# THE IMPACTS OF A REDUCTION IN 11KV VOLTAGE SETTINGS IN SOUTH WALES

Gavin SHADDICK
University of Bath – UK
g.shaddick@bath.ac.uk

Amelia GREEN
University of Bath – UK
a.c.a.jobling@bath.ac.uk

Matthew WATSON
WPD – UK
mwatson@westernpower.co.uk

## *ABSTRACT*

*This paper investigates the impacts on the low voltage (LV) distribution network of a reduction in 11kV voltage control settings. Through the use of statistical modelling, the effects of a real-life reduction in voltage settings were measured and quantified. This highlighted statistically significant reductions in average real power demand, maximum real power demand and average reactive power demand. A reduction in demand of the magnitude observed would equate to an estimated saving of £14.9 million for customers if all substations in South Wales were changed.*

## INTRODUCTION

Voltages on the LV network in the UK must be kept within statutory limits: 230V + 10% or - 6% (253.3V-216.2V). As such, LV network voltages are generally set as high as possible to allow for voltage drop along the network. Designs are based on demand dominated networks with minimal active voltage control beyond the 33/11kV transformers.

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

Extensive monitoring was installed on LV networks in South Wales as part of the Low Voltage Network Templates (LVNT) Tier 2 Low Carbon Network Fund project between 2009 and 2013. This showed that voltages at both substations and feeder ends sat at the higher end of the allowable range, with very few (only 0.015%) measurements below the statutory limits. Following this project, a programme of voltage reduction was carried out in the LVNT area, with the settings at the 33/11kV transformers being changed; from a target of 11.4kV (±200V) to 11.3kV (±165V), a reduction of approximately 0.88%.

This paper investigates the effects of this change in voltage settings and presents the learning from the Voltage Reduction Analysis (VRA) Network Innovation Allowance (NIA) project. Results of the analyses of the effects of these changes at both substations and feeder ends are presented. Within the analyses, 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 known and change-point models are used to try to assess when a fundamental change in the underlying levels of demand may have occurred. In addition to the demand based analyses there is an analysis of voltage profiles at both substation and feeder ends in which voltages are examined over time and compared to statutory limits.

## DATA

Full details of the LVNT project can be found at http://www.westernpowerinnovation.co.uk. The aim of the project was to see whether there was a simple method, outside of costly widespread monitoring, that could assist in providing additional visibility needed to improve the design, planning and operation of the LV distribution network [1][2]. As part of the project, monitoring was installed at ca. 900 substations and 3600 feeder-ends (including customer premises). The measured data included measurements made on 10 minute intervals of voltage, current, real and reactive power delivered and power received at LV substations and voltages at remote feeders-ends. Since May 2012 the data delivery has been fully automated, via Western Power Distribution (WPD), to a dedicated secure server at the University of Bath. Since the official end of the LVNT project, monitoring has continued together with data delivery to the University of Bath and subsequent analysis.

The study period for the analyses performed was 2014-2015 and the study area was South Wales. At the time of the analysis 50 million data points were available from over 750 substations and over 100 million data points were available from over 2800 voltage monitors at feeder ends. The monitored substations covered a wide range of customer mixes; from those highly dominated by residential customers, to those exclusively industrial and commercial. The location of the substations can be seen in **Figure 1**, in which red dots show the locations of substations that had the change in voltage settings and blue dots show the locations where voltage settings remained unchanged.

The number of substations available and suitable for

analysis varied 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 exact date of the change was known for 140 and unknown for 262 of the substations.

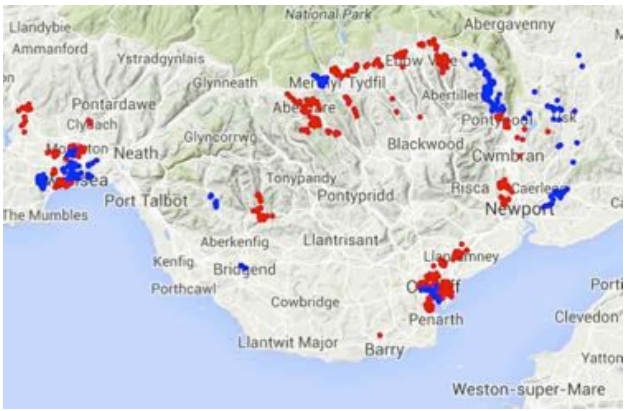


**Figure 1: Locations of substations providing data for analysis. Red dots show the location of substations that had changes in 11kVsettings, blue dots show the locations of those that did not have a change in settings.**

The choice of substations which had the change in voltage settings was not based on any pre-specified criteria but was, in pragmatic terms, random. **Figure 2** shows a schematic of the available data from substations.

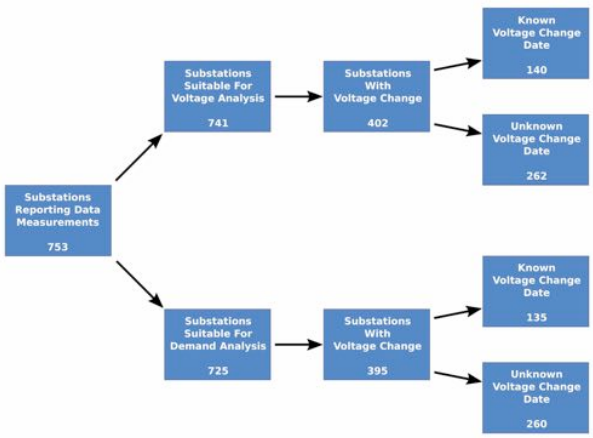


**Figure 2: Schematic showing the number of substation monitors providing data for analysis for January 2014.**

## METHOD

The aim of the analyses of demand data was to ascertain whether there were any discernible changes associated with the change in 11kV settings. Since the majority of the voltage changes occurred in November and December of 2014, the primary analysis was a comparison of demands before and after this period. The requirement for measurements to be available for a particular substation in each period resulted in varying numbers of substations contributing to the tests in different months.

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

Sense–checking the data at this stage included excluding differences that were likely 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 stage (daily comparison sense-checking) being more stringent than the latter (monthly comparison) while also placing more emphasis on the weather adjustments being able to correct demands. Sensitivity to the choice of cut-off was assessed by repeating the analyses for a range of values.

The primary analysis consisted of comparisons of demand data on a month-by-month basis (2015 vs. 2014). This allowed for the dependence (or correlation) that might be expected within measurements from the same substation to be acknowledged and correctly incorporated into the assessment of whether observed changes were statistically significant. Each monthly comparison was made using both a paired t-test and the non-parametric equivalent, the Wilcoxon rank sum test (the latter being less sensitive to the possibility of skewed distributions for demands).

Where no data were available for estimating the effects associated with the voltage reduction, or where the results were considered unstable, statistical smoothing techniques [5] were used to estimate missing values and to produce more reasonable estimates than were provided when using the data directly.

A more complex, though underlying equivalent, approach was to use random effects models [3]. These allowed for both monthly and daily comparisons, allowing for the potential influence of other factors, such as overall longer-term patterns in demand, when assessing the effects of any changes. Using daily data increased the sample size and allowed changes at a higher temporal resolution to be investigated, although this came with an associated increase in model complexity and computational burden. Random effects models were also constructed to provide a framework which incorporated data from all substations (including those that had not changed) to be considered together. These models allowed for three states: (i) no change at all; (ii) chosen for change but change had not yet occurred and (iii) change had occurred.

In addition to the analyses based on the comparison of patterns before and after a change, change-point models [5] were used to detect possible underlying changes in demand where no information was supplied as to when changes to voltage settings occurred. Three separate sets of analysis were considered:

1. Cases where there had been a change and the exact date was known.

2. Cases where there had been a change and the exact date was not known.
3. Cases where there had been no change.

The efficacy of the approach was assessed by calculating the proportion of times that the method detected a potential change-point. In the first case the aim was for as few change-points to be detected as possible (false positives), in cases (ii) and (iii) the aim was for as many change-points to be detected as possible (true positives).
Applying the models directly to the demand data would have resulted in detecting changes due to seasonal patterns rather than any change in voltage settings. The first step in the analysis was therefore to de-seasonalise the data. This was done by fitting a smoothed curve through the time-series data, representing the underlying pattern. The residuals (differences) between the data and the corresponding curve then provided a deseasonalised series. The smoothed curve was fit using penalised splines [6].

## RESULTS

### Changes in demand

Testing comprised of detecting differences between demands for each month: January 2015 vs. January 2014, ..., December 2015 vs. December 2014, e.g. before and after the changes in voltage settings had been made. **Figure 3** shows an example of daily demands at a single substation for January where a clear decrease in the average demand can be seen.

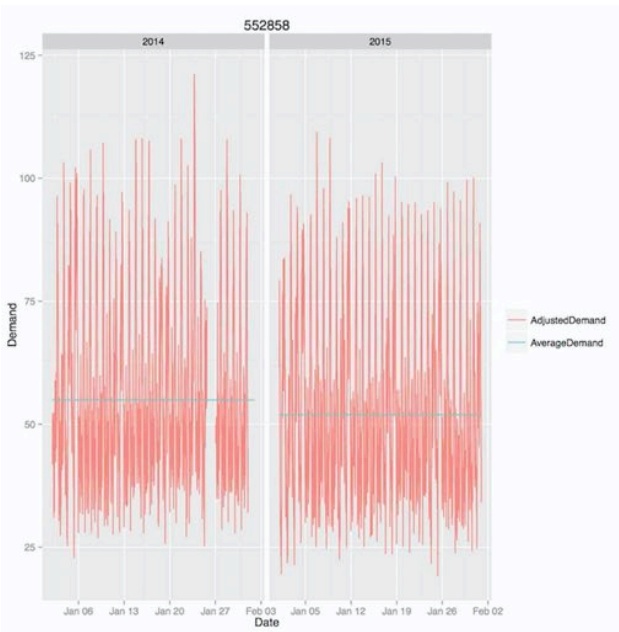


**Figure 3: Weather corrected ten minute demand data for substation 552858. Daily average demand is shown for January in 2014 and 2015 with the horizontal line showing the average demand for each of the months.**

Comparisons for all months (averaged over substations) can be seen in **Table 1**. As no data was recorded in March 2015, as the monitoring network was not functioning, no formal comparison was made for that month. Due to a marked contrast with measurements from the other weeks of July, the last week of July data was removed from the calculations for that month. 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 ($p < 0.05$) with July being of borderline significance, with a value of $p = 0.08$ for the Wilcoxon rank sum test. 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.

| *Month* | *Mean 2014* | *Mean 2015* | *Mean difference* | *Perc. diference* | *p-value* |
|---|---|---|---|---|---|
| **January** | 95.83 | 94.49 | 1.34 | 1.4 | <0.001 |
| **February** | 94.53 | 93.61 | 0.92 | 0.97 | <0.001 |
| **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 | 58.3 | 0.87 | 1.48 | <0.001 |
| **July** | 58.82 | 58.41 | 0.41 | 0.7 | 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 | <0.001 |
| **November** | 77.19 | 75.97 | 1.22 | 1.58 | <0.001 |
| **December** | 82.52 | 81.12 | 1.4 | 1.7 | <0.001 |

**Table 1: Differences between monthly average real power delivered for 2014 and 2015.**

Including the data from the last week of July resulted in an overall increase in demand between the years. Also noticeable in **Table 1** is the very high decrease observed for October. This was the subject of an extensive examination of measurements and weather corrections for October 2015 in comparison with same period for all other years in the LVNT database. It was found that: (i) measurements in October 2015 were significantly less than might be expected based on patterns observed in other years, and (ii) the weather corrections, during what was a mild period, were less than would have been expected (based on comparisons of their effects in other periods) and not of sufficient magnitude to adequately correct the raw measurements for this period.
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 was likely 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 these substations 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%). Using random effects models, to allow for potential differences in substation characteristics in the groups (with and without changes in voltage settings), produced the same overall pattern in results as seen in **Table 1**. Again, as with the main analysis, in October the decrease in 2015 remained in the region of 4%. This remained even when making allowance for this, and when 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).

**Figure 4** 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 estimated values for March and October were 1.09 and 1.24, respectively. Updating **Table 1** with these estimates results in an average decrease of 1.16% (the same value obtained when taking an average of the smoothed estimates shown in **Figure 4**).

The same pattern of results was observed when performing a similar paired analyses with comparisons of (i) the maximum daily demands (defined as the 99.9th percentile) between substations and (ii) reactive power.

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 very fine values of the daily comparison cut-offs. The resulting default setting for both was (i) no more than 20kW difference between daily (weather adjusted) demands and (ii) no more than 20kW difference between aggregated monthly demands. This allowed for a reasonable amount of inherent variability in demands to propagate through the analyses whilst excluding very large differences.

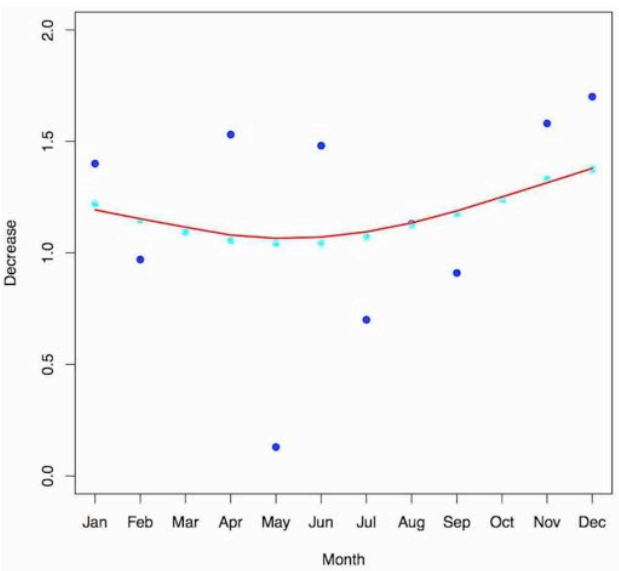


**Figure 4: Estimates of the percentage decrease in average demand, by month. Comparisons are between 2014 and 2015. The dark blue dots indicate the estimates from a paired comparison by substation and the light blue dots a set of 'smoothed' estimates**

## Detecting changes

Change-point analyses were performed using a period of 4 months (01/10/2014 - 16/2/2015), centred on the period in which the changes were made (or should have been made in the case where the exact date was not known). 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 in the Methods section. **Figure 5** shows an example of the first case, where the date of change is known.

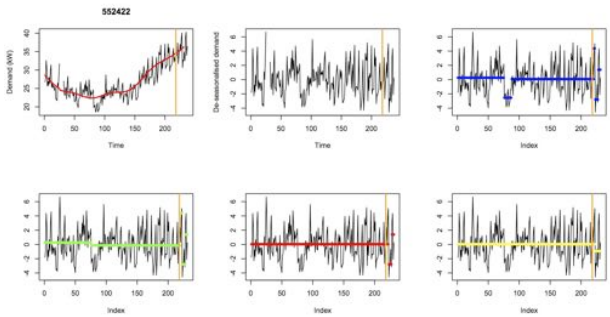


**Figure 5: Daily demands for May to December 2014 for substation 552422, together with results of change-point analyses.**

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 5** 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 was 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 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.

In the first case, the known dates of changes were 10th October (14 sub- stations), 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. Of those for which the full period of data was available, change-points within a week of the specified dates were identified in ca. 60% of cases. 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 were likely 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%.

### Voltage profiles

In the analysis of data from both substations and feeder ends, voltages were observed to sit at the higher end of the allowable spectrum with substation voltages higher and less spread than those at the feeder ends. As expected, the voltages were higher in the summer than the winter. The average monthly percentages of over-excursions and under-excursions for all substations was 0.534% and 0.0038% for 2014, respectively, and 0.335% and 0.0036% for 2015, respectively The total number of voltage excursions measured at feeder ends was very low across all months in the study, with just 0.33% of measurements being over voltage and 0.004% under, with the majority of excursions coming from a small number of substations.

## DISCUSSION

The analysis carried out as part of the VRA project has presented some clear learning which will feed into WPD's design and operation of the LV network. The permanent reduction in voltages could deliver a significant benefit to customers, mainly in the form of a reduction in consumption.

The 0.88% reduction trial showed an average demand consumption drop of 1.16%. If scaled across the whole of South Wales it is estimated that this would equate to a saving of approximately £14.9 million annually to customers. There are also network benefits to be found due to the reduction in maximum demand, helping release additional capacity. There is also a significant reduction in reactive power consumed by the networks associated with the voltage changes which must be accounted for.

A detailed investigation of the voltage profiles highlighted the effects of reduction and its ability to reduce voltage excursions on the network. The shift in voltage has a noticeable impact on voltage excursions, reducing the overall number. Whilst the number of under voltage excursions increased, the number of over voltages decreased significantly more. This is to be expected considering the distribution of voltages, where voltages sit at the higher end of the allowable range, and this analysis suggests that lowering the voltage would not have an ill-effect on the number of excursions and may in fact, increase compliance.

This also highlights the scope for further reduction in the monitored network; reducing voltage by a further 1.2%, optimising the distribution to minimise excursions, could result in an additional £15.41 million being saved by customers.

However, these benefits must be weighed up against the other potential uses of foot-room and the additional costs incurred resolving individual under voltage issues caused by the widespread changes as well as the operational restrictions this might bring.

Following this investigation, WPD have planned on implementing a further reduction in 11kV voltage settings across its networks. This will be conducted as part of its standard maintenance cycle over 3 years.

## REFERENCES

[1] Li, R., Gu, C., Li, F., Shaddick, G. and Dale, M., 2015. Development of low voltage network templates—part I: substation clustering and classification. IEEE Transactions on Power Systems, 30(6), pp.3036-3044.

[2] Li, R., Gu, C., Li, F., Shaddick, G. and Dale, M., 2015. Development of low voltage network templates—Part II: Peak load estimation by clusterwise regression. IEEE Transactions on Power Systems, 30(6), pp.3045-3052.

[3] Faraway, J.J., 2016. Extending the linear model with R: generalized linear, mixed effects and nonparametric regression models (Vol. 124). CRC press.

[4] Chen, J. and Gupta, A.K., 2011. Parametric statistical change point analysis: with applications to genetics, medicine, and finance. Springer.

[5] Cleveland, W.S., 1979. Robust locally weighted regression and smoothing scatterplots. Journal of the American Statistical Association, 74(368), pp.829-836.

[6] Wood, S., 2006. Generalized additive models: an introduction with R. CRC press.