This is done by fitting a smoothed curve through the time-series data, which represents the underlying pattern, and then the residuals (differences) between the data and this curve provide a de-seasonalised series. The smoothed curve is 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.

In contrast to the change-point analysis presented in SWVRA, where in many cases there was little, or no, data available after the changes had been made, here we have used a period of 4 months 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 1st of October 2014 to the 16th of February 2015. The upper limit here was chosen to reflect the latest time at which reliable data was readily available before the March period in which communications to the network were not functioning – this period started in mid-February. The analysis was repeated for a selection of earlier time points with longer periods giving more data on which to base the underlying mean values but increasing the possibility of long-term seasonal patterns being incorporated within the data.

The method was then applied to the three cases listed above. Figure 2.4 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 are shown together with the smoothed line representing seasonal patterns. In the top middle panel, the de-seasonalised series is shown in which the seasonal pattern has been omitted. Figure 2.4 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, 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 this example, there is 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.

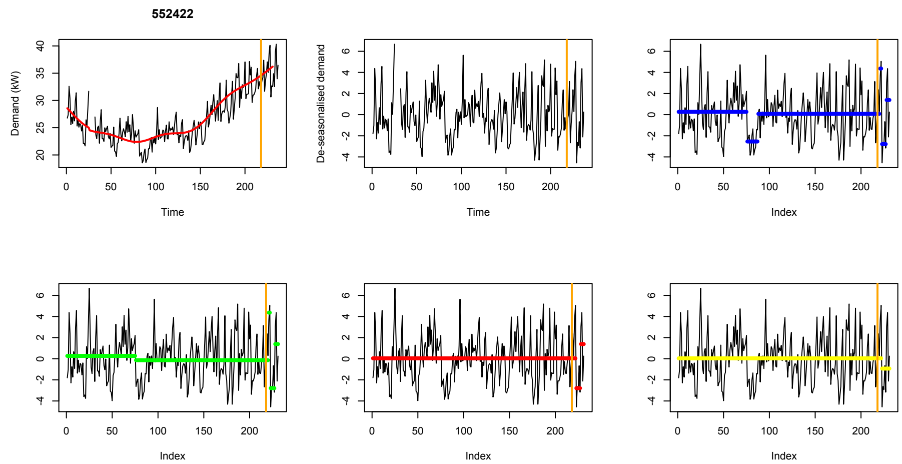



Figure 2.4: Daily demand data for substation 552422 and results of change-point analyses. The top left panel shows the daily (weather corrected) demand data for 2014 together with a smoothed line representing seasonal patterns in demand. The top middle panel shows the de-seasonalised data. The top right panel shows the results of applying a change-point model with no restrictions on the number of changes (in this case there are 5 estimated changes resulting in 6 horizontal lines). The bottom row shows the results of change-point analyses with constraints on the maximum number of changes; four (bottom left panel), two (bottom middle) and one (bottom right). In all cases, the vertical orange line shows when the changes in voltage settings were made.

Figure 2.5 shows the same information as Figure 2.4 for the second case, where the exact date of change is not known (hence no orange line). Here, restricting the number of possible changes to one, results in a change in the underlying average demand on December 13th. This would be in accordance with the known dates for changes.

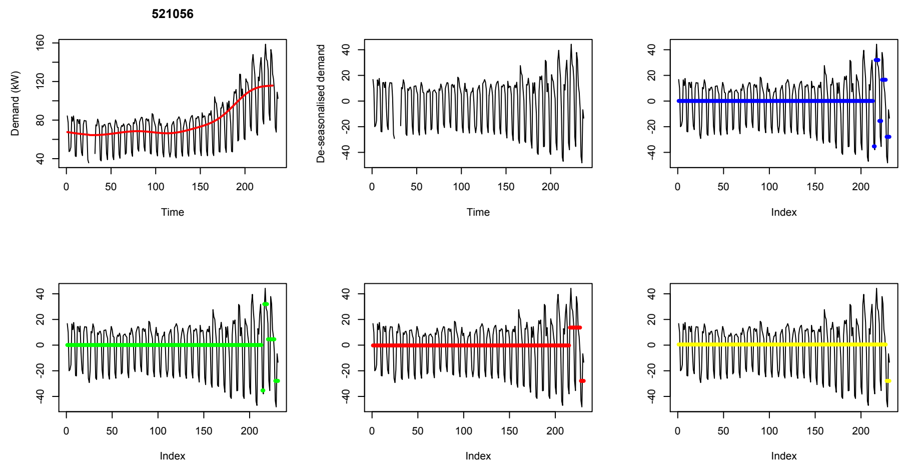



Figure 2.5: Daily demand data for substation 521056 and results of change-point analyses. The top left panel shows the daily (weather corrected) demand data for 2014 together with a smoothed line representing seasonal patterns in demand. The top middle panel shows the de-seasonalised data. The top right panel shows the results of applying a change-point model with no restrictions on the number of changes (in this case there are 5 estimated changes resulting in 6 horizontal lines). The bottom row shows the results of change-point analyses with constraints on the maximum number of changes; four (bottom left panel), two (bottom middle) and one (bottom right). In this case the exact date of change in voltage settings is not known.

In the first case, the known dates of changes were 10th October (14 substations), 11th (34), 12th (4) and 18th (4) November and 4th (20), 8th (56), 18th (9) and 19th (1) of December. Overall, data was available for 137 of these, but about half had data missing from the March period until the beginning of December. An analyses including all substations for which any data was available before their change date, change-points within a week of the specified dates were identified in ca. 60% of cases. When this analyses was preformed only on substations for which there were adequate data available before and after the time of change (at least 2 months before and after) to create a stable underlying model then suitable change-points were detected ca. 75% of the time. Of the 267 substations that had the change in voltage settings, but for which a date was not recorded, data was available for 128. Performance was similar to that when dates were known (but not used in the analysis) with indicated changes within the period of November to December (the timeframe in which the majority of changes would have been made) for ca. 65% of the substations. In the third case, where there was no change to voltage settings, data was available for 204 (out of 208) 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%.

## 2.5 Results for reactive power analysis

In this section, the reactive power, measured in kVAr, is analysed using the same methodology used to analyse demand data in Section 2.2. As reported in Section 2.2, the demand data was sense-checked to ensure it was suitable for analysis. If a substation passed the sense-checking in the demand analysis, it was considered suitable for reactive power analysis.

In order to ensure that the reactive power measurements were comparable across years, the recorded values were adjusted for weather. To do this, correction ratios were calculated by comparing the uncorrected consumption values, for each half hour for the entire South Wales, to weather-corrected values. The correction ratios were then applied to the reactive power data to produce a weather adjusted value.

As with the demand analysis, the number of substations reporting data varied by month. No data was recorded in March 2015 and so a comparison based on that month was not possible. Results are displayed in the tables below.

| Month | Mean 2014 | Mean 2015 | Mean difference | 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 2.7: Differences between monthly average reactive power (kVAr) for years 2014 and 2015.

| Month | Weekday | | Weekend | |
|---|---|---|---|---|
| | (%) Difference | p-value | (%) Difference | p-value |
| January | 8.38 | 0.00 | 9.30 | 0.00 |
| February | 8.03 | 0.00 | 7.70 | 0.00 |
| April | 4.28 | 0.01 | 5.92 | 0.00 |
| May | 8.31 | 0.00 | 6.28 | 0.00 |
| June | 8.22 | 0.00 | 8.24 | 0.00 |
| July | 8.52 | 0.00 | 7.71 | 0.00 |
| August | 6.28 | 0.00 | 7.26 | 0.00 |
| September | 9.15 | 0.00 | 10.00 | 0.00 |
| October | 6.08 | 0.00 | 8.11 | 0.00 |
| November | 5.39 | 0.00 | 7.80 | 0.00 |
| December | 3.65 | 0.00 | 4.24 | 0.00 |

Table 2.8: Comparison of differences between monthly average reactive power (kVAr), for years 2014 and 2015, split by weekday and weekend.

| Month | % I&C $\leq$ 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 2.9: Comparison of differences between monthly average reactive power (kVAr), for years 2014 and 2015, split by %I&C.

| Month | Transformer rating $< 500$ | | Transformer rating $\geq 500$ | |
|---|---|---|---|---|
| | (%) 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 2.10: Comparison of differences between monthly average reactive power (kVAr), for years 2014 and 2015, split by Transformer rating.

| Month | Template 1 | | Template 2 | | Template 3 | | Template 4 | | Template 5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | (%) Difference | p-value | (%) Difference | p-value | (%) Difference | p-value | (%) Difference | p-value | (%) Difference | p-value |
| January | 5.80 | 0.01 | 14.06 | 0.00 | 9.96 | 0.00 | 9.60 | 0.00 | 9.61 | 0.12 |
| February | 5.74 | 0.01 | 13.15 | 0.00 | 11.32 | 0.00 | 8.67 | 0.00 | 13.52 | 0.09 |
| April | -3.95 | 0.71 | 10.78 | 0.00 | 7.45 | 0.00 | 10.83 | 0.00 | -3.86 | 0.80 |
| May | 1.23 | 0.35 | 11.29 | 0.00 | 11.20 | 0.00 | 11.86 | 0.00 | 9.61 | 0.12 |
| June | 2.70 | 0.17 | 12.62 | 0.00 | 13.20 | 0.00 | 12.60 | 0.00 | – | – |
| July | 6.19 | 0.03 | 11.80 | 0.00 | 10.52 | 0.00 | 10.77 | 0.00 | – | – |
| August | 1.57 | 0.32 | 11.85 | 0.00 | 10.38 | 0.00 | 8.55 | 0.00 | – | – |
| September | 5.28 | 0.07 | 14.10 | 0.00 | 15.69 | 0.00 | 12.70 | 0.00 | – | – |
| October | 0.39 | 0.42 | 11.80 | 0.00 | 13.56 | 0.00 | 11.35 | 0.00 | – | – |
| November | -0.56 | 0.59 | 9.30 | 0.00 | 12.65 | 0.00 | 8.29 | 0.00 | 13.63 | 0.21 |
| December | -4.74 | 0.83 | 4.81 | 0.00 | 8.87 | 0.00 | 7.81 | 0.00 | 14.78 | 0.20 |

Table 2.11: Comparison of differences between monthly average reactive power (kVAr), for years 2014 and 2015, for substations within 1-5 of the LVNT.

# Section 3

# Voltage profiles

## 3.1 Voltage monitored at substations

In this section, we use voltage data monitored at substations to assess adherence to the statutory limits of 230V +10%, -6%. Analysis was performed for January 2014 and 2015. Data was available for 741 substations in January 2014. Of these, information on whether the change in voltage settings was made was available for 607 substations (402 changed, 205 not changed). In those where it was known that the change in voltage settings occurred, the exact date was known for 140 substations and unknown for 262 substations. In January 2015, data was available for 621 substations. Of these, information on whether the change in voltage settings was made was available for 615 substations (407 changed, 208 not changed). In those where it was known that the change in voltage settings occurred, the exact date was known for 141 substations and unknown for 266 substations. Of the known dates of voltage changes, 40% were during October or November 2014.

In the demand analysis in Section 2, the analysis consisted of direct comparisons between the values from individual substations over time. This was possible as the analysis was restricted to the group of substations for which data was available for each year (assessed on a month-by-month basis).The analysis presented in this section is on all of the data that was available for January 2014 and 2015. As there were different substations and feeder ends reporting data in these periods, a direct comparison between the two years is not appropriate.

Substations were selected for inclusion in the following analysis based on whether they were providing sensible data as of 31/12/2015. For a substation to be included in the analysis, the average monthly voltage must lie between 150 V and 300 V. In addition to this, any voltage measurement of 2V or less was treated as a missing value. If substations met these requirement they were deemed available for analysis.

Table 3.1 displays the average voltage recorded across substations with and without a voltage change for every month in 2014 and 2015, in addition to the percentage decrease from 2014 to 2015. Table 3.2 displays the percentage of ten-minute periods over 253 V and under 216.2 V for substations with and without a voltage change, for every month in 2014 and 2015. The analyses in this section, performed for months of the year other than January, are available in digital format.

| Month | Substations without a Voltage Change | | | Substations with a Voltage Change | | |
|---|---|---|---|---|---|---|
| | 2014 | 2015 | % decrease | 2014 | 2015 | % decrease |
| January | 243.03 | 242.77 | 0.11 | 243.31 | 242.03 | 0.52 |
| February | 243.00 | 242.43 | 0.23 | 243.09 | 241.96 | 0.46 |
| March | 242.99 | | | 243.50 | | |
| April | 243.09 | 242.93 | 0.07 | 243.90 | 242.86 | 0.42 |
| May | 243.18 | 242.83 | 0.14 | 244.42 | 242.91 | 0.62 |
| June | 243.18 | 242.97 | 0.09 | 244.51 | 243.23 | 0.52 |
| July | 242.54 | 242.96 | -0.17 | 244.55 | 243.05 | 0.62 |
| August | 242.38 | 242.74 | -0.15 | 244.41 | 243.06 | 0.55 |
| September | 242.46 | 242.62 | -0.07 | 244.25 | 242.99 | 0.52 |
| October | 242.21 | 242.55 | -0.14 | 243.64 | 242.89 | 0.31 |
| November | 242.63 | 242.48 | 0.06 | 243.07 | 242.48 | 0.24 |
| December | 243.08 | 242.49 | 0.24 | 242.31 | 242.50 | -0.08 |

Table 3.1: The average voltage for 2014 and 2015, and the percentage decrease from 2014 to 2015, for all substations and for substations with a voltage change.

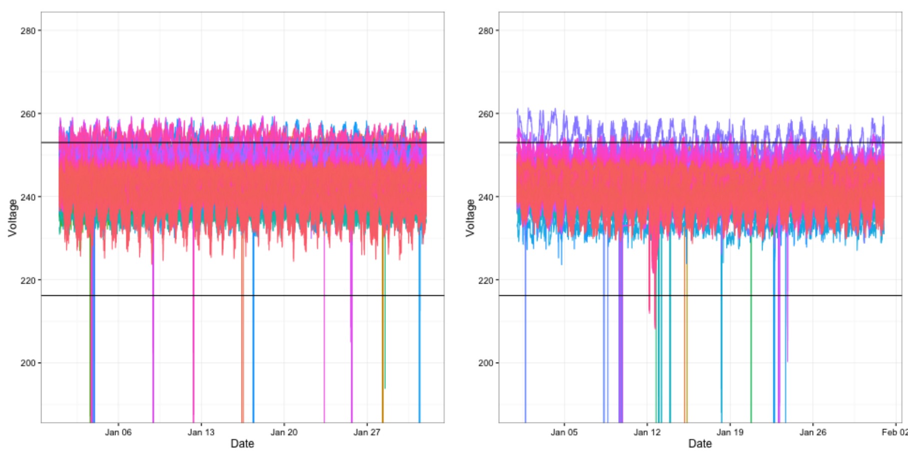
| Month | % of Ten-Minutes Over 253 V | | | | % of Ten-Minutes Under 216.2 V | | | |
|---|---|---|---|---|---|---|---|---|
| | No Voltage Change | | Voltage Change | | No Voltage Change | | Voltage Change | |
| | 2014 | 2015 | 2014 | 2015 | 2014 | 2015 | 2014 | 2015 |
| January | 0.27 | 0.04 | 0.31 | 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 3.2: The percentage of ten-minute periods over 253 V and under 216.2 V, for every month. The percentages are given for substations with and without a voltage change.

### 3.1.1 January 2014 versus January 2015

Within the voltage data collected from January 01/01/2014 – 31/12/2015, 741 substations were available for analysis. Of these 741 substations, 402 had a voltage change. Of these 402, 284 had feeder end voltage monitors that also provided data associated with them. Data was available for 1211 such voltage monitors at feeder ends.

Within the voltage data collected from January 01/01/2015 – 31/01/2015, 621 substations were available for analysis. Of these 621 substations, 407 had a voltage change. Of these 407, 286 had feeder end voltage monitors that also provided data associated with them. Data was available for 1172 such voltage monitors at feeder ends. Figure 3.1 shows voltage data for all substations for every ten-minute period in January 2014 and 2015.




(a) January 2014.

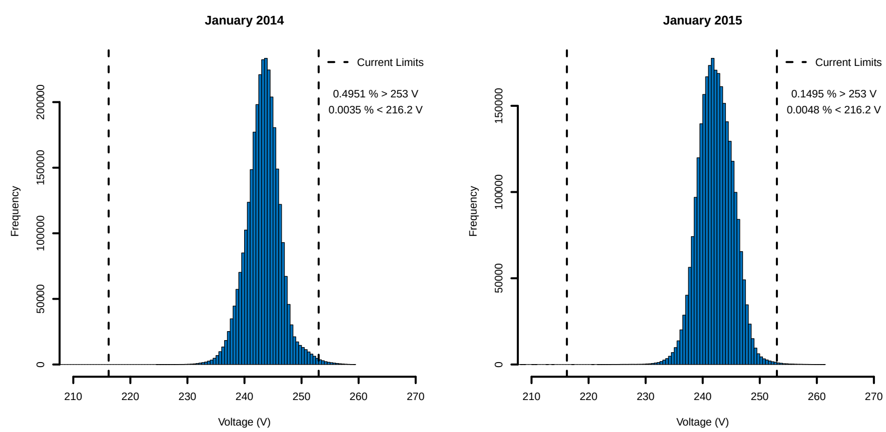
(b) January 2015.

Figure 3.1: Voltage data measured at all substations. Measurements are for each ten-minute periods in January 2014 and 2015. The black horizontal lines indicate the statutory limits of 230V +10%, -6% .

Of the 402 substations considered in January 2014, 16 substations had a measurement above 253V and 21 below 216.2V for at least one ten-minute period during January 2014. The average percentage of ten-minute periods exceeding 253V for each day in January 2014 was 0.4951% for all substations and 0.3108% for substations that would go on to have a voltage change, over the month. The average percentage of ten-minute periods below 216.2V for each day in January 2014 was 0.0035% for all substations and an average of 0.0023% for substations that would go on to have a voltage change, over the month.

Of the 407 substations considered in January 2015, 8 substations had a measurement above 253V and 51 below 216.2V for at least one ten-minute period during January 2015. The average percentage of ten-minute periods exceeding 253V for each day in January 2015 was of 0.1495% for all substations and 0.2034% for substations with a voltage change, over the month. The average percentage of ten-minute periods below 216.2V for each day in January 2015 was 0.0048% both for all substations and substations with a voltage change, over the month.

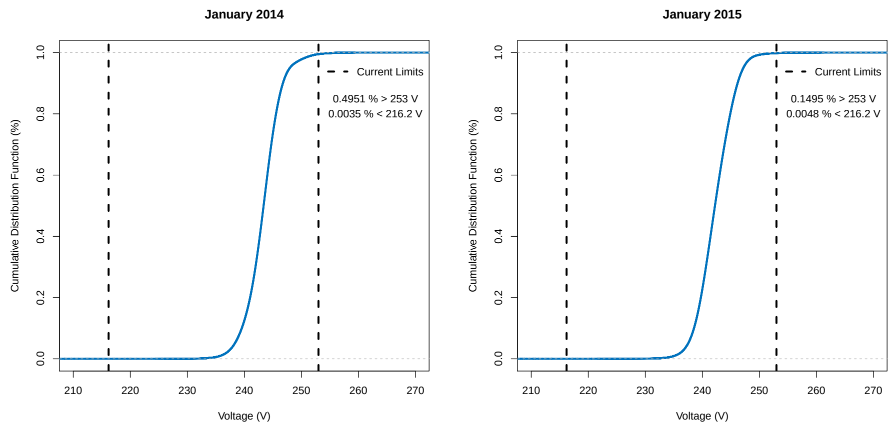
Figure 3.2 shows the frequencies of voltages measured at all substations in January 2014 and January 2015. Figure 3.3 displays the cumulative distribution function for voltages measures at all substations in January 2014 and 2015. The current statutory limits are marked on both graphs by the black dashed lines. Figure 3.4 displays the percentage of voltages measured close to the lower statutory limits for January 2014 and 2015. Figure 3.5 displays the percentage of voltages measured close to the upper statutory limits for January 2014 and 2015. Again, the current statutory limit is marked by the black dashed lines.




(a) January 2014.

(b) January 2015.

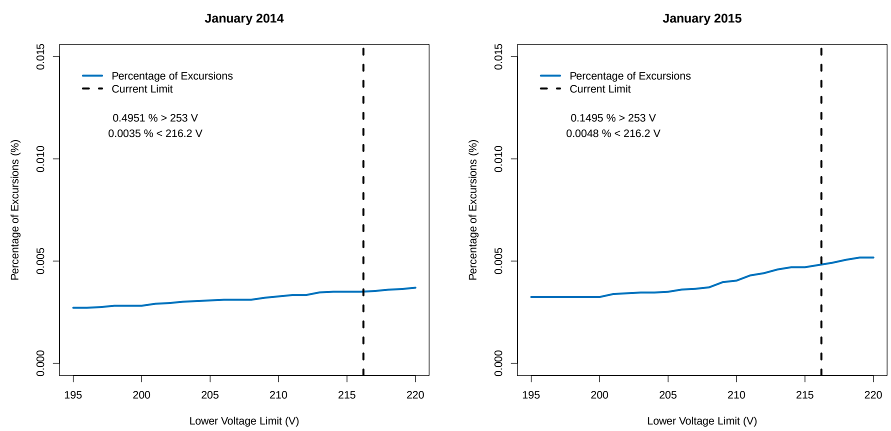
Figure 3.2: The frequencies of voltage values measured at all substations.




(a) January 2014.

(b) January 2015.

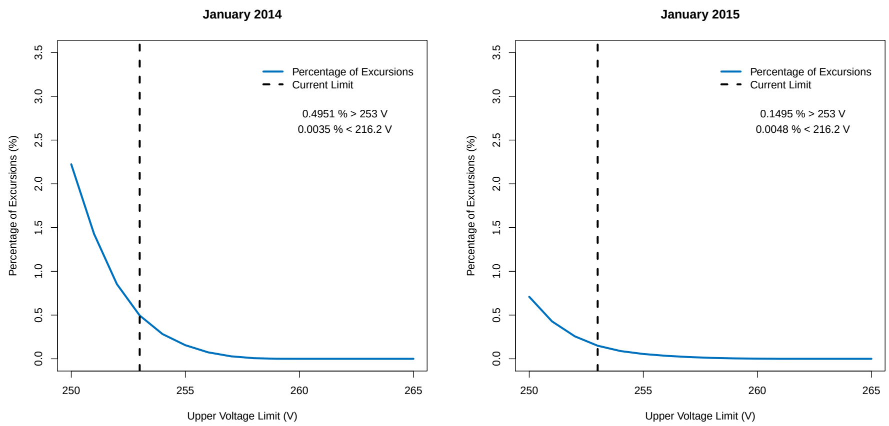
Figure 3.3: The cumulative distribution function for voltages measured at all substations.




(a) January 2014.

(b) January 2015.

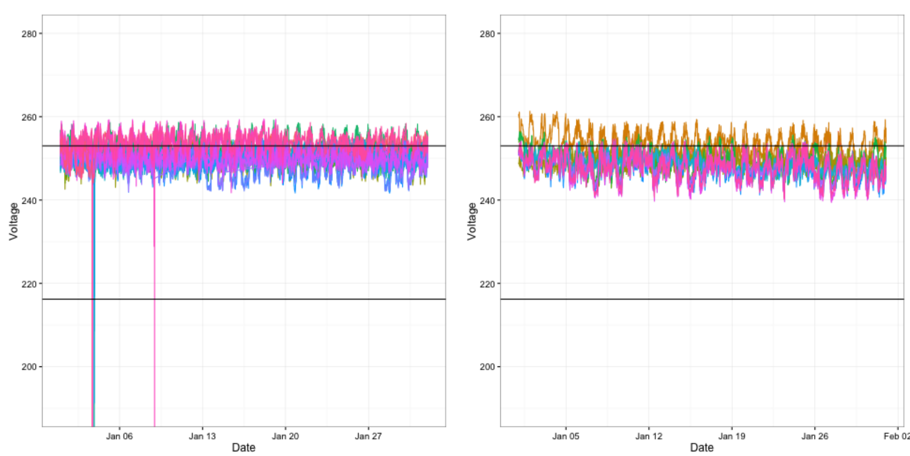
Figure 3.4: Excursions at the lower statutory limits for all substations in January 2014 and 2015. The current limit is marked by the black dashed line.




(a) January 2014. (b) January 2015.

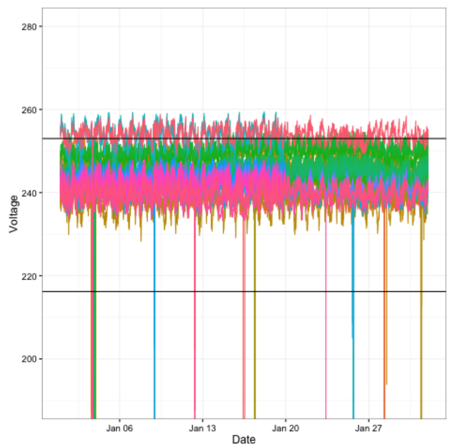
Figure 3.5: Excursions at the upper statutory limits for all substations in January 2014 and 2015. The current limit is marked by the black dashed line.

Figure 3.6 shows the voltage profiles for those substations where at least one ten-minute period exceeded the statutory limit and Figure 3.7 for those substations where at least one ten-minute period was lower than the statutory limit.

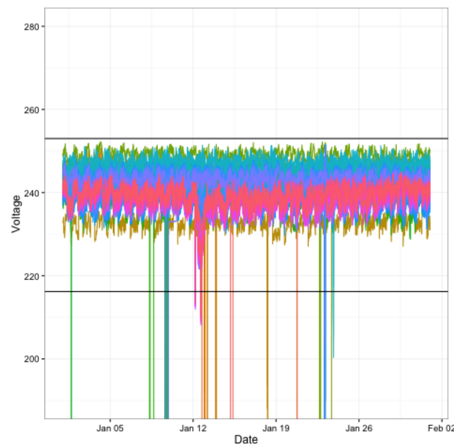



(a) January 2014. (b) January 2015.

Figure 3.6: Ten-minute voltage data plotted for each substation where at least one ten-minute period exceeds the statutory limit, for January 2014 and 2015.



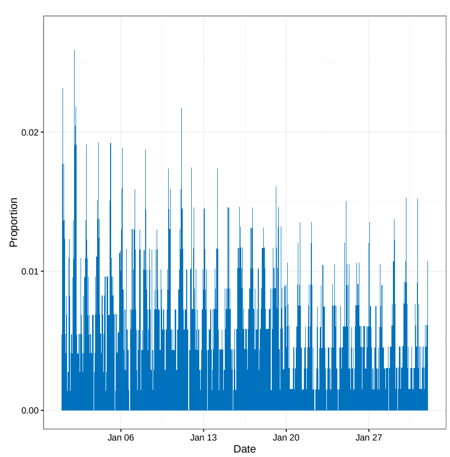

(a) January 2014.



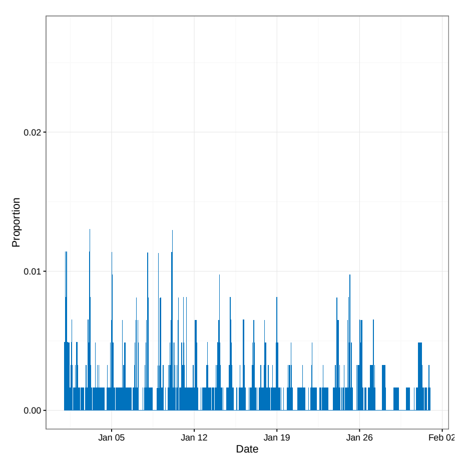

(b) January 2015.

Figure 3.7: Ten-minute voltage data plotted for each substation where at least one ten-minute period is below the statutory limit, for January 2014 and 2015.

Figures 3.8 and 3.9 show the number of excursions at every ten-minute period of the month. Figures 3.10 and 3.11 show the number of excursions at each hour of the day over the course of the month. Figures 3.12 and 3.13 show the breakdown of the occurrences of excursions by substation, showing that the points outside the limits arise from a small number of substations.

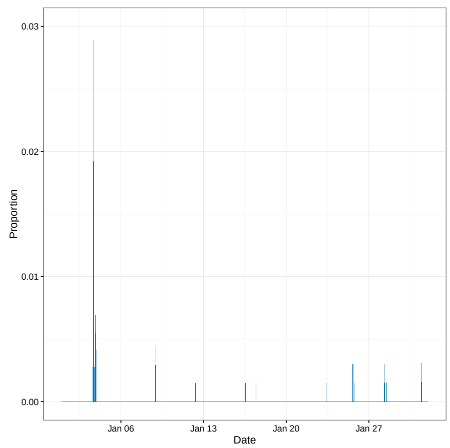



(a) January 2014.

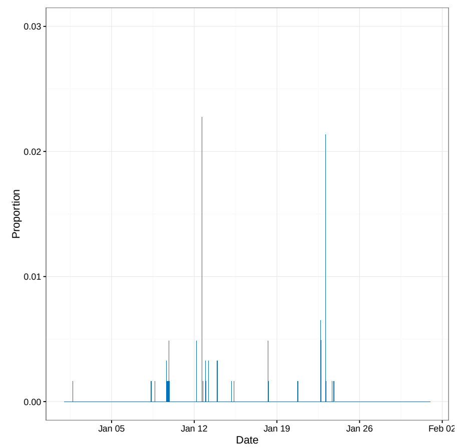



(b) January 2015.

Figure 3.8: Proportion of substations exceeding the statutory limit in each ten-minute period in January 2014 and 2015.

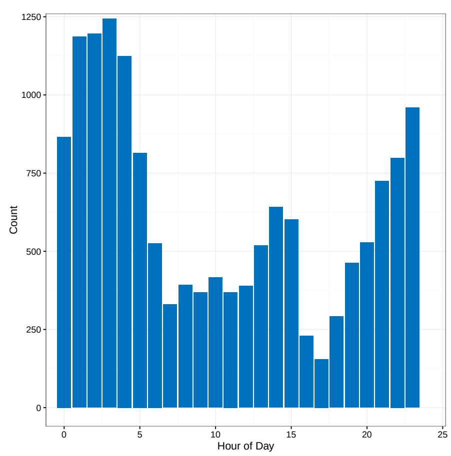



(a) January 2014.

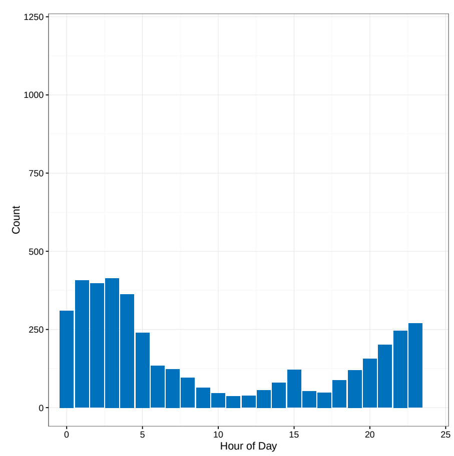



(b) January 2015.

Figure 3.9: Proportion of substations below the statutory limit in each ten-minute period in January 2014 and 2015.

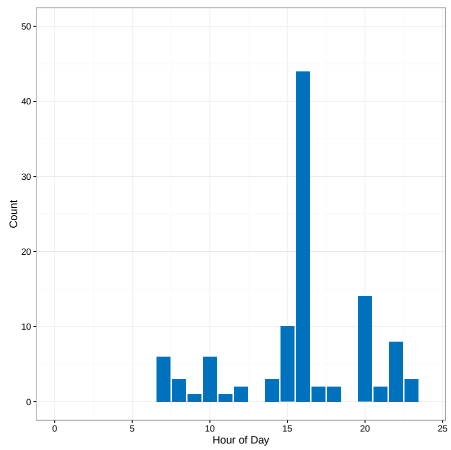


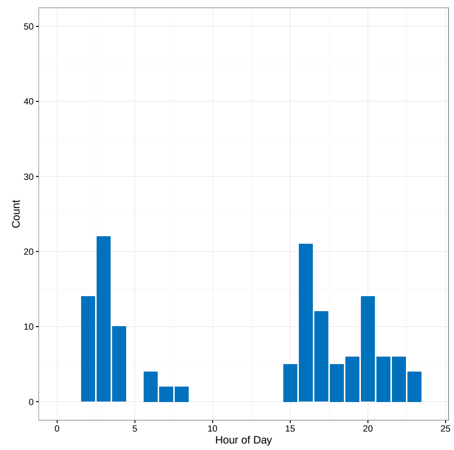

(a) January 2014.




(b) January 2015.

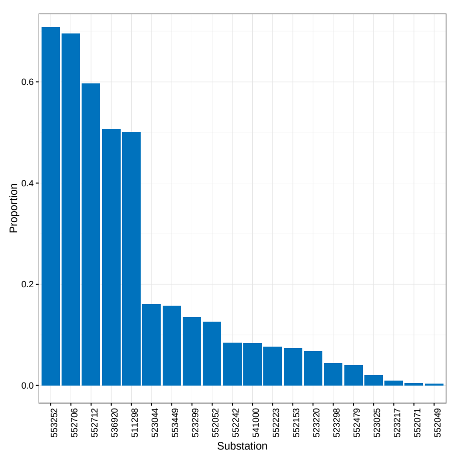
Figure 3.10: The number of over-excursions for each hour of the day over the entire month, for January 2014 and 2015.

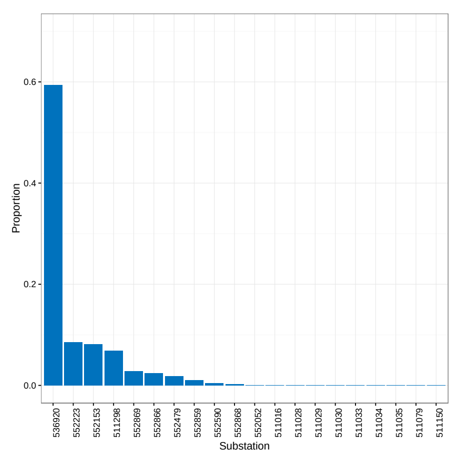



(a) January 2014. (b) January 2015.

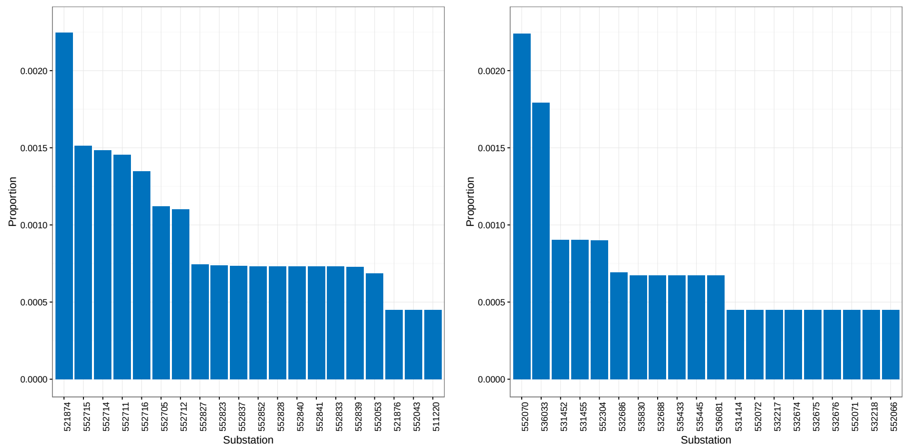
Figure 3.11: The number of under-excursions for each hour of the day over the entire month, for January 2014 and 2015.




(a) January 2014. (b) January 2015.

Figure 3.12: Proportion of ten-minute periods a substation exceeds the statutory limit, for the twenty substations with the most over-excursions, in January 2014 and 2015.




(a) January 2014.

(b) January 2015.

Figure 3.13: Proportion of ten-minute periods that a substation is below the statutory limit, for the twenty substations with the most under-excursions, in January 2014 and 2015.

## 3.2 Voltage monitored at feeder ends

As in 3.1, the voltage data is analysed, this time at feeder ends, for January. Table 3.3 displays the average voltage recorded across feeder ends that were and were not associated with a voltage change for every month in 2014 and 2015, in addition to the percentage decrease from 2014 to 2015. Table 3.4 displays the percentage of ten-minute periods over 253 V and under 216.2 V for feeder ends that were and were not associated with a voltage change, for every month in 2014 and 2015.

| Month | Feeder Ends without a Voltage Change | | | Feeder Ends with a Voltage Change | | |
|---|---|---|---|---|---|---|
| | 2014 | 2015 | % decrease | 2014 | 2015 | % decrease |
| January | 242.01 | 241.68 | 0.14 | 241.84 | 240.50 | 0.56 |
| February | 242.00 | 241.31 | 0.28 | 241.63 | 240.56 | 0.44 |
| March | 242.08 | 241.52 | 0.23 | 242.21 | 240.96 | 0.52 |
| April | 242.21 | 242.01 | 0.08 | 242.61 | 241.81 | 0.33 |
| May | 242.24 | 242.04 | 0.08 | 242.79 | 241.96 | 0.35 |
| June | 242.58 | 242.19 | 0.16 | 242.91 | 242.15 | 0.31 |
| July | 241.88 | 242.17 | -0.12 | 242.94 | 242.11 | 0.34 |
| August | 241.78 | 241.92 | -0.06 | 242.83 | 242.02 | 0.34 |
| September | 241.94 | 241.85 | 0.04 | 242.70 | 241.78 | 0.38 |
| October | 241.54 | 241.65 | -0.04 | 242.04 | 241.57 | 0.19 |
| November | 241.94 | 241.50 | 0.18 | 241.40 | 241.06 | 0.14 |
| December | 242.00 | 241.42 | 0.24 | 240.81 | 241.04 | -0.10 |

Table 3.3: The average voltage for 2014 and 2015, and the percentage decrease from 2014 to 2015, for feeder ends with and without a voltage change.

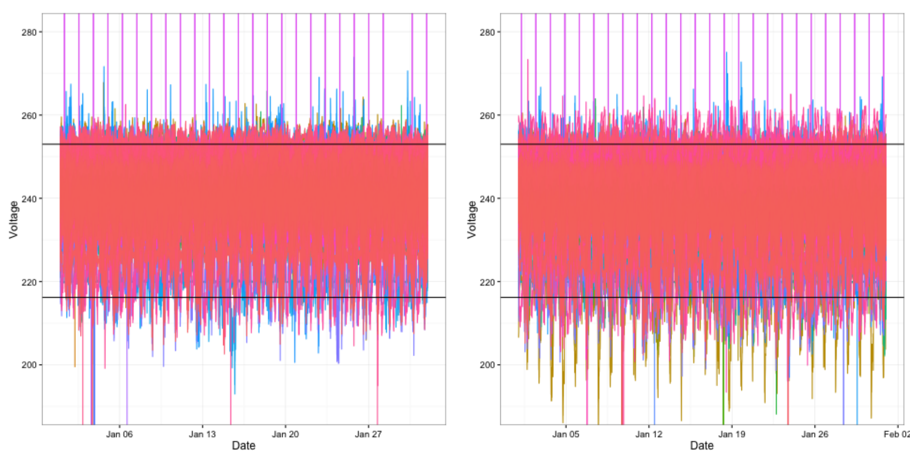
| Month | % of Ten-Minutes Over 253 V | | | | % of Ten-Minutes Under 216.2 V | | | |
|---|---|---|---|---|---|---|---|---|
| | No Voltage Change | | Voltage Change | | No Voltage Change | | Voltage Change | |
| | 2014 | 2015 | 2014 | 2015 | 2014 | 2015 | 2014 | 2015 |
| January | 0.47 | 0.11 | 0.20 | 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 3.4: The percentage of ten-minute periods over 253 V and under 216.2 V, for every month. The percentages are given for feeder ends with and without a voltage change.

### 3.2.1 January 2014 versus January 2015

For January 2014, 2806 feeder ends had ten-minute voltage data available for analysis. Of these 2806 monitors, 1211 were associated with substations that were suitable for analysis and that would go on to have a voltage change.

For January 2015, 2737 feeder ends had ten-minute voltage data available for analysis. Of these 2737 monitors, 1172 had working feeder ends associated with substations suitable for analysis that had a voltage change. Figure 3.14 shows voltage data from all feeder end monitors for every ten-minute period in January.



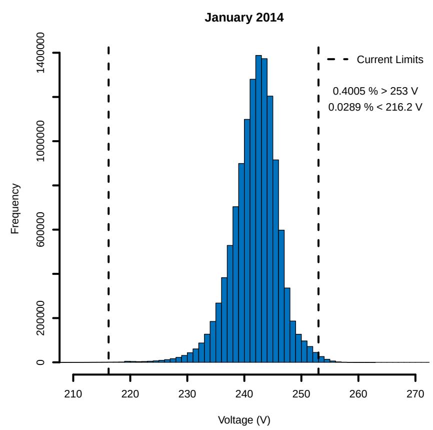

(a) January 2014. (b) January 2015.

Figure 3.14: Voltage data measured at all feeder end monitors. Measurements are for each ten-minute periods in January 2014 and 2015. The black horizontal lines indicate the statutory limits of 230V +10%, -6% .

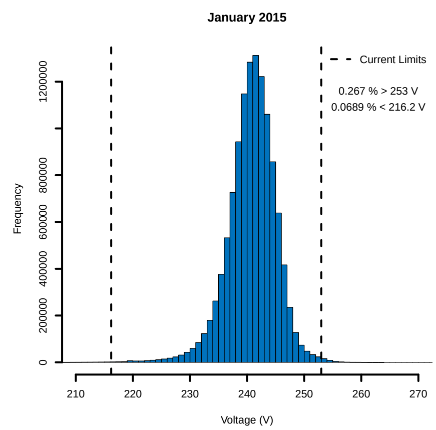
Of the 1211 feeder end monitors considered in January 2014, 77 had at least one ten-minute period above 253V and 39 had at least one ten-minute period below 216.2V during January 2014. The average percentage of ten-minute periods exceeding 253V for each day in January 2014 was 0.4005% for all feeder ends and 0.1970% for monitors associated with a voltage change, over the month. The average percentage of ten-minute periods below 216.2V for each day in January 2014 was 0.0289% for all monitors and 0.0440% for monitors associated with a voltage change, over the month.

Of the 1172 feeder end monitors considered in January 2015, 32 had a measurement above 253V and 44 below 216.2V for at least one ten-minute period during January 2015. The average percentage of ten-minute periods exceeding 253V for each day in January 2015 was 0.2670% for all monitors and 0.0974% for monitors associated with a voltage change, over the month. The average percentage of ten-minute periods below 216.2V for each day in January 2015 was 0.0689% for all monitors and 0.0887% for monitors associated with a voltage change, over the month.

Figure 3.15 shows the frequencies of voltages measured at all feeder ends in January 2014 and January 2015. Figure 3.16 displays the cumulative distribution function for voltages measures at all feeder ends in January 2014 and 2015. The current statutory limits are marked on both graphs by the black dashed lines. Figure 3.17 displays the percentage of voltages measured close to the lower statutory limits for January 2014 and 2015. Figure 3.18 displays the percentage of voltages measured close to the upper statutory limits for January 2014 and 2015. Again, the current statutory limit is marked by the black dashed lines.

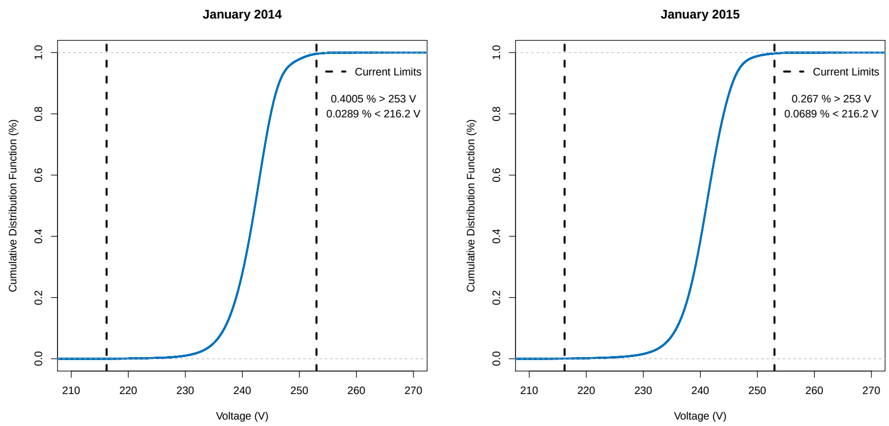



(a) January 2014.



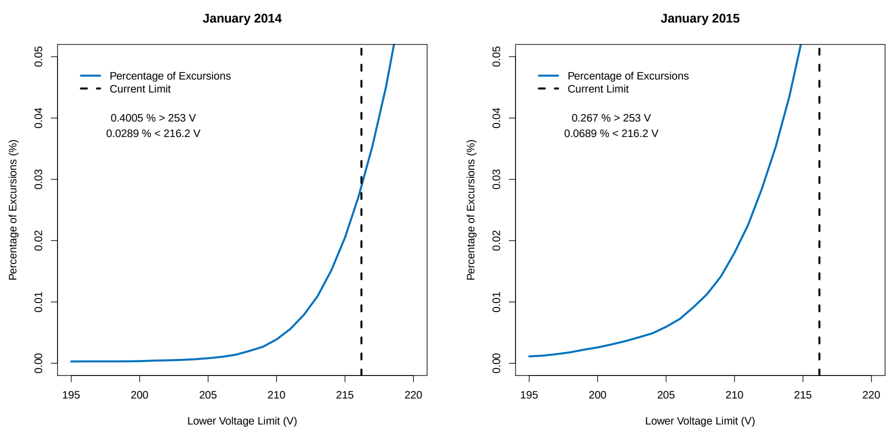

(b) January 2015.

Figure 3.15: The frequencies of voltage values measured at all feeder ends.



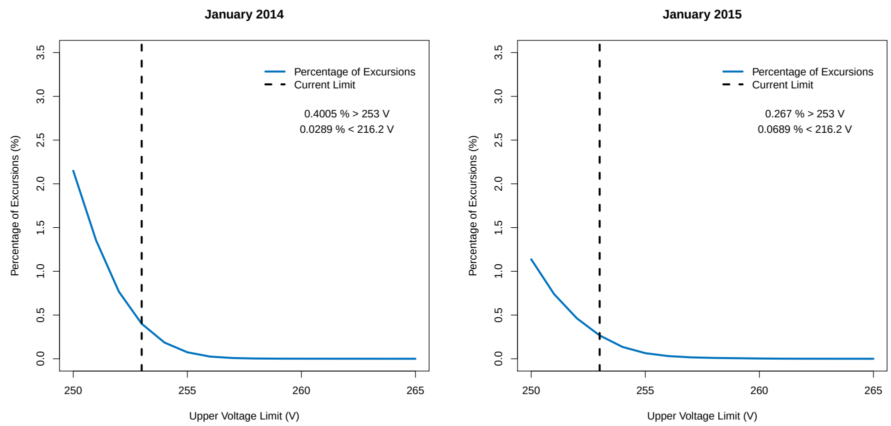

(a) January 2014. (b) January 2015.

Figure 3.16: The cumulative distribution function for voltages measured at all feeder ends.




(a) January 2014. (b) January 2015.

Figure 3.17: Excursions at the lower statutory limits for all feeder ends in January 2014 and 2015. The current limit is marked by the black dashed line.

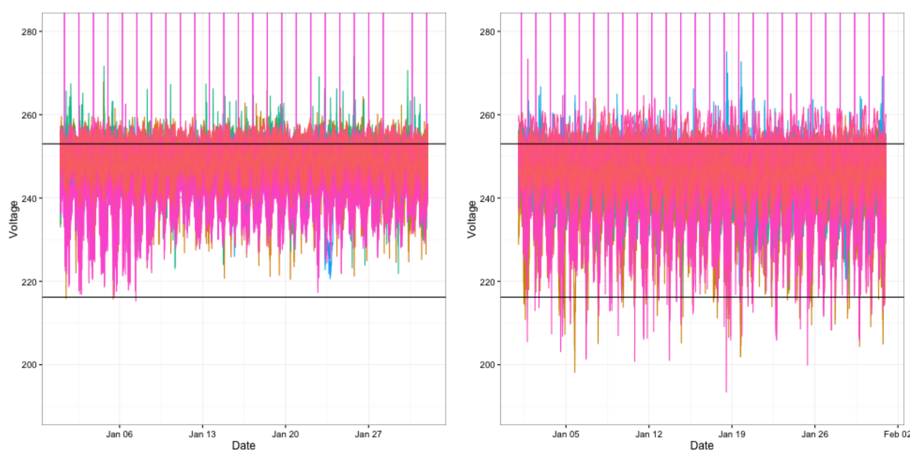



(a) January 2014.

(b) January 2015.

Figure 3.18: Excursions at the upper statutory limits for all feeder ends in January 2014 and 2015. The current limit is marked by the black dashed line.

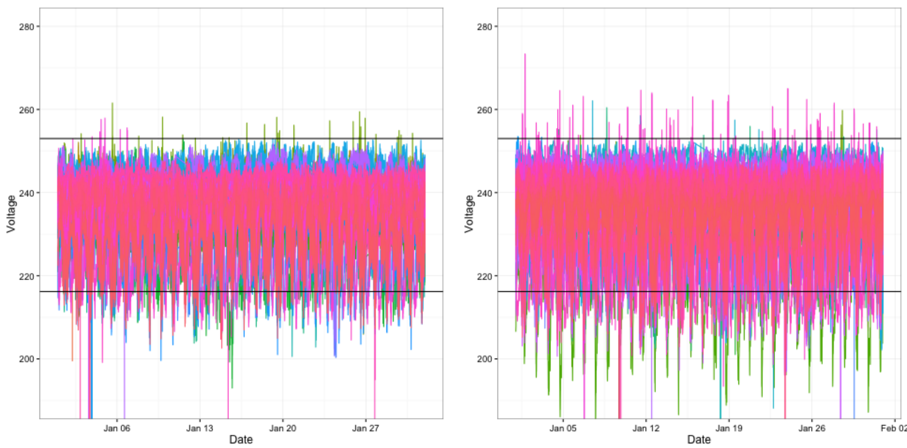
Figure 3.19 shows the voltage profiles for those monitors at feeder ends where at least one ten-minute period exceeded the statutory limit and Figure 3.20 for those substations where at least one ten-minute period was lower than the statutory limit.




(a) January 2014.

(b) January 2015.

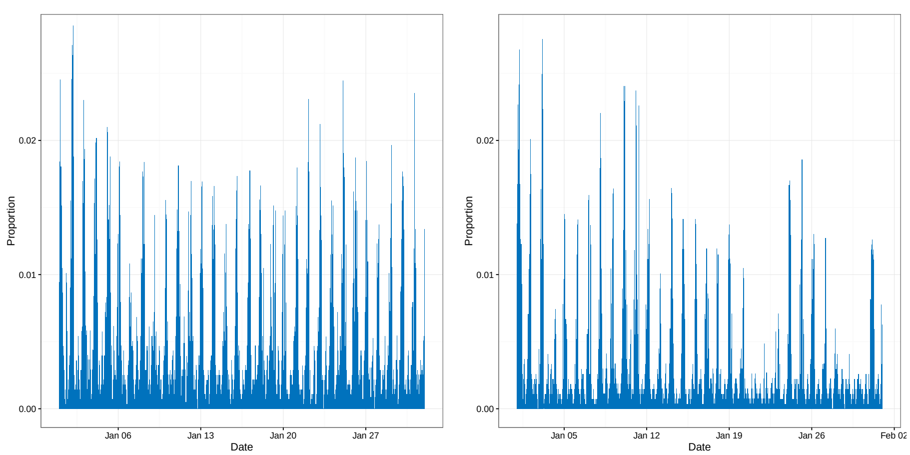
Figure 3.19: Ten-minute voltage data plotted for each monitor at feeder end where at least one ten-minute period exceeds the statutory limit, for January 2014 and 2015.




(a) January 2014. (b) January 2015.

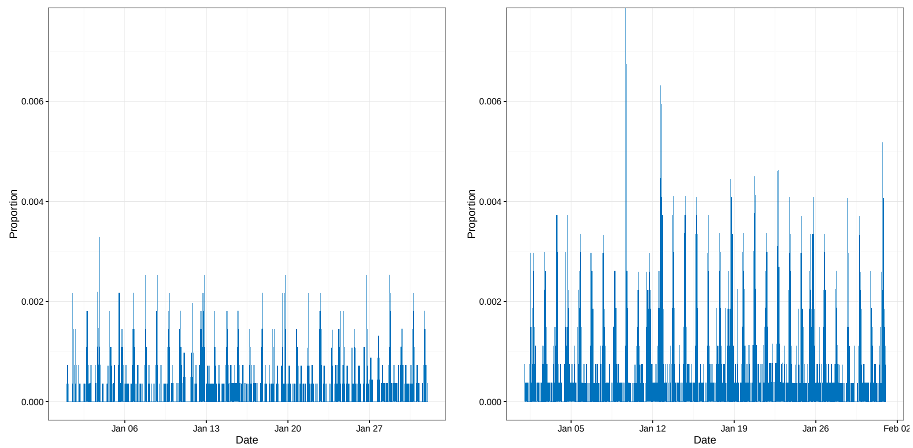
Figure 3.20: Ten-minute voltage data plotted for each monitor at feeder end where at least one ten-minute period is below the statutory limit, for January 2014 and 2015.

Figures 3.21 and 3.22 show the number of excursions at every ten-minute period of the month. Figures 3.23 and 3.24 show the number of excursions at each hour of the day over the course of the month. Figures 3.25 and 3.26 show the breakdown of the occurrences of excursions by feeder end, showing that the points outside the limits arise from a small number of feeder ends.




(a) January 2014. (b) January 2015.

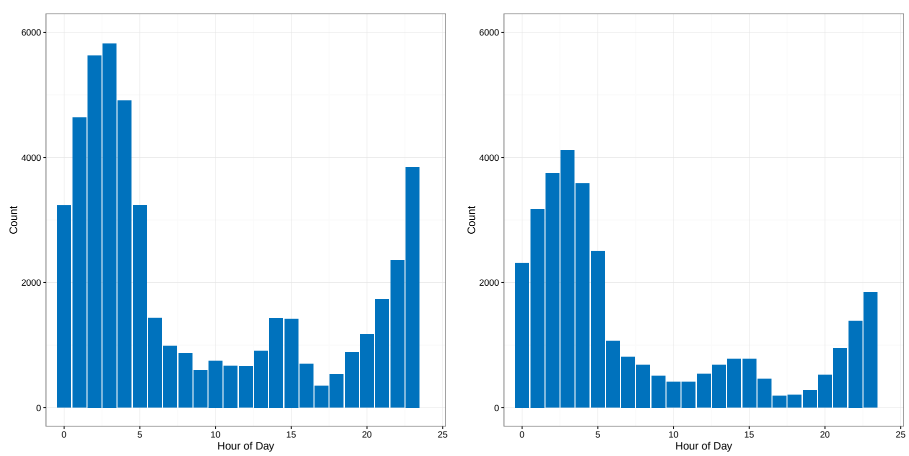
Figure 3.21: Proportion of monitors at feeder ends exceeding the statutory limit in each ten-minute period in January 2014 and 2015.




(a) January 2014.

(b) January 2015.

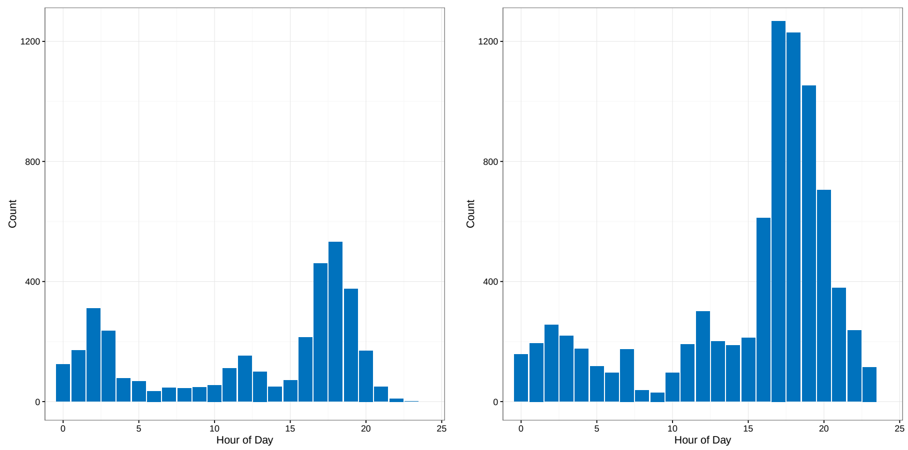
Figure 3.22: Proportion of monitors at feeder ends below the statutory limit in each ten-minute period in January 2014 and 2015.




(a) January 2014.

(b) January 2015.

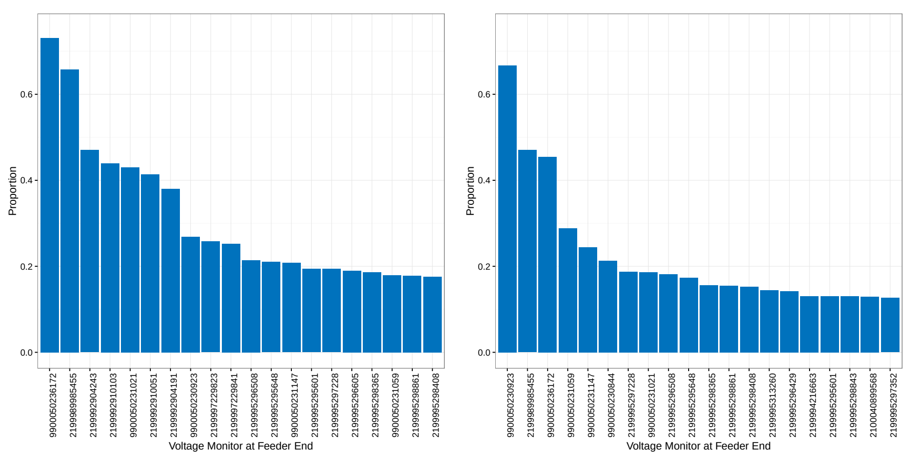
Figure 3.23: The number of over-excursions for each hour of the day over the entire month, for January 2014 and 2015.




(a) January 2014.

(b) January 2015.

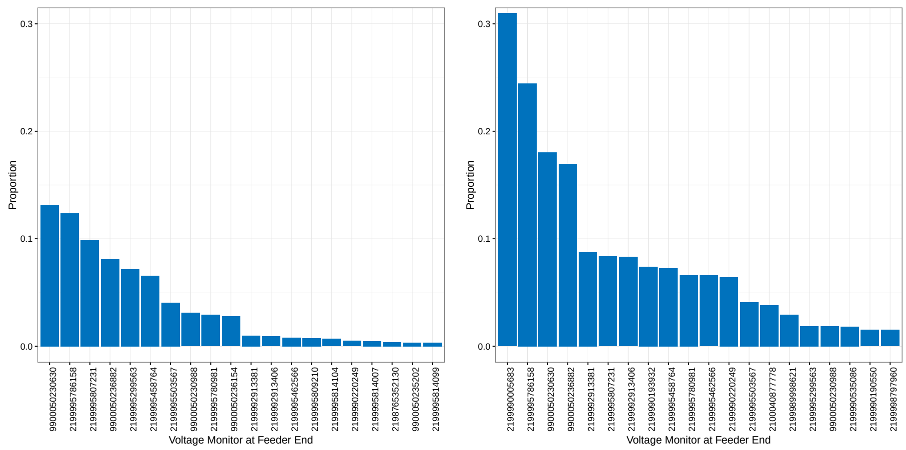
Figure 3.24: The number of under-excursions for each hour of the day over the entire month, for January 2014 and 2015.




(a) January 2014.

(b) January 2015.

Figure 3.25: Proportion of ten-minute periods that a monitor at feeder end exceeds the statutory limit, for the twenty feeder end monitors with the most over-excursions, in January 2014 and 2015.




(a) January 2014. (b) January 2015.

Figure 3.26: Proportion of ten-minute periods that a monitor at feeder end is below the statutory limit, for the twenty feeder end monitors with the most under-excursions, in January 2014 and 2015.

## 3.3 Intersections of Excursions

This section looks at the frequency of an excursion at a substation occurring simultaneously with an excursion at one or more of the substation's feeder ends and vice versa. As this section is concerned with an excursion occurring at both a substation and a feeder end, only data from linked substations and feeder ends are considered. There are two ways of investigating the intersection of excursions. The first is to start with excursions at substations and count the number of excursions at feeder ends associated with those substations. This information is given in Table 3.5 for January 2014 and 2015, for substations with and without the voltage change. Tables for other months are given in the appendix.

Another method is to begin with excursions at feeder ends and then note whether there is a simultaneous excursion at the associated substation. This analysis is shown in Table 3.6 for January 2014 and 2015, for feeder ends that were and were not associated with a voltage change.

The values given in the last six rows of Tables 3.5 and 3.6 are the percentage of times an excursion occurred simultaneously at a substation and feeder end, for all excursions of that type (either over-excursion or under-excursion). As a toy example, consider 8 substations with over-excursions in a given month, each substation having only one over-excursion each. These 8 substations have 4 feeder ends each. Therefore, there are 32 feeder end voltages that need to be checked. If 4 are greater than 253 V, 28 are within the statutory limits and none are less than 216.2 V, then that would be reported as: 12.5% of feeder ends are *over* when a substation is over; 87.5% of feeder ends are *in* when a substation is over; and 0% of feeder ends are *under* when a substation is over.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | No Voltage Change | Voltage Change | No Voltage Change | Voltage Change |
| No. Substations with Overs | | 2 | 12 | 3 | 5 |
| No. Substations with Unders | | 0 | 15 | 10 | 40 |
| No. Over-Excursions | | 2416 | 1924 | 408 | 1032 |
| No. Under-Excursions | | 0 | 32 | 29 | 71 |
| No. Feeder Ends linked to Overs | | 16 | 63 | 30 | 28 |
| No. Feeder Ends linked to Unders | | 0 | 47 | 40 | 210 |
| Sub Over | % Feeder Ends Over | 66.09 | 53.54 | 57.50 | 57.73 |
| | % Feeder Ends In | 33.91 | 46.46 | 42.50 | 42.27 |
| | % Feeder Ends Under | 0.00 | 0.00 | 0.00 | 0.00 |
| Sub Under | % Feeder Ends Over | | 0.00 | 0.00 | 0.00 |
| | % Feeder Ends In | | 94.12 | 98.67 | 92.66 |
| | % Feeder Ends Under | | 5.88 | 1.33 | 7.34 |

Table 3.5: January: Substations that have associated feeder end voltage monitors. A summary of the intersection of excursions at substations and feeder ends, from the perspective of substations.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | No Voltage Change | Voltage Change | No Voltage Change | Voltage Change |
| No. Feeder Ends with Overs | | 27 | 77 | 28 | 32 |
| No. Feeder Ends with Unders | | 6 | 39 | 12 | 44 |
| No. Over-Excursions | | 12222 | 10392 | 2862 | 4995 |
| No. Under-Excursions | | 50 | 2321 | 188 | 4550 |
| No. Substations linked to Overs | | 6 | 23 | 7 | 11 |
| No. Substations linked to Unders | | 5 | 26 | 10 | 30 |
| Feeder End Over | % Substations Over | 83.76 | 29.88 | 46.19 | 68.53 |
| | % Substations In | 16.24 | 70.12 | 53.81 | 31.47 |
| | % Substations Under | 0.00 | 0.00 | 0.00 | 0.00 |
| Feeder End Under | % Substations Over | 0.00 | 0.00 | 0.00 | 0.00 |
| | % Substations In | 100.00 | 99.81 | 99.46 | 99.58 |
| | % Substations Under | 0.00 | 0.19 | 0.54 | 0.42 |

Table 3.6: January: Feeder ends that have associated substations. A summary of the intersection of excursions at feeder ends and substations, from the perspective of feeder ends.

| | Substations without a Voltage Change | | Substations with a Voltage Change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| No. Substations | 205 | 208 | 402 | 407 |
| No. Substations with Over-Excursions | 2 | 3 | 16 | 8 |
| No. Substations with Under-Excursions | 5 | 18 | 21 | 51 |
| No. Over-Excursions | 2416 | 408 | 5533 | 3696 |
| No. Under-Excursions | 17 | 45 | 41 | 88 |

Table 3.7: An overview of the number of substations, and their over- under-excursions for January 2014 and 2015.

| 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 3.8: The number of substations with repeated excursions (or not) in January 2014 and 2015, grouped by substations with and without a voltage change.

### 3.3.1 Repeated excursions

Table 3.7 gives some information on the number of substations, the number of substations with excursions, and the number of ten-minute periods outside statutory limits for January 2014 and 2015. Table 3.8 shows the number of substations that had repeated excursions from January 2014 to January 2015, for substations with and without a voltage change. Table 3.9 gives information on the number of feeder ends, the number of feeder ends with excursions, and the number of ten-minute periods outside statutory limits for January 2014 and 2015. Table 3.10 shows the number of feeder ends that had repeated excursions from 2014 to 2014, for feeder ends that were and were not associated with a voltage change.

| | Feeder Ends without a Voltage Change | | Feeder Ends with a Voltage Change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| No. Feeder Ends | 600 | 590 | 1211 | 1172 |
| No. Feeder Ends with Over-Excursions | 27 | 28 | 77 | 32 |
| No. Feeder Ends with Under-Excursions | 6 | 12 | 39 | 44 |
| No. Over-Excursions | 12222 | 2862 | 10392 | 4995 |
| No. Under-Excursions | 50 | 188 | 2321 | 4550 |

Table 3.9: An overview of the number of feeder ends, and their over- and under-excursions for January 2014 and 2015.

| 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 3.10: The number of feeder ends with repeated excursions (or not) in January 2014 and 2015, grouped by feeder ends that were and were not associated with a voltage change.

# Section 4

# Dynamic Response: Operation Juniper

Historically, a 3% reduction in voltage has previously been expected to deliver a 5% reduction in demand. More recently, however, it has been suggested that the demand reduction arising from a 3% voltage reduction is variable, and more likely to be in the region of 3%.

In an attempt to quantify the reduction in demand that might be associated with a reduction in voltage, a voltage reduction trial, *Operation Juniper* was run in October 2013, by National Grid. The aim of Operation Juniper was to assess voltage reduction delivery timescales and to enable the actual demand reduction delivered by a 3% voltage reduction to be established. Reductions in demands were carried out during two load windows; morning (10:00am-12:00pm) and afternoon (14:00pm-16:00pm) on October 15th, 2013, which are considered to be periods of relatively low demand.

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%. All of the demand reductions were observed within the proposed 10 minute requirements, with 70% of these reductions occurring within 5 minutes.

The aim of the analyses presented in this section is to compare the findings of Operation Juniper, as described above, to those observed after the change in voltage settings within the Low Voltage Network Templates monitoring network. Any observed drops in voltage and demand, both at substations and feeder ends, are assessed for statistical significance, comparing levels before and after the period of Operation Juniper. The findings from the period of the Operation Juniper trial will be placed in the context of the time period in which it took place, both in terms of the time of day and the month, and an assessment of whether greater (or otherwise) reductions might have been expected if it had taken place during another period.

## 4.1 Data

The main analysis comprises of a comparison of voltage and demand before, during and after the period of the Operation Juniper trial. In October 2013, data was available from 733 substations (demand and voltage) and 2188 voltage monitors at feeder ends, each producing measurements at ten minute intervals.

## 4.2 Reductions in voltage and demand

Figure 4.1 shows an example of the voltage profile measured at a substation (511151) 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. A similar drop in voltage is observed at feeder ends as can be seen in Figure 4.2.

The corresponding demand profile can be seen in Figure 4.3 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 in digital format.

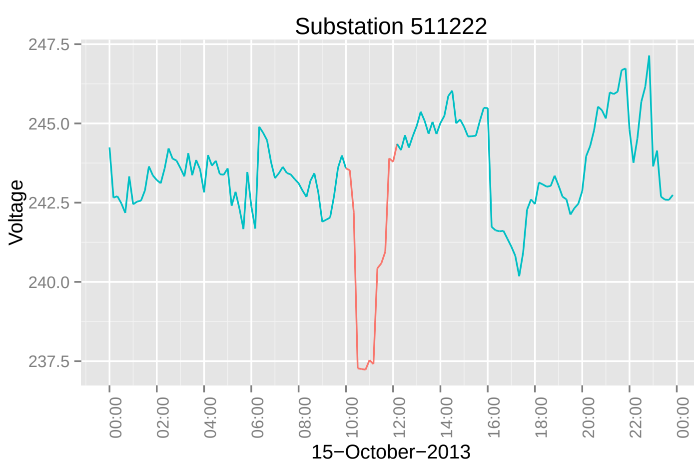



Figure 4.1: Voltage profile for substation 511222 on October 15th, 2013, the day of the Operation Juniper trial during which voltages were dropped between 10:00am and 12:00pm.

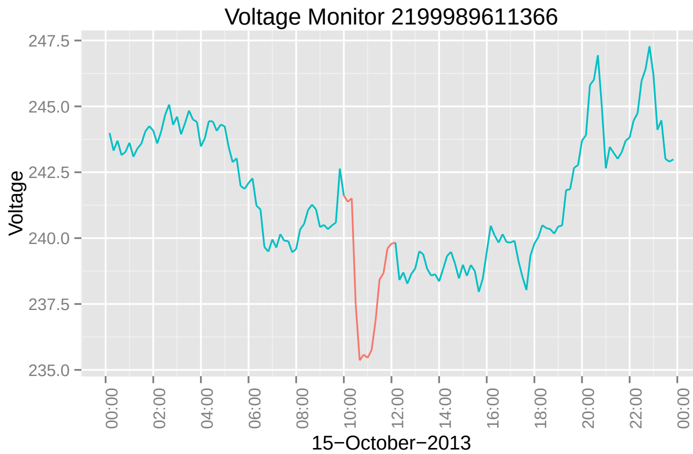



Figure 4.2: Demand profile for substation 511222 on October 15th, 2013, the day of the Operation Juniper trial during which voltages were dropped between 10:00am and 12:00pm.

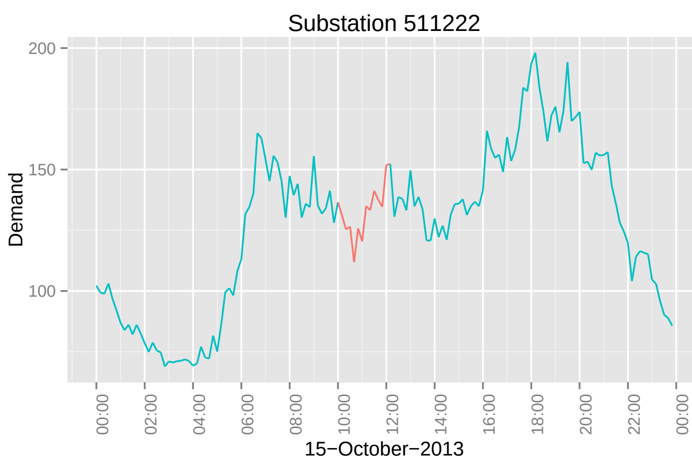



Figure 4.3: Demand profile for Substation 511222 on October 15th, 2013, the day of the Operation Juniper trial during which voltages were dropped between 10:00am and 12:00pm.

The average voltage measured in substations during the two hours before the trial period was 241.7 V, compared to 239.9 V during the trial period, a drop of 0.75%. Performing a paired analysis between differences observed in these two periods on a substation level gave a mean difference of -1.8 V (95%

CI; -1.9, -1.7) which was significant with $p < 0.001$. Voltage profiles might not be expected to be flat during the period around 10am - 12pm and further tests were performed comparing the trial period with the immediate following two hours (average 242.2 V) and the average of the two hours before and after the trial (average 241.9 V). In each case, the differences were found to be highly significant (all $p < 0.001$) with reductions of 0.9% (vs. before) and 0.8% (vs. average of before and after).

Similar, statistically significant, reductions of voltage was measured at feeder ends. The average voltage over the 2188 monitors in the two hours prior to the trial was 240.3 V compared to 238.6 V during the trial and 241.1 V in the next two hours (the average of the two hours before and after the trial was 240.7 V). Reductions were 0.7% (vs. before), 1.0% (vs. after) and 0.9% (vs. average of before and after). In all cases, the reductions were highly statistically significant (all $p < 0.0001$).

Table 4.1 shows the average demands measured at substations for October 2013 for different periods of the day and for different days of the month.

| | Weekdays | Weekends | Tuesdays | Juniper |
|---|---|---|---|---|
| | (Excluding 15th October) | | | Trial day |
| 8 pm – 6 am | 56.06 | 54.29 | 56.28 | 55.68 |
| 6 am – 8 am | 74.90 | 56.04 | 73.56 | 77.52 |
| 8 am – 10 am | 83.14 | 75.61 | 82.90 | 82.87 |
| 10am – 12 pm | 85.59 | 84.12 | 85.22 | 82.71 |
| 12 pm – 2 pm | 84.65 | 81.93 | 83.84 | 82.07 |
| 2 pm – 6 pm | 87.98 | 81.80 | 87.25 | 88.17 |
| 6 pm – 8 pm | 99.18 | 93.33 | 100.26 | 101.23 |

Table 4.1: Average demands (kW) by period of day for October 2013; weekdays, weekends and Tuesdays (all excluding the day of the Juniper trial day) and for the 15th October.

Reductions in demand (measured at substations) associated with the reductions in voltage were less clear during to increased variability in the demand profiles throughout the day with the trial period having slightly lower average demand, 82.7 kW, than the preceding two hours, 82.9 kW, and the following two hours, 82.1 kW. Comparing the average demand in the trial period with the average of the two hours before and afterwards (82.4 vs 82.5 kW) gave a non-significant decrease, but this is not a very suitable test in this instance, given the need to allow for the underlying demand profile. It is noted that the demand for the previous two hours on the trial day (82.9) is the same as for the other Tuesdays in the month but that the average during the two hours of the trial is less (82.7 vs. 85.2) with the following two hours indicating that demand was also less on the 15th (82.1 vs. 83.8 for other Tuesdays).

For this reason, alternative methods used 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. Four approaches were used to estimate the measurements during the trial period as if the reduction in voltage hadn't occurred. Two are based on data from the day of the trial; (i) linear interpolation between the periods before and after the trial, (ii) smoothing splines and two are based on historical patterns; using data from (iii) weekdays in October and (iv) Tuesdays in October. For the latter two, patterns were estimated in the forms of ratios (using the mean as the baseline) than were applied to the average demand for the 15th October.

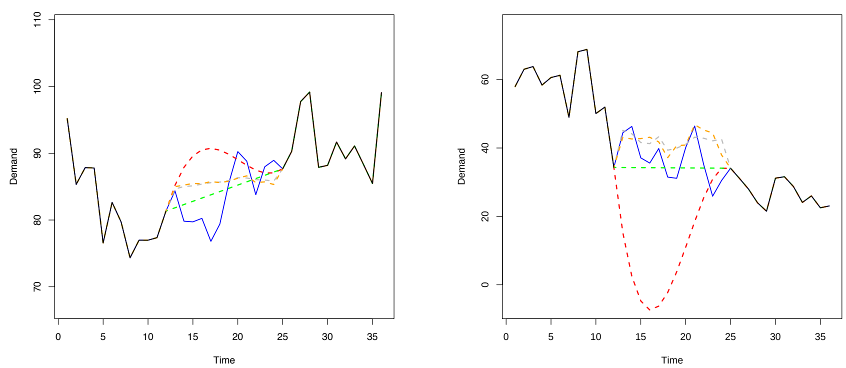



Figure 4.4: Example of predicting the demand during the Operation Juniper trial period using data before and after the trial. The solid line shows the measurements of demand with the dotted lines indicated the values that are predicted if the Juniper trial had not taken place. Green and red lines show estimates based data from the day of the Juniper trial, using linear interpolation and smoothing splines respectively. The grey and orange lines show estimates using data from weekdays and Tuesday in October respectively. The actual measurements recorded during the Juniper trial period, which are treated as missing values, are shown in blue.

An example can be seen in Figure 4.4 for substation 512443, on the left hand side, and substation 532219, on the right hand side. This example shows the tendency for the smoothing splines model to over–react to short–term changes in the profile just before and after the trial period. Using this method, a significant reduction of 0.6% was observed using linear interpolation ($p = 0.017$) and 0.5% using splines (non–significant). Using patterns based on data from other weekdays and Tuesdays in October showed similar, non-significant, differences overall with a (non–significant) decrease of 0.5% ($p = 0.232$).

## 4.3 Predicted effect 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 demand analysis, described in Section 2, was based on differences in monthly averages and this analysis can be used to estimate the effect of the same action performed at a different time of the year. It would be possible to produce a similar analysis for the same action performed at a different time of day but this would require the demand analysis be done by time of day.

The average reductions in demand, given in Section 2, are 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 4.2 presents the predicted reductions using the measured values of average demand reduction for each month and Table 4.3 shows the same analysis using the smoothed values of the monthly average demand reduction.

| Month | Average Reduction (Measured) (%) | Reduction Relative to Baseline (Oct) | Predicted Reduction due to Juniper (%) |
|---|---|---|---|
| January | 1.4 | 1.13 | 0.68 |
| February | 0.97 | 0.78 | 0.47 |
| March | N/A | N/A | N/A |
| April | 1.53 | 1.23 | 0.74 |
| May | 0.13 | 0.10 | 0.06 |
| June | 1.48 | 1.19 | 0.72 |
| July | 0.70 | 0.56 | 0.34 |
| August | 1.13 | 0.91 | 0.55 |
| September | 0.91 | 0.73 | 0.44 |
| October | N/A | N/A | N/A |
| November | 1.58 | 1.27 | 0.76 |
| December | 1.70 | 1.37 | 0.82 |

Table 4.2: The estimated reduction per month that would occur as a result of Operation Juniper, based on smoothed average demand reductions.

| 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 |

Table 4.3: The estimated reduction per month that would occur as a result of Operation Juniper, based on smoothed average demand reductions.

# Appendix A

## A.1 Differences in demand by substation characteristics and time of day

| Month | ≤80% I&C customers | | >80% I&C customers | |
|---|---|---|---|---|
| | (%) Difference | p-value | (%) Difference | p-value |
| January | 1.17 | 0.00 | -0.05 | 0.53 |
| February | 1.04 | 0.01 | -1.04 | 0.91 |
| April | 2.51 | 0.00 | -2.21 | 0.92 |
| May | 0.07 | 0.45 | -0.50 | 0.66 |
| June | 1.00 | 0.04 | 1.58 | 0.07 |
| July | -0.93 | 0.97 | 2.06 | 0.06 |
| August | 0.70 | 0.07 | 2.62 | 0.02 |
| September | -0.15 | 0.62 | 2.92 | 0.01 |
| October | 4.09 | 0.00 | 1.66 | 0.07 |
| November | 1.20 | 0.01 | 0.92 | 0.17 |
| December | 1.31 | 0.00 | 1.98 | 0.03 |

Table A.1: Comparison of differences between monthly averages, for years 2014 and 2015, for substations with more than 80% I&C customers vs substations with less than or equal to 80% I&C customers. Result are based on a sense checking of (i) no more than 20kW difference between daily (weather adjusted) demands and (ii) no more than 20kW difference between aggregated monthly demands.

| Month | Transformer rating >500 | | Transformer rating $\leq$ 500 | |
|---|---|---|---|---|
| | (%) Difference | p-value | (%) Difference | p-value |
| January | 0.89 | 0.04 | 0.98 | 0.01 |
| February | 1.52 | 0.00 | 0.39 | 0.18 |
| April | 1.70 | 0.01 | 0.84 | 0.18 |
| May | -0.41 | 0.84 | -0.19 | 0.62 |
| June | 1.00 | 0.02 | 1.23 | 0.04 |
| July | -1.69 | 1.00 | 0.62 | 0.21 |
| August | 0.30 | 0.26 | 1.52 | 0.01 |
| September | -0.07 | 0.56 | 0.75 | 0.14 |
| October | 3.74 | 0.00 | 2.81 | 0.00 |
| November | 0.40 | 0.21 | 1.40 | 0.01 |
| December | 0.72 | 0.07 | 1.81 | 0.00 |

Table A.2: Comparison of differences between monthly averages, for years 2014 and 2015, for substations with a transformer rating of more than 500 vs substations with a transformer rating of less than or equal to 500. Result are based on a sense checking of (i) no more than 20kW difference between daily (weather adjusted) demands and (ii) no more than 20kW difference between aggregated monthly demands.

| Month | Template 1 | | Template 2 | | Template 3 | | Template 4 | | Template 5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | (%) Difference | p-value | (%) Difference | p-value | (%) Difference | p-value | (%) Difference | p-value | (%) Difference | p-value |
| January | 0.07 | 0.47 | 0.93 | 0.09 | 2.17 | 0.01 | 0.85 | 0.13 | 1.35 | 0.22 |
| February | -0.33 | 0.62 | 1.38 | 0.04 | 1.35 | 0.15 | 0.77 | 0.18 | 0.08 | 0.48 |
| April | -2.95 | 0.89 | 4.83 | 0.00 | 1.55 | 0.10 | 2.58 | 0.00 | 5.70 | 0.29 |
| May | -0.61 | 0.64 | 0.14 | 0.43 | 0.30 | 0.38 | 0.40 | 0.23 | -0.02 | 0.50 |
| June | 1.36 | 0.23 | 1.79 | 0.04 | 2.87 | 0.04 | 1.36 | 0.01 | 3.38 | 0.03 |
| July | 2.87 | 0.07 | -1.52 | 0.99 | -0.00 | 0.50 | -1.32 | 0.98 | 0.90 | 0.14 |
| August | -0.45 | 0.63 | 0.51 | 0.20 | 3.25 | 0.01 | -0.23 | 0.63 | 0.91 | 0.41 |
| September | 1.13 | 0.30 | 0.02 | 0.49 | 0.95 | 0.18 | -0.48 | 0.76 | -3.93 | 0.86 |
| October | 4.00 | 0.04 | 4.04 | 0.00 | 5.10 | 0.02 | 3.54 | 0.00 | 4.03 | 0.04 |
| November | 4.01 | 0.03 | 0.68 | 0.17 | 2.73 | 0.10 | 0.67 | 0.17 | 1.34 | 0.32 |
| December | 3.36 | 0.07 | 0.71 | 0.22 | 1.35 | 0.19 | 1.66 | 0.03 | 8.85 | 0.08 |

Table A.3: Comparison of differences between monthly averages, for years 2014 and 2015, for substations within 1-5 of the LVNTs. Result are based on a sense checking of (i) no more than 20kW difference between daily (weather adjusted) demands and (ii) no more than 20kW difference between aggregated monthly demands.

| Month | 8 pm – 6 am | | 6 am – 8 am | | 8 am – 10 am | | 10am – 12 pm | | 12 pm – 2 pm | | 2 pm – 6 pm | | 6 pm – 8 pm | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | %.diff | p-value | %.diff | p-value | %.diff | p-value | %.diff | p-value | %.diff | p-value | %.diff | p-value | %.diff | p-value |
| January | 1.39 | 0.00 | 1.65 | 0.00 | 1.07 | 0.00 | 1.14 | 0.00 | 1.72 | 0.00 | 1.53 | 0.00 | 0.93 | 0.00 |
| February | 0.85 | 0.03 | – | – | – | – | – | – | – | – | – | – | – | – |
| April | 0.24 | 0.37 | -1.51 | 0.89 | 4.31 | 0.00 | 5.44 | 0.00 | 5.53 | 0.00 | 2.45 | 0.00 | 0.87 | 0.08 |
| May | -0.29 | 0.71 | 0.42 | 0.20 | 0.51 | 0.16 | 0.65 | 0.11 | 0.93 | 0.04 | 0.70 | 0.06 | -0.22 | 0.71 |
| June | 1.42 | 0.01 | 1.43 | 0.00 | 1.17 | 0.01 | 1.36 | 0.01 | 1.31 | 0.02 | 1.81 | 0.00 | 0.79 | 0.03 |
| July | 1.55 | 0.00 | 0.74 | 0.05 | 0.92 | 0.03 | 0.77 | 0.07 | 1.12 | 0.02 | 1.08 | 0.01 | 0.54 | 0.11 |
| August | 1.68 | 0.00 | 0.69 | 0.07 | 1.35 | 0.00 | 1.59 | 0.00 | 1.57 | 0.00 | 1.33 | 0.00 | 0.60 | 0.06 |
| September | 1.73 | 0.00 | 2.11 | 0.00 | 1.08 | 0.03 | 0.77 | 0.09 | 0.77 | 0.08 | 0.54 | 0.15 | 0.51 | 0.13 |
| October | 3.51 | 0.00 | 3.19 | 0.00 | 3.40 | 0.00 | 4.29 | 0.00 | 4.28 | 0.00 | 3.72 | 0.00 | 3.10 | 0.00 |
| November | 9.71 | 0.00 | -7.80 | 1.00 | -1.52 | 1.00 | -0.85 | 0.96 | 1.48 | 0.00 | -3.89 | 1.00 | 10.40 | 0.00 |
| December | 1.98 | 0.00 | 2.47 | 0.00 | 3.07 | 0.00 | 1.73 | 0.00 | 1.15 | 0.01 | 1.75 | 0.00 | 2.73 | 0.00 |

Table A.4: Differences between monthly averages for all periods of the years 2014 and 2015, based on a sense checking of (i) no more than 20kW difference between daily (weather adjusted) demands and (ii) no more than 20kW difference between aggregated monthly demands.

## A.2 Voltage profiles

### A.2.1 Voltage quantiles at substations

| Quantile | All substations | | Substations with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 234.78 | 234.11 | 234.62 | 233.59 |
| 1% | 235.83 | 235.16 | 235.63 | 234.75 |
| 5% | 238.31 | 237.50 | 238.07 | 237.18 |
| 50% | 243.37 | 242.22 | 243.37 | 241.72 |
| 95% | 247.98 | 247.19 | 248.38 | 247.42 |
| 99% | 251.71 | 249.39 | 251.53 | 249.52 |
| 99.5% | 252.98 | 250.68 | 252.42 | 250.92 |

Table A.5: January: Voltage quantiles at for 2014 and 2015 at all substations and at substations with a voltage change.

| Quantile | All substations | | Substations with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 234.48 | 234.52 | 234.30 | 234.31 |
| 1% | 235.56 | 235.47 | 235.35 | 235.30 |
| 5% | 238.12 | 237.60 | 237.85 | 237.43 |
| 50% | 243.25 | 241.94 | 243.19 | 241.64 |
| 95% | 247.75 | 247.13 | 248.06 | 247.29 |
| 99% | 251.24 | 249.03 | 251.24 | 249.22 |
| 99.5% | 252.35 | 249.91 | 252.11 | 250.43 |

Table A.6: February: Voltage quantiles at for 2014 and 2015 at all substations and at substations with a voltage change.

| Quantile | All substations | | Substations with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 235.47 | | 235.57 | |
| 1% | 236.37 | | 236.43 | |
| 5% | 238.60 | | 238.52 | |
| 50% | 243.44 | | 243.52 | |
| 95% | 247.91 | | 248.34 | |
| 99% | 251.70 | | 251.78 | |
| 99.5% | 252.84 | | 252.70 | |

Table A.7: March: Voltage quantiles at for 2014 and 2015 at all substations and at substations with a voltage change.

| Quantile | All substations | | Substations with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 236.12 | 236.24 | 236.37 | 236.37 |
| 1% | 236.97 | 236.94 | 237.18 | 237.07 |
| 5% | 239.00 | 238.62 | 239.11 | 238.67 |
| 50% | 243.60 | 242.73 | 243.87 | 242.50 |
| 95% | 248.19 | 247.72 | 248.69 | 248.10 |
| 99% | 252.03 | 249.94 | 252.50 | 250.34 |
| 99.5% | 253.13 | 250.93 | 253.50 | 251.63 |

Table A.8: April: Voltage quantiles at for 2014 and 2015 at all substations and at substations with a voltage change.

| Quantile | All substations | | Substations with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 236.24 | 236.25 | 236.43 | 236.34 |
| 1% | 237.09 | 236.95 | 237.35 | 237.08 |
| 5% | 239.14 | 238.62 | 239.41 | 238.69 |
| 50% | 243.78 | 242.69 | 244.39 | 242.49 |
| 95% | 249.03 | 247.78 | 250.06 | 248.19 |
| 99% | 252.61 | 250.16 | 253.20 | 250.82 |
| 99.5% | 253.46 | 251.66 | 254.02 | 253.00 |

Table A.9: May: Voltage quantiles at for 2014 and 2015 at all substations and at substations with a voltage change.

| Quantile | All substations | | Substations with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 235.16 | 236.50 | 236.69 | 236.53 |
| 1% | 236.14 | 237.12 | 237.54 | 237.20 |
| 5% | 238.56 | 238.72 | 239.54 | 238.82 |
| 50% | 243.94 | 242.96 | 244.47 | 242.77 |
| 95% | 249.55 | 248.17 | 250.05 | 248.67 |
| 99% | 252.75 | 250.90 | 253.31 | 251.93 |
| 99.5% | 253.61 | 252.67 | 254.15 | 253.67 |

Table A.10: June: Voltage quantiles at for 2014 and 2015 at all substations and at substations with a voltage change.

| Quantile | All substations | | Substations with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 234.15 | 236.29 | 236.72 | 236.42 |
| 1% | 235.07 | 236.98 | 237.60 | 237.12 |
| 5% | 237.57 | 238.58 | 239.61 | 238.64 |
| 50% | 243.79 | 242.84 | 244.51 | 242.62 |
| 95% | 249.63 | 248.01 | 249.98 | 248.44 |
| 99% | 252.77 | 250.56 | 253.21 | 251.33 |
| 99.5% | 253.63 | 251.97 | 254.09 | 252.97 |

Table A.11: July: Voltage quantiles at for 2014 and 2015 at all substations and at substations with a voltage change.

| Quantile | All substations | | Substations with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 234.16 | 236.39 | 236.62 | 236.60 |
| 1% | 235.07 | 236.97 | 237.56 | 237.14 |
| 5% | 237.69 | 238.48 | 239.42 | 238.59 |
| 50% | 243.61 | 242.76 | 244.37 | 242.60 |
| 95% | 249.27 | 248.04 | 249.63 | 248.47 |
| 99% | 252.54 | 250.57 | 253.00 | 251.50 |
| 99.5% | 253.52 | 252.52 | 253.89 | 253.78 |

Table A.12: August: Voltage quantiles at for 2014 and 2015 at all substations and at substations with a voltage change.

| Quantile | All substations | | Substations with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 233.67 | 236.24 | 236.16 | 236.36 |
| 1% | 234.65 | 236.82 | 237.16 | 236.94 |
| 5% | 237.38 | 238.37 | 239.21 | 238.44 |
| 50% | 243.65 | 242.69 | 244.24 | 242.57 |
| 95% | 249.39 | 247.95 | 249.59 | 248.36 |
| 99% | 252.21 | 250.33 | 252.42 | 251.00 |
| 99.5% | 253.01 | 251.96 | 253.36 | 253.02 |

Table A.13: September: Voltage quantiles at for 2014 and 2015 at all substations and at substations with a voltage change.

| Quantile | All substations | | Substations with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 233.74 | 235.86 | 235.39 | 235.80 |
| 1% | 234.68 | 236.54 | 236.42 | 236.54 |
| 5% | 237.30 | 238.16 | 238.64 | 238.20 |
| 50% | 243.15 | 242.58 | 243.68 | 242.43 |
| 95% | 248.45 | 247.98 | 248.48 | 248.48 |
| 99% | 251.48 | 250.89 | 251.08 | 251.82 |
| 99.5% | 252.38 | 252.90 | 252.49 | 253.85 |

Table A.14: October: Voltage quantiles at for 2014 and 2015 at all substations and at substations with a voltage change.

| Quantile | All substations | | Substations with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 233.85 | 234.91 | 234.51 | 234.44 |
| 1% | 234.97 | 235.82 | 235.55 | 235.50 |
| 5% | 237.42 | 237.79 | 237.75 | 237.68 |
| 50% | 242.88 | 242.32 | 242.96 | 242.06 |
| 95% | 248.44 | 247.68 | 248.42 | 248.11 |
| 99% | 251.27 | 250.33 | 250.72 | 251.27 |
| 99.5% | 252.24 | 252.30 | 251.81 | 253.36 |

Table A.15: November: Voltage quantiles at for 2014 and 2015 at all substations and at substations with a voltage change.

| Quantile | All substations | | Substations with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 234.68 | 235.03 | 234.33 | 234.66 |
| 1% | 235.55 | 235.87 | 235.27 | 235.62 |
| 5% | 237.64 | 237.83 | 237.36 | 237.72 |
| 50% | 242.52 | 242.33 | 241.99 | 242.10 |
| 95% | 247.69 | 247.68 | 247.75 | 248.11 |
| 99% | 250.44 | 250.42 | 250.04 | 251.29 |
| 99.5% | 252.01 | 252.37 | 251.54 | 253.54 |

Table A.16: December: Voltage quantiles at for 2014 and 2015 at all substations and at substations with a voltage change.

### A.2.2 Voltage quantiles at feeder ends

| Quantile | All feeder ends | | Feeder ends with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 227.39 | 225.00 | 226.63 | 223.92 |
| 1% | 229.92 | 228.18 | 229.26 | 227.13 |
| 5% | 234.92 | 233.84 | 234.49 | 233.26 |
| 50% | 242.23 | 241.07 | 242.21 | 240.69 |
| 95% | 247.87 | 246.92 | 248.32 | 247.05 |
| 99% | 251.55 | 250.31 | 251.28 | 249.34 |
| 99.5% | 252.67 | 251.84 | 252.09 | 250.42 |

Table A.17: January: Voltage quantiles at for 2014 and 2015 at all feeder ends and at feeder ends with a voltage change.

| Quantile | All feeder ends | | Feeder ends with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 227.05 | 225.79 | 226.11 | 225.04 |
| 1% | 229.68 | 228.77 | 228.83 | 228.11 |
| 5% | 234.87 | 234.06 | 234.24 | 233.70 |
| 50% | 242.16 | 240.93 | 242.01 | 240.70 |
| 95% | 247.73 | 246.67 | 248.04 | 246.96 |
| 99% | 251.41 | 249.46 | 251.08 | 249.01 |
| 99.5% | 252.52 | 251.06 | 251.90 | 249.89 |

Table A.18: February: Voltage quantiles at for 2014 and 2015 at all feeder ends and at feeder ends with a voltage change.

| Quantile | All feeder ends | | Feeder ends with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 228.59 | 227.23 | 228.29 | 226.66 |
| 1% | 231.11 | 230.00 | 230.74 | 229.54 |
| 5% | 235.79 | 234.87 | 235.45 | 234.58 |
| 50% | 242.51 | 241.26 | 242.46 | 241.03 |
| 95% | 248.03 | 246.76 | 248.40 | 247.03 |
| 99% | 251.80 | 249.63 | 251.56 | 249.10 |
| 99.5% | 252.84 | 251.20 | 252.38 | 249.99 |

Table A.19: March: Voltage quantiles at for 2014 and 2015 at all feeder ends and at feeder ends with a voltage change.

| Quantile | All feeder ends | | Feeder ends with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 230.06 | 229.57 | 229.57 | 229.33 |
| 1% | 232.44 | 231.93 | 232.04 | 231.65 |
| 5% | 236.59 | 236.07 | 236.38 | 235.95 |
| 50% | 242.73 | 241.92 | 242.81 | 241.83 |
| 95% | 248.14 | 247.26 | 248.33 | 247.56 |
| 99% | 251.81 | 250.20 | 251.48 | 249.66 |
| 99.5% | 252.98 | 251.62 | 252.46 | 250.55 |

Table A.20: April: Voltage quantiles at for 2014 and 2015 at all feeder ends and at feeder ends with a voltage change.

| Quantile | All feeder ends | | Feeder ends with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 230.52 | 229.98 | 229.90 | 229.51 |
| 1% | 232.91 | 232.19 | 232.54 | 231.76 |
| 5% | 236.90 | 236.23 | 236.79 | 236.10 |
| 50% | 242.79 | 241.98 | 242.91 | 241.93 |
| 95% | 248.27 | 247.47 | 248.57 | 247.80 |
| 99% | 252.10 | 250.83 | 251.82 | 250.29 |
| 99.5% | 253.11 | 252.60 | 252.69 | 251.94 |

Table A.21: May: Voltage quantiles at for 2014 and 2015 at all feeder ends and at feeder ends with a voltage change.

| Quantile | All feeder ends | | Feeder ends with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 231.07 | 230.55 | 230.75 | 230.29 |
| 1% | 233.11 | 232.63 | 233.14 | 232.37 |
| 5% | 236.90 | 236.45 | 237.10 | 236.46 |
| 50% | 242.98 | 242.06 | 243.00 | 242.05 |
| 95% | 248.74 | 247.70 | 248.71 | 248.00 |
| 99% | 252.20 | 251.49 | 251.83 | 250.97 |
| 99.5% | 253.17 | 253.13 | 252.74 | 252.58 |

Table A.22: June: Voltage quantiles at for 2014 and 2015 at all feeder ends and at feeder ends with a voltage change.

| Quantile | All feeder ends | | Feeder ends with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 230.64 | 230.04 | 230.80 | 229.40 |
| 1% | 232.58 | 232.31 | 233.26 | 231.82 |
| 5% | 236.33 | 236.35 | 237.18 | 236.33 |
| 50% | 242.83 | 242.03 | 243.03 | 242.05 |
| 95% | 248.87 | 247.69 | 248.71 | 248.01 |
| 99% | 252.29 | 251.30 | 251.82 | 250.85 |
| 99.5% | 253.22 | 252.82 | 252.71 | 252.42 |

Table A.23: July: Voltage quantiles at for 2014 and 2015 at all feeder ends and at feeder ends with a voltage change.

| Quantile | All feeder ends | | Feeder ends with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 230.24 | 229.87 | 230.58 | 229.37 |
| 1% | 232.23 | 232.16 | 232.99 | 231.82 |
| 5% | 236.21 | 236.21 | 236.98 | 236.23 |
| 50% | 242.75 | 241.90 | 242.94 | 241.90 |
| 95% | 248.59 | 247.68 | 248.51 | 248.01 |
| 99% | 252.09 | 251.49 | 251.69 | 251.35 |
| 99.5% | 253.08 | 253.20 | 252.55 | 253.28 |

Table A.24: August: Voltage quantiles at for 2014 and 2015 at all feeder ends and at feeder ends with a voltage change.

| Quantile | All feeder ends | | Feeder ends with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 230.01 | 229.46 | 230.07 | 228.91 |
| 1% | 231.99 | 231.74 | 232.48 | 231.30 |
| 5% | 235.96 | 235.90 | 236.70 | 235.75 |
| 50% | 242.77 | 241.76 | 242.83 | 241.70 |
| 95% | 248.63 | 247.54 | 248.42 | 247.88 |
| 99% | 252.05 | 251.03 | 251.38 | 250.64 |
| 99.5% | 253.00 | 252.71 | 252.24 | 252.37 |

Table A.25: September: Voltage quantiles at for 2014 and 2015 at all feeder ends and at feeder ends with a voltage change.

| Quantile | All feeder ends | | Feeder ends with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 228.32 | 228.64 | 227.94 | 228.11 |
| 1% | 230.72 | 230.92 | 230.66 | 230.50 |
| 5% | 235.18 | 235.25 | 235.56 | 235.10 |
| 50% | 242.24 | 241.52 | 242.29 | 241.50 |
| 95% | 247.94 | 247.61 | 247.68 | 248.00 |
| 99% | 251.31 | 251.88 | 250.21 | 251.38 |
| 99.5% | 252.37 | 253.73 | 251.15 | 253.12 |

Table A.26: October: Voltage quantiles at for 2014 and 2015 at all feeder ends and at feeder ends with a voltage change.

| Quantile | All feeder ends | | Feeder ends with a voltage change | |
|---|---|---|---|---|
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 226.83 | 227.36 | 225.75 | 226.77 |
| 1% | 229.60 | 229.72 | 228.77 | 229.20 |
| 5% | 234.64 | 234.41 | 234.32 | 234.12 |
| 50% | 241.92 | 241.17 | 241.63 | 241.07 |
| 95% | 247.89 | 247.26 | 247.69 | 247.67 |
| 99% | 251.28 | 251.18 | 250.29 | 250.77 |
| 99.5% | 252.37 | 253.14 | 251.22 | 252.80 |

Table A.27: November: Voltage quantiles at for 2014 and 2015 at all feeder ends and at feeder ends with a voltage change.

| Quantile | All feeder ends | | Feeder ends with a voltage change | |
| --- | --- | --- | --- | --- |
| | 2014 | 2015 | 2014 | 2015 |
| 0.5% | 225.77 | 227.21 | 224.60 | 226.94 |
| 1% | 228.85 | 229.63 | 227.84 | 229.36 |
| 5% | 234.18 | 234.38 | 233.59 | 234.11 |
| 50% | 241.41 | 241.18 | 241.00 | 241.11 |
| 95% | 247.49 | 247.07 | 247.36 | 247.49 |
| 99% | 251.16 | 250.75 | 249.87 | 250.55 |
| 99.5% | 252.55 | 252.70 | 251.00 | 252.56 |

Table A.28: December: Voltage quantiles at for 2014 and 2015 at all feeder ends and at feeder ends with a voltage change.

## A.3 Intersection of excursions

### A.3.1 From substations to feeder ends

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Substations | Substations with a Voltage Change | All Substations | Substations with a Voltage Change |
| No. Substations with Over-Excursions | | 19 | 12 | 8 | 5 |
| No. Substations with Under-Excursions | | 32 | 15 | 50 | 40 |
| No. Over-Excursions | | 9858 | 1924 | 1440 | 1032 |
| No. Under-Excursions | | 67 | 32 | 100 | 71 |
| No. Feeder Ends linked to Over-Excursions | | 106 | 63 | 58 | 28 |
| No. Feeder Ends linked to Under-Excursions | | 108 | 47 | 250 | 210 |
| Sub Over | % Feeder Ends Over Limit | 69.09 | 53.54 | 57.67 | 57.73 |
| | % Feeder Ends Within Limits | 30.91 | 46.46 | 42.33 | 42.27 |
| | % Feeder Ends Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Sub Under | % Feeder Ends Over Limit | 0.63 | 0.00 | 0.00 | 0.00 |
| | % Feeder Ends Within Limits | 96.20 | 94.12 | 94.01 | 92.66 |
| | % Feeder Ends Under Limit | 3.16 | 5.88 | 5.99 | 7.34 |

Table A.29: January: Substations that have associated feeder end voltage monitors. A summary of the intersection of excursions at substations and feeder ends, from the perspective of substations.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Substations | Substations with a Voltage Change | All Substations | Substations with a Voltage Change |
| No. Substations with Over-Excursions | | 23 | 15 | 8 | 8 |
| No. Substations with Under-Excursions | | 40 | 25 | 6 | 5 |
| No. Over-Excursions | | 6008 | 1176 | 607 | 607 |
| No. Under-Excursions | | 124 | 35 | 9 | 8 |
| No. Feeder Ends linked to Over-Excursions | | 149 | 89 | 39 | 39 |
| No. Feeder Ends linked to Under-Excursions | | 183 | 125 | 37 | 33 |
| Sub Over | % Feeder Ends Over Limit | 66.91 | 52.62 | 55.79 | 55.79 |
| | % Feeder Ends Within Limits | 33.09 | 47.38 | 44.21 | 44.21 |
| | % Feeder Ends Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Sub Under | % Feeder Ends Over Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| | % Feeder Ends Within Limits | 98.99 | 98.67 | 100.00 | 100.00 |
| | % Feeder Ends Under Limit | 1.01 | 1.33 | 0.00 | 0.00 |

Table A.30: February: Substations that have associated feeder end voltage monitors. A summary of the intersection of excursions at substations and feeder ends, from the perspective of substations.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Substations | Substations with a Voltage Change | All Substations | Substations with a Voltage Change |
| No. Substations with Over-Excursions | | 20 | 14 | | |
| No. Substations with Under-Excursions | | 22 | 12 | | |
| No. Over-Excursions | | 9168 | 2993 | | |
| No. Under-Excursions | | 40 | 20 | | |
| No. Feeder Ends linked to Over-Excursions | | 132 | 86 | | |
| No. Feeder Ends linked to Under-Excursions | | 106 | 52 | | |
| Sub Over | % Feeder Ends Over Limit | 63.49 | 48.57 | | |
| | % Feeder Ends Within Limits | 36.51 | 51.43 | | |
| | % Feeder Ends Under Limit | 0.00 | 0.00 | | |
| Sub Under | % Feeder Ends Over Limit | 0.00 | 0.00 | | |
| | % Feeder Ends Within Limits | 100.00 | 100.00 | | |
| | % Feeder Ends Under Limit | 0.00 | 0.00 | | |

Table A.31: March: Substations that have associated feeder end voltage monitors. A summary of the intersection of excursions at substations and feeder ends, from the perspective of substations.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Substations | Substations with a Voltage Change | All Substations | Substations with a Voltage Change |
| No. Substations with Over-Excursions | | 22 | 12 | 4 | 4 |
| No. Substations with Under-Excursions | | 12 | 9 | 25 | 1 |
| No. Over-Excursions | | 8221 | 5661 | 579 | 579 |
| No. Under-Excursions | | 22 | 16 | 159 | 1 |
| No. Feeder Ends linked to Over-Excursions | | 133 | 60 | 27 | 27 |
| No. Feeder Ends linked to Under-Excursions | | 47 | 36 | 130 | 7 |
| Sub Over | % Feeder Ends Over Limit | 58.70 | 51.77 | 58.41 | 58.41 |
| | % Feeder Ends Within Limits | 41.30 | 48.23 | 41.59 | 41.59 |
| | % Feeder Ends Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Sub Under | % Feeder Ends Over Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| | % Feeder Ends Within Limits | 100.00 | 100.00 | 22.08 | 100.00 |
| | % Feeder Ends Under Limit | 0.00 | 0.00 | 77.92 | 0.00 |

Table A.32: April: Substations that have associated feeder end voltage monitors. A summary of the intersection of excursions at substations and feeder ends, from the perspective of substations.

| | | 2014 | | 2015 | |
| --- | --- | --- | --- | --- | --- |
| | | All Substations | Substations with a Voltage Change | All Substations | Substations with a Voltage Change |
| No. Substations with Over-Excursions | | 23 | 14 | 8 | 5 |
| No. Substations with Under-Excursions | | 16 | 9 | 7 | 6 |
| No. Over-Excursions | | 6536 | 5490 | 3578 | 3532 |
| No. Under-Excursions | | 30 | 16 | 7 | 6 |
| No. Feeder Ends linked to Over-Excursions | | 136 | 69 | 38 | 28 |
| No. Feeder Ends linked to Under-Excursions | | 68 | 27 | 27 | 26 |
| Sub Over | % Feeder Ends Over Limit | 51.65 | 44.40 | 65.11 | 65.23 |
| | % Feeder Ends Within Limits | 48.35 | 55.60 | 34.89 | 34.77 |
| | % Feeder Ends Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Sub Under | % Feeder Ends Over Limit | 3.45 | | 0.00 | 0.00 |
| | % Feeder Ends Within Limits | 96.55 | | 100.00 | 100.00 |
| | % Feeder Ends Under Limit | 0.00 | | 0.00 | 0.00 |

Table A.33: May: Substations that have associated feeder end voltage monitors. A summary of the intersection of excursions at substations and feeder ends, from the perspective of substations.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Substations | Substations with a Voltage Change | All Substations | Substations with a Voltage Change |
| No. Substations with Over-Excursions | | 22 | 13 | 22 | 16 |
| No. Substations with Under-Excursions | | 9 | 7 | 6 | 5 |
| No. Over-Excursions | | 8727 | 6928 | 4816 | 4658 |
| No. Under-Excursions | | 14 | 11 | 16 | 9 |
| No. Feeder Ends linked to Over-Excursions | | 136 | 68 | 114 | 80 |
| No. Feeder Ends linked to Under-Excursions | | 40 | 30 | 34 | 32 |
| Sub Over | % Feeder Ends Over Limit | 54.53 | 54.79 | 64.61 | 64.63 |
| | % Feeder Ends Within Limits | 45.47 | 45.21 | 35.39 | 35.37 |
| | % Feeder Ends Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Sub Under | % Feeder Ends Over Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| | % Feeder Ends Within Limits | 97.37 | 100.00 | 74.58 | 93.33 |
| | % Feeder Ends Under Limit | 2.63 | 0.00 | 25.42 | 6.67 |

Table A.34: June: Substations that have associated feeder end voltage monitors. A summary of the intersection of excursions at substations and feeder ends, from the perspective of substations.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Substations | Substations with a Voltage Change | All Substations | Substations with a Voltage Change |
| No. Substations with Over-Excursions | | 22 | 14 | 6 | 5 |
| No. Substations with Under-Excursions | | 25 | 4 | 10 | 3 |
| No. Over-Excursions | | 9196 | 6271 | 3868 | 3834 |
| No. Under-Excursions | | 34 | 7 | 18 | 5 |
| No. Feeder Ends linked to Over-Excursions | | 128 | 74 | 39 | 28 |
| No. Feeder Ends linked to Under-Excursions | | 145 | 17 | 27 | 9 |
| Sub Over | % Feeder Ends Over Limit | 53.27 | 55.50 | 66.39 | 66.37 |
| | % Feeder Ends Within Limits | 46.73 | 44.50 | 33.61 | 33.63 |
| | % Feeder Ends Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Sub Under | % Feeder Ends Over Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| | % Feeder Ends Within Limits | 100.00 | 100.00 | 69.70 | 71.43 |
| | % Feeder Ends Under Limit | 0.00 | 0.00 | 30.30 | 28.57 |

Table A.35: July: Substations that have associated feeder end voltage monitors. A summary of the intersection of excursions at substations and feeder ends, from the perspective of substations.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Substations | Substations with a Voltage Change | All Substations | Substations with a Voltage Change |
| No. Substations with Over-Excursions | | 48 | 13 | 6 | 5 |
| No. Substations with Under-Excursions | | 40 | 6 | 4 | 1 |
| No. Over-Excursions | | 7361 | 4836 | 6348 | 6177 |
| No. Under-Excursions | | 65 | 12 | 5 | 1 |
| No. Feeder Ends linked to Over-Excursions | | 258 | 68 | 39 | 28 |
| No. Feeder Ends linked to Under-Excursions | | 180 | 19 | 18 | 2 |
| Sub Over | % Feeder Ends Over Limit | 54.44 | 53.49 | 72.50 | 72.14 |
| | % Feeder Ends Within Limits | 45.56 | 46.51 | 27.50 | 27.86 |
| | % Feeder Ends Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Sub Under | % Feeder Ends Over Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| | % Feeder Ends Within Limits | 70.09 | 51.85 | 100.00 | 100.00 |
| | % Feeder Ends Under Limit | 29.91 | 48.15 | 0.00 | 0.00 |

Table A.36: August: Substations that have associated feeder end voltage monitors. A summary of the intersection of excursions at substations and feeder ends, from the perspective of substations.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Substations | Substations with a Voltage Change | All Substations | Substations with a Voltage Change |
| No. Substations with Over-Excursions | | 31 | 20 | 6 | 5 |
| No. Substations with Under-Excursions | | 6 | 3 | 13 | 9 |
| No. Over-Excursions | | 4698 | 2786 | 4512 | 3794 |
| No. Under-Excursions | | 9 | 4 | 21 | 10 |
| No. Feeder Ends linked to Over-Excursions | | 173 | 102 | 39 | 28 |
| No. Feeder Ends linked to Under-Excursions | | 19 | 16 | 80 | 52 |
| Sub Over | % Feeder Ends Over Limit | 55.32 | 55.11 | 74.23 | 71.61 |
| | % Feeder Ends Within Limits | 44.68 | 44.89 | 25.77 | 28.39 |
| | % Feeder Ends Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Sub Under | % Feeder Ends Over Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| | % Feeder Ends Within Limits | 100.00 | 100.00 | 98.85 | 100.00 |
| | % Feeder Ends Under Limit | 0.00 | 0.00 | 1.15 | 0.00 |

Table A.37: September: Substations that have associated feeder end voltage monitors. A summary of the intersection of excursions at substations and feeder ends, from the perspective of substations.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Substations | Substations with a Voltage Change | All Substations | Substations with a Voltage Change |
| No. Substations with Over-Excursions | | 18 | 10 | 18 | 16 |
| No. Substations with Under-Excursions | | 65 | 49 | 15 | 5 |
| No. Over-Excursions | | 1901 | 815 | 7861 | 6981 |
| No. Under-Excursions | | 96 | 70 | 24 | 9 |
| No. Feeder Ends linked to Over-Excursions | | 123 | 60 | 96 | 80 |
| No. Feeder Ends linked to Under-Excursions | | 348 | 257 | 68 | 31 |
| Sub Over | % Feeder Ends Over Limit | 44.26 | 49.88 | 73.02 | 69.90 |
| | % Feeder Ends Within Limits | 55.74 | 50.12 | 26.98 | 30.10 |
| | % Feeder Ends Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Sub Under | % Feeder Ends Over Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| | % Feeder Ends Within Limits | 100.00 | 100.00 | 93.33 | 100.00 |
| | % Feeder Ends Under Limit | 0.00 | 0.00 | 6.67 | 0.00 |

Table A.38: October: Substations that have associated feeder end voltage monitors. A summary of the intersection of excursions at substations and feeder ends, from the perspective of substations.

|  |  | 2014 |  | 2015 |  |
|---|---|---|---|---|---|
|  |  | All Substations | Substations with a Voltage Change | All Substations | Substations with a Voltage Change |
| No. Substations with Over-Excursions |  | 15 | 6 | 14 | 8 |
| No. Substations with Under-Excursions |  | 7 | 3 | 45 | 43 |
| No. Over-Excursions |  | 3608 | 534 | 5744 | 5321 |
| No. Under-Excursions |  | 21 | 5 | 52 | 49 |
| No. Feeder Ends linked to Over-Excursions |  | 104 | 39 | 83 | 42 |
| No. Feeder Ends linked to Under-Excursions |  | 13 | 6 | 215 | 213 |
| Sub Over | % Feeder Ends Over Limit | 31.95 | 55.57 | 68.39 | 67.09 |
|  | % Feeder Ends Within Limits | 68.05 | 44.43 | 31.61 | 32.91 |
|  | % Feeder Ends Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Sub Under | % Feeder Ends Over Limit | 0.00 | 0.00 | 0.00 | 0.00 |
|  | % Feeder Ends Within Limits | 100.00 | 100.00 | 99.52 | 99.51 |
|  | % Feeder Ends Under Limit | 0.00 | 0.00 | 0.48 | 0.49 |

Table A.39: November: Substations that have associated feeder end voltage monitors. A summary of the intersection of excursions at substations and feeder ends, from the perspective of substations.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Substations | Substations with a Voltage Change | All Substations | Substations with a Voltage Change |
| No. Substations with Over-Excursions | | 10 | 6 | 6 | 5 |
| No. Substations with Under-Excursions | | 12 | 3 | 13 | 7 |
| No. Over-Excursions | | 5788 | 1455 | 5702 | 5126 |
| No. Under-Excursions | | 18 | 5 | 31 | 9 |
| No. Feeder Ends linked to Over-Excursions | | 71 | 39 | 39 | 28 |
| No. Feeder Ends linked to Under-Excursions | | 78 | 21 | 29 | 23 |
| Sub Over | % Feeder Ends Over Limit | 41.71 | 59.61 | 70.86 | 68.40 |
| | % Feeder Ends Within Limits | 58.29 | 40.39 | 29.14 | 31.60 |
| | % Feeder Ends Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Sub Under | % Feeder Ends Over Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| | % Feeder Ends Within Limits | 95.40 | 100.00 | 88.57 | 86.36 |
| | % Feeder Ends Under Limit | 4.60 | 0.00 | 11.43 | 13.64 |

Table A.40: December: Substations that have associated feeder end voltage monitors. A summary of the intersection of excursions at substations and feeder ends, from the perspective of substations.

## A.3.2 From feeder ends to substations

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Feeder Ends | Feeder Ends with a Voltage Change | All Feeder Ends | Feeder ends with a Voltage Change |
| No. Feeder Ends with Over-Excursions | | 147 | 77 | 105 | 32 |
| No. Feeder Ends with Under-Excursions | | 68 | 39 | 119 | 44 |
| No. Over-Excursions | | 43359 | 10392 | 24796 | 4995 |
| No. Under-Excursions | | 2788 | 2321 | 7317 | 4550 |
| No. Substations linked to Over-Excursions | | 42 | 23 | 31 | 11 |
| No. Substations linked to Under-Excursions | | 51 | 26 | 75 | 30 |
| Feeder End Over | % Substations Over Limit | 62.59 | 29.88 | 60.39 | 68.53 |
| | % Substations Within Limits | 37.40 | 70.12 | 39.61 | 31.47 |
| | % Substations Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Feeder End Under | % Substations Over Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| | % Substations Within Limits | 99.77 | 99.81 | 99.58 | 99.58 |
| | % Substations Under Limit | 0.23 | 0.19 | 0.42 | 0.42 |

Table A.41: January: Feeder ends that have associated substations. A summary of the intersection of excursions at feeder ends and substations, from the perspective of feeder ends.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Feeder Ends | Feeder Ends with a Voltage Change | All Feeder Ends | Feeder ends with a Voltage Change |
| No. Feeder Ends with Over-Excursions | | 158 | 82 | 74 | 33 |
| No. Feeder Ends with Under-Excursions | | 64 | 33 | 68 | 30 |
| No. Over-Excursions | | 32317 | 7696 | 16890 | 3194 |
| No. Under-Excursions | | 3094 | 2412 | 5010 | 2813 |
| No. Substations linked to Over-Excursions | | 45 | 25 | 31 | 15 |
| No. Substations linked to Under-Excursions | | 47 | 23 | 53 | 22 |
| Feeder End Over | % Substations Over Limit | 51.97 | 22.70 | 85.51 | 86.77 |
| | % Substations Within Limits | 48.03 | 77.30 | 14.49 | 13.23 |
| | % Substations Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Feeder End Under | % Substations Over Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| | % Substations Within Limits | 99.89 | 99.96 | 100.00 | 100.00 |
| | % Substations Under Limit | 0.11 | 0.04 | 0.00 | 0.00 |

Table A.42: February: Feeder ends that have associated substations. A summary of the intersection of excursions at feeder ends and substations, from the perspective of feeder ends.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Feeder Ends | Feeder Ends with a Voltage Change | All Feeder Ends | Feeder ends with a Voltage Change |
| No. Feeder Ends with Over-Excursions | | 179 | 94 | | |
| No. Feeder Ends with Under-Excursions | | 48 | 22 | | |
| No. Over-Excursions | | 46609 | 13834 | | |
| No. Under-Excursions | | 1971 | 1179 | | |
| No. Substations linked to Over-Excursions | | 47 | 24 | | |
| No. Substations linked to Under-Excursions | | 36 | 16 | | |
| Feeder End Over | % Substations Over Limit | 53.12 | 32.43 | | |
| | % Substations Within Limits | 46.88 | 67.57 | | |
| | % Substations Under Limit | 0.00 | 0.00 | | |
| Feeder End Under | % Substations Over Limit | 0.00 | 0.00 | | |
| | % Substations Within Limits | 100.00 | 100.00 | | |
| | % Substations Under Limit | 0.00 | 0.00 | | |

Table A.43: March: Feeder ends that have associated substations. A summary of the intersection of excursions at feeder ends and substations, from the perspective of feeder ends.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Feeder Ends | Feeder Ends with a Voltage Change | All Feeder Ends | Feeder ends with a Voltage Change |
| No. Feeder Ends with Over-Excursions | | 220 | 65 | 80 | 30 |
| No. Feeder Ends with Under-Excursions | | 48 | 21 | 204 | 15 |
| No. Over-Excursions | | 50273 | 16148 | 21886 | 3565 |
| No. Under-Excursions | | 487 | 306 | 2220 | 344 |
| No. Substations linked to Over-Excursions | | 61 | 19 | 34 | 13 |
| No. Substations linked to Under-Excursions | | 34 | 14 | 63 | 10 |
| Feeder End Over | % Substations Over Limit | 57.80 | 56.22 | 64.38 | 68.63 |
| | % Substations Within Limits | 42.20 | 43.78 | 35.62 | 31.37 |
| | % Substations Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Feeder End Under | % Substations Over Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| | % Substations Within Limits | 100.00 | 100.00 | 31.52 | 100.00 |
| | % Substations Under Limit | 0.00 | 0.00 | 68.48 | 0.00 |

Table A.44: April: Feeder ends that have associated substations. A summary of the intersection of excursions at feeder ends and substations, from the perspective of feeder ends.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Feeder Ends | Feeder Ends with a Voltage Change | All Feeder Ends | Feeder ends with a Voltage Change |
| No. Feeder Ends with Over-Excursions | | 133 | 59 | 91 | 34 |
| No. Feeder Ends with Under-Excursions | | 13 | 6 | 32 | 16 |
| No. Over-Excursions | | 11566 | 3704 | 43364 | 15772 |
| No. Under-Excursions | | 81 | 46 | 973 | 246 |
| No. Substations linked to Over-Excursions | | 37 | 16 | 31 | 11 |
| No. Substations linked to Under-Excursions | | 10 | 4 | 25 | 11 |
| Feeder End Over | % Substations Over Limit | 60.93 | 60.24 | 86.81 | 88.02 |
| | % Substations Within Limits | 39.04 | 39.76 | 13.19 | 11.98 |
| | % Substations Under Limit | 0.03 | 0.00 | 0.00 | 0.00 |
| Feeder End Under | % Substations Over Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| | % Substations Within Limits | 100.00 | 100.00 | 100.00 | 100.00 |
| | % Substations Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |

Table A.45: May: Feeder ends that have associated substations. A summary of the intersection of excursions at feeder ends and substations, from the perspective of feeder ends.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Feeder Ends | Feeder Ends with a Voltage Change | All Feeder Ends | Feeder ends with a Voltage Change |
| No. Feeder Ends with Over-Excursions | | 186 | 81 | 155 | 72 |
| No. Feeder Ends with Under-Excursions | | 24 | 10 | 40 | 14 |
| No. Over-Excursions | | 55232 | 19290 | 54317 | 19925 |
| No. Under-Excursions | | 413 | 66 | 713 | 38 |
| No. Substations linked to Over-Excursions | | 57 | 26 | 50 | 21 |
| No. Substations linked to Under-Excursions | | 18 | 6 | 24 | 10 |
| Feeder End Over | % Substations Over Limit | 58.77 | 60.80 | 81.95 | 82.84 |
| | % Substations Within Limits | 41.23 | 39.20 | 18.05 | 17.16 |
| | % Substations Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Feeder End Under | % Substations Over Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| | % Substations Within Limits | 99.66 | 100.00 | 85.58 | 90.00 |
| | % Substations Under Limit | 0.34 | 0.00 | 14.42 | 10.00 |

Table A.46: June: Feeder ends that have associated substations. A summary of the intersection of excursions at feeder ends and substations, from the perspective of feeder ends.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Feeder Ends | Feeder Ends with a Voltage Change | All Feeder Ends | Feeder ends with a Voltage Change |
| No. Feeder Ends with Over-Excursions | | 191 | 76 | 92 | 36 |
| No. Feeder Ends with Under-Excursions | | 21 | 9 | 35 | 14 |
| No. Over-Excursions | | 62217 | 19948 | 46663 | 17932 |
| No. Under-Excursions | | 722 | 65 | 567 | 118 |
| No. Substations linked to Over-Excursions | | 59 | 23 | 31 | 12 |
| No. Substations linked to Under-Excursions | | 17 | 7 | 25 | 9 |
| Feeder End Over | % Substations Over Limit | 56.30 | 57.58 | 75.29 | 76.50 |
| | % Substations Within Limits | 43.70 | 42.42 | 24.71 | 23.50 |
| | % Substations Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Feeder End Under | % Substations Over Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| | % Substations Within Limits | 100.00 | 100.00 | 97.18 | 96.15 |
| | % Substations Under Limit | 0.00 | 0.00 | 2.82 | 3.85 |

Table A.47: July: Feeder ends that have associated substations. A summary of the intersection of excursions at feeder ends and substations, from the perspective of feeder ends.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Feeder Ends | Feeder Ends with a Voltage Change | All Feeder Ends | Feeder ends with a Voltage Change |
| No. Feeder Ends with Over-Excursions | | 337 | 68 | 86 | 35 |
| No. Feeder Ends with Under-Excursions | | 159 | 21 | 28 | 13 |
| No. Over-Excursions | | 54862 | 16749 | 59874 | 28286 |
| No. Under-Excursions | | 595 | 175 | 465 | 122 |
| No. Substations linked to Over-Excursions | | 85 | 22 | 29 | 12 |
| No. Substations linked to Under-Excursions | | 61 | 8 | 22 | 10 |
| Feeder End Over | % Substations Over Limit | 47.52 | 46.90 | 82.70 | 85.24 |
| | % Substations Within Limits | 52.48 | 53.10 | 17.30 | 14.76 |
| | % Substations Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Feeder End Under | % Substations Over Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| | % Substations Within Limits | 77.56 | 84.15 | 100.00 | 100.00 |
| | % Substations Under Limit | 22.44 | 15.85 | 0.00 | 0.00 |

Table A.48: August: Feeder ends that have associated substations. A summary of the intersection of excursions at feeder ends and substations, from the perspective of feeder ends.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Feeder Ends | Feeder Ends with a Voltage Change | All Feeder Ends | Feeder ends with a Voltage Change |
| No. Feeder Ends with Over-Excursions | | 215 | 88 | 82 | 36 |
| No. Feeder Ends with Under-Excursions | | 34 | 12 | 65 | 24 |
| No. Over-Excursions | | 46008 | 11060 | 45298 | 18289 |
| No. Under-Excursions | | 325 | 137 | 488 | 219 |
| No. Substations linked to Over-Excursions | | 63 | 24 | 29 | 12 |
| No. Substations linked to Under-Excursions | | 27 | 9 | 32 | 14 |
| Feeder End Over | % Substations Over Limit | 43.31 | 37.53 | 79.74 | 81.21 |
| | % Substations Within Limits | 56.69 | 62.47 | 20.26 | 18.79 |
| | % Substations Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Feeder End Under | % Substations Over Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| | % Substations Within Limits | 100.00 | 100.00 | 99.64 | 100.00 |
| | % Substations Under Limit | 0.00 | 0.00 | 0.36 | 0.00 |

Table A.49: September: Feeder ends that have associated substations. A summary of the intersection of excursions at feeder ends and substations, from the perspective of feeder ends.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Feeder Ends | Feeder Ends with a Voltage Change | All Feeder Ends | Feeder ends with a Voltage Change |
| No. Feeder Ends with Over-Excursions | | 152 | 55 | 99 | 51 |
| No. Feeder Ends with Under-Excursions | | 48 | 20 | 42 | 15 |
| No. Over-Excursions | | 30536 | 4720 | 43797 | 15611 |
| No. Under-Excursions | | 2426 | 1219 | 459 | 262 |
| No. Substations linked to Over-Excursions | | 40 | 14 | 36 | 18 |
| No. Substations linked to Under-Excursions | | 41 | 15 | 26 | 9 |
| Feeder End Over | % Substations Over Limit | 37.73 | 43.50 | 90.62 | 90.26 |
| | % Substations Within Limits | 62.27 | 56.50 | 9.38 | 9.74 |
| | % Substations Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Feeder End Under | % Substations Over Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| | % Substations Within Limits | 100.00 | 100.00 | 99.66 | 100.00 |
| | % Substations Under Limit | 0.00 | 0.00 | 0.34 | 0.00 |

Table A.50: October: Feeder ends that have associated substations. A summary of the intersection of excursions at feeder ends and substations, from the perspective of feeder ends.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Feeder Ends | Feeder Ends with a Voltage Change | All Feeder Ends | Feeder ends with a Voltage Change |
| No. Feeder Ends with Over-Excursions | | 140 | 39 | 102 | 46 |
| No. Feeder Ends with Under-Excursions | | 54 | 26 | 75 | 39 |
| No. Over-Excursions | | 29585 | 4713 | 56667 | 22176 |
| No. Under-Excursions | | 4820 | 2982 | 2088 | 1516 |
| No. Substations linked to Over-Excursions | | 38 | 10 | 42 | 18 |
| No. Substations linked to Under-Excursions | | 42 | 19 | 54 | 25 |
| Feeder End Over | % Substations Over Limit | 32.06 | 37.61 | 87.78 | 89.18 |
| | % Substations Within Limits | 67.94 | 62.39 | 12.22 | 10.82 |
| | % Substations Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Feeder End Under | % Substations Over Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| | % Substations Within Limits | 100.00 | 100.00 | 99.94 | 99.93 |
| | % Substations Under Limit | 0.00 | 0.00 | 0.06 | 0.07 |

Table A.51: November: Feeder ends that have associated substations. A summary of the intersection of excursions at feeder ends and substations, from the perspective of feeder ends.

| | | 2014 | | 2015 | |
|---|---|---|---|---|---|
| | | All Feeder Ends | Feeder Ends with a Voltage Change | All Feeder Ends | Feeder ends with a Voltage Change |
| No. Feeder Ends with Over-Excursions | | 148 | 38 | 89 | 39 |
| No. Feeder Ends with Under-Excursions | | 68 | 34 | 71 | 33 |
| No. Over-Excursions | | 38250 | 7337 | 49781 | 21448 |
| No. Under-Excursions | | 6713 | 3952 | 2529 | 1817 |
| No. Substations linked to Over-Excursions | | 45 | 11 | 37 | 14 |
| No. Substations linked to Under-Excursions | | 52 | 23 | 47 | 19 |
| Feeder End Over | % Substations Over Limit | 60.00 | 67.53 | 90.84 | 91.56 |
| | % Substations Within Limits | 40.00 | 32.47 | 9.16 | 8.44 |
| | % Substations Under Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| Feeder End Under | % Substations Over Limit | 0.00 | 0.00 | 0.00 | 0.00 |
| | % Substations Within Limits | 99.89 | 100.00 | 99.78 | 99.82 |
| | % Substations Under Limit | 0.11 | 0.00 | 0.22 | 0.18 |

Table A.52: December: Feeder ends that have associated substations. A summary of the intersection of excursions at feeder ends and substations, from the perspective of feeder ends.

## A.4 Investigation into October 2015

The increase in the percentage decrease observed in October 2015 was markedly greater than those seen in other months. An extensive examination of the data for October 2015 suggested that the measurements were significantly less than might be expected based on historical demands extracted from the LVNT database. The average demands for October in 2013, 2014 and 2015 were 67.5, 67.5 and 65.4 respectively, with the decrease observed in 2015 being observed at all times of day and night. Comparison of the distributions also showed a marked decrease in demands for October 2015 with, for example, the $3^{rd}$ quartiles being 101.1 (2013), 101.2 (2014) and 97.7 (2015).

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. An example can be seen in Figure A.1 which shows the unadjusted and adjusted demands for four substations in October 2014 and 2015. In three of the four examples shown, the difference in demand can be clearly seen. There was no evidence that the decrease in October 2015 was due to incorrect weather adjustments.

In further analysis, random effects models were constructed to provide a framework which incorporated data from all substations (including those that had not changed) to be considered together. This was done to investigate whether the underlying change in October 2015 might be due to any other factors, including whether the substations with a voltage change were fundamentally different to the substations with no voltage change and whether, based on this, a more suitable difference in our substations could be detected.

It is known that the average demands for substations with the change (77.1 kW average for 2014) were greater than those without (74.8 kW average for 2014), which is is likely to be due to the characteristics of the substations which were chosen to have the change in settings, although the choice was not made with reference to this. Overall, they tended to be more urban (84% ground mounted vs. 70% in the non-chosen group); have higher transformer ratings (median 500 vs. 315); and have a high proportion of industrial and commercial customers (median 20% in Elexon categories 3 to 8 vs. 10%). It is noted that for other months, these models produced the same pattern of results as the paired t-test analysis. Again, as with the main analysis, in October the decrease in 2015 remained in the region of 4% even when making allowance for this, and even allowing for the possibility of different responses over time for the three sets of substations (changed with dates, changed with no dates and not changed). The exact reason for this decrease, which is greater than could be attributable to the voltage change, is the subject of ongoing investigation.

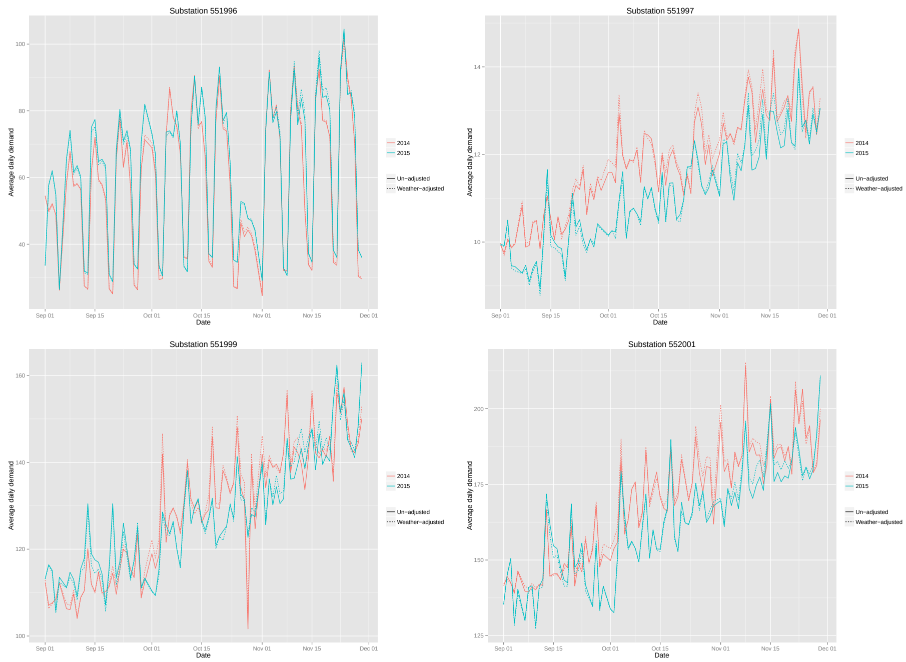

Substation 551996
Substation 551997
Substation 551999
Substation 552001
Average daily demand
Date
Sep 01
Sep 15
Oct 01
Oct 15
Nov 01
Nov 15
Dec 01
2014
2015
Un−adjusted
Weather−adjusted

Figure A.1