SP ENERGY NETWORKS

Flexible Networks for a Low Carbon Future

Analysis of 2015 Voltage Reduction Experiment

- Ruabon Primary Substation

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INSTITUTE FOR ENERGY AND ENVIRONMENT

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1. Introduction and Key Learning Points

Following a previous voltage reduction experiment at Ruabon primary substation in January 2014, a second experiment has been conducted, beginning on 21 May 2015. The voltage reduction is still in effect at the time of writing this report. The measurements taken at Ruabon primary substation, monitored secondary substations and selected LV customer premises during this experiment have been inspected and analysed to identify changes in load behaviour and constraints on the application of voltage reduction.

The following key learning points have been identified:

- The previously made recommendation to assume a 1% reduction in active power demand for a 1% voltage reduction is not changed.
- The experiment showed a 5.5% reduction in primary transformer current, corresponding to an increase in capacity headroom. However, it was not possible to conclusively connect this change to the voltage reduction.
- The experiment shows that larger reductions in load than the default '1% for 1%' are possible.
- Reductions in primary substation voltage propagate to LV customer connections, and will release voltage-constrained generation capacity there.
- Low LV customer voltage may be a constraint on year-round voltage reduction.
- Statistical analysis is effective in identifying load changes which are not apparent from inspection of time-series data.
- Secondary substation monitoring is not essential to the evaluation of the effects of primary substation voltage reduction, except where there is specific interest in particular secondary substations. However, it does provide some additional redundancy in case of measurement problems.
- Careful experimental design is important in ensuring that sufficient data is available to support the analysis of voltage reduction experiments.
- Further voltage reduction experiments, outwith the Flexible Networks project, should be undertaken to better evaluate the effect of voltage reduction in different locations and at different times of year.

2. Motivation

Primary substation voltage reduction has been cited as a possible vehicle for providing increased network capacity headroom for both demand and generation. For demand, it has been suggested that load current will be reduced as a consequence of the voltage change, deferring or avoiding the need for reinforcement. For generation, propagation of the voltage reduction to customer connections would allow the network to accommodate small-scale generation which would otherwise be prevented by unacceptably high voltages in the LV network. Primary substation voltage reduction is of particular interest since this is the nearest point to the customer at which voltage can, in general, be remotely controlled via on-load tapchangers.

The previous experiment at Ruabon was curtailed following a complaint of low voltage by a customer. That experiment was undertaken in winter, when the value of the reduced voltage in permitting extra PV generation would be less than in summer. In addition, no comparator 'normal voltage' data was available for the Ruabon area in 2014, since installation of Flexible Networks substation monitors had not begun in the previous January.

It was therefore considered desirable to conduct a further experiment in spring and summer 2015. The lower load in these seasons would mitigate the risk of customers experiencing unacceptably low voltage and of consequent curtailment of the experiment. More data would therefore be available, together with comparator data from Flexible Networks monitors operational in the same part of 2014. Statistical analysis could then be applied to detect long-term changes in load, and to identify any changes to the pattern of load behaviour: the increased volume of data would tend to increase the ability of this analysis to robustly detect changes.

3. Summary of Method

A 3% reduction in the voltage control setpoint at Ruabon primary substation was made on the morning of 21 May 2015. The change has remained in place since that date. Measurement data for analysis was obtained from iHost (or from a local mirror at the University of Strathclyde) on 15 August 2015, at which point the most recently available data related to 12 August 2015. The data collected is described in more detail below.

Parts of the collected data were directly visualised as time-series graphs, but the main element of the analysis involved the application of simple statistical techniques and comparisons to the data. Principal statistics calculated included maximum, minimum and mean values, and percentile values of particular interest. Statistical distributions of quantities were also calculated and visualised to identify similarities and differences in the behaviour of voltage and load. The techniques applied are described in more detail in section 5 below.

4. Measured Data

Data was obtained from all Ruabon area secondary substations for the period 2 March 2015 – 12 August 2015, a period of 80 days before and 83 days after the day of the voltage reduction. Primary substation transformer and feeder measurements were also obtained for this period. In all cases, voltage measurements are made and recorded once per minute, while current is measured once every 10 minutes. All other quantities used are recorded as averages over a 10-minute period. Data for the same period in 2014 was also obtained for comparison purposes. Since no data for the period of 2014 after 20 July was available from Ruabon primary substation, primary substation analysis was restricted to the period before this date in both years.

Measurements obtained included the three phase voltages and currents, and active and reactive power. For secondary substations which are monitored at the level of individual LV feeders, current and power measurements were aggregated to substation level, by vector addition with respect to the power factor for currents.

The availability of data from other substations for comparison purposes was investigated. Of the Whitchurch area primary substations, no data was available from Yockings Gate for the 2015 period of interest. No data was available from Liverpool Road and Whitchurch for the period after the voltage reduction at Ruabon. The St Andrews test area was felt to be too geographically distant to permit meaningful comparison of load patterns. The use of primary substation data for comparison was therefore discounted as infeasible. Secondary substation data from the Whitchurch test area was however collected and analysed for comparison.

Weather data was obtained via iHost for the weather station at Ruabon primary substation for the same periods of 2014 and 2015 as the substation data. No additional weather data from other Flexible Networks weather stations or from public sources was required.

In addition, data from eight Landis & Gyr smart meters located at customer premises was obtained. These meters monitor voltage only: no load information is recorded. At the time of collection, data was only available from these meters for the period to 9 August 2015. No data from 2014 was available.

5. Analysis

5.1 Primary Substation Behaviour

5.1.1 Raw Measurements

The three phase voltages measured at Ruabon primary substation are shown in Figure 1:

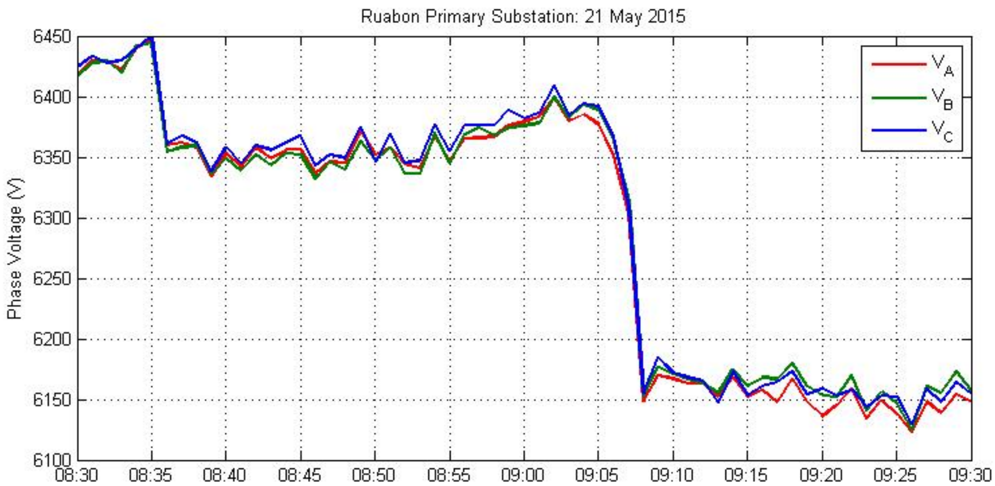


Figure 1: Application of voltage reduction at Ruabon

The voltage reduction begins at 09:06 and is complete at 09:08. The voltage reduction achieved is between 203V and 212V, depending on phase (phase A has a slightly lower pre-reduction voltage, and reduced to a similar level to the other phases at 09:08), corresponding to a reduction of 3.2% – 3.3% of measured pre-reduction voltage.

Figure 2 shows the measured phase currents and total primary transformer power flow at the time of the voltage reduction:

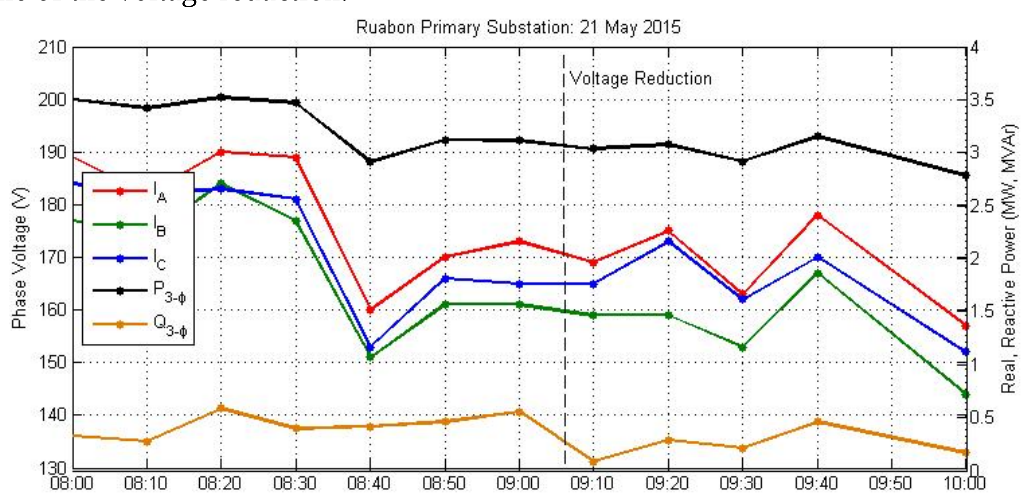


Figure 2: Response of primary substation load to voltage reduction

As a result of the measurement processes, the power measurements at 09:00 will be composed entirely of pre-reduction currents and powers, those at 09:10 will contain a mixture of pre- and post-reduction values, and those at 09:20 will be composed entirely of post-reduction measurements. Current measurements are ‘snapshots’ calculated over a short duration, and are not therefore expected to mix pre- and post-reduction conditions.

From inspection of Figure 2, it is very difficult to discern any reduction in load as a result of the voltage reduction. Indeed, over the period from 09:00 to 09:20, the A and C phase currents rise slightly, while the total active power and B-phase current are essentially static. The reactive power shows a noticeable reduction, especially over the period 09:00 to 09:10. As reported in the previous literature review[1] it is expected that reactive load will be more responsive to voltage reduction than active load.

It should be noted that any expected change in load will be small – from the literature, the expected change in active power would be of the order of 1% for every 1% reduction in voltage. For the voltage reduction achieved at Ruabon, and the observed level of active load, that would correspond to around 100kW, or one fifth of a vertical division in Figure 2. Such a change is smaller than the measurement-to-measurement changes in load observed away from the voltage reduction. As such, it would be impossible to reliably distinguish such a load reduction from the natural variability of load on the substation.

5.1.2 Statistical Analysis

The objective of the statistical analysis was to determine whether any change in the statistical distribution of the load on Ruabon primary substation could be ascribed to the voltage reduction. Statistical distributions were to be calculated for the following periods:

- Before the voltage reduction: 2 March – 20 May
- After the voltage reduction: 22 May – 20 July

The statistical distributions of measured voltages at Ruabon for 2014 and 2015 are shown in Figure 3:

[1] “Technical Note on Modelling of Load”, University of Strathclyde report SP/LCNF/TR/2014-003, June 2014.

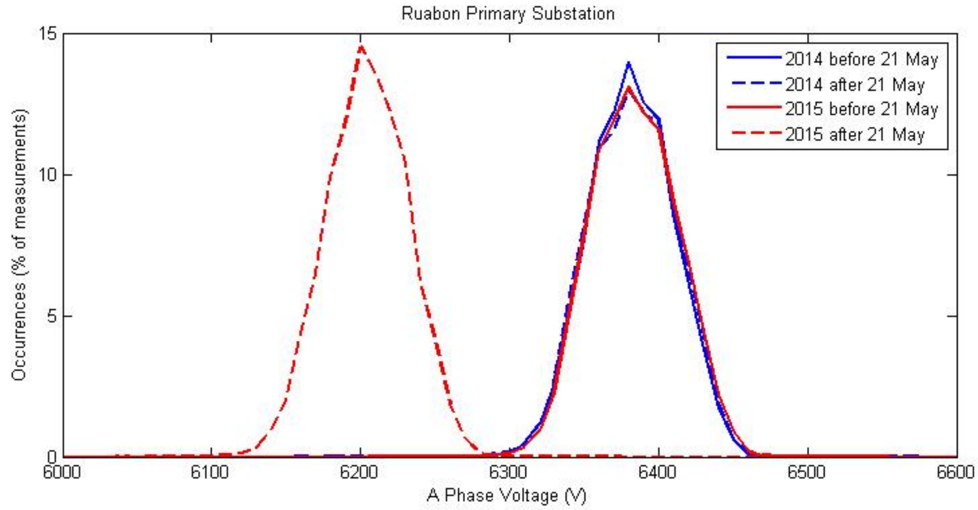


Figure 3: Statistical distribution of measured voltages at Ruabon primary substation

It is clear that there is good correspondence between the 2014 and 2015 distributions for the period before the voltage reduction on 21 May 2015, and in the 2014 distributions before and after 21 May. The 2015 distribution after 21 May is of a similar shape, but shifted towards the lower end of the voltage axis. The mean voltage reduces by 2.8%.

The corresponding distributions of measured primary transformer active power flow are shown in Figure 4:

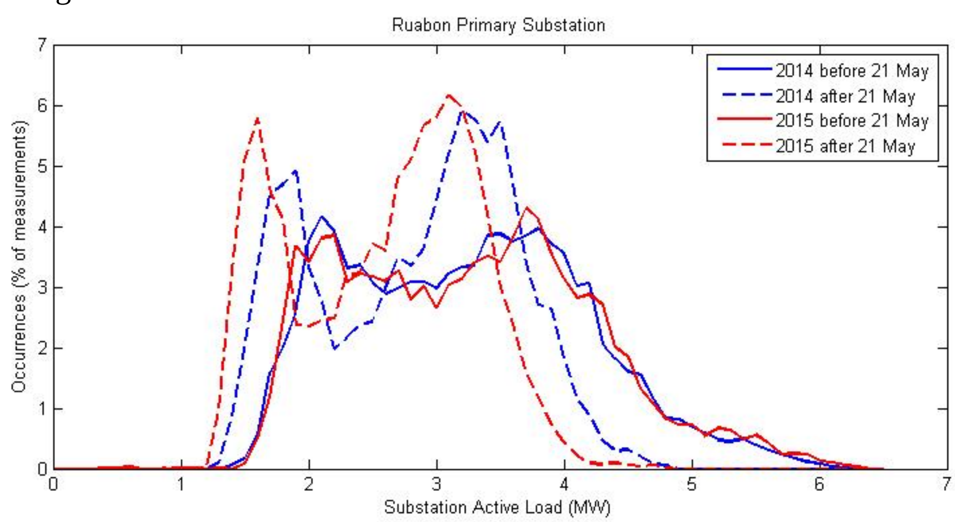


Figure 4: Statistical distribution of measured active power flow through Ruabon primary transformer

The solid lines in Figure 4 show that the distributions of power flow were quite similar in 2014 and 2015 for the period before 21 May. The difference in mean load was 21kW, or 0.6% of mean 2014 load for the period. For the period after 21 May, the distributions, although similarly shaped, are displaced on the power axis. This suggests that, although the pattern of load was similar in both years, the load was reduced in 2015. The difference in mean load for this period was 247kW, or 8.7% of mean 2014 load for the period. This is considerably more than the expected 1% for each 1% voltage reduction.

For the period after 21 May, the maximum observed power flow in 2015 was 56kW (or 1.2%) lower that in 2014. However, it has been found[2] that the absolute maximum load can show significant random variation, and that the 98th percentile load may provide a better indication of peak load behaviour. In this case, the 98th percentile load shows a reduction of 351kW (or 8.4%) in comparison to 2014, which agrees well with the change in mean load, and suggests that this may be a reliable estimate of the change in load.

The statistical distribution of A-phase current measurements from the Ruabon primary transformer is shown in Figure 5:

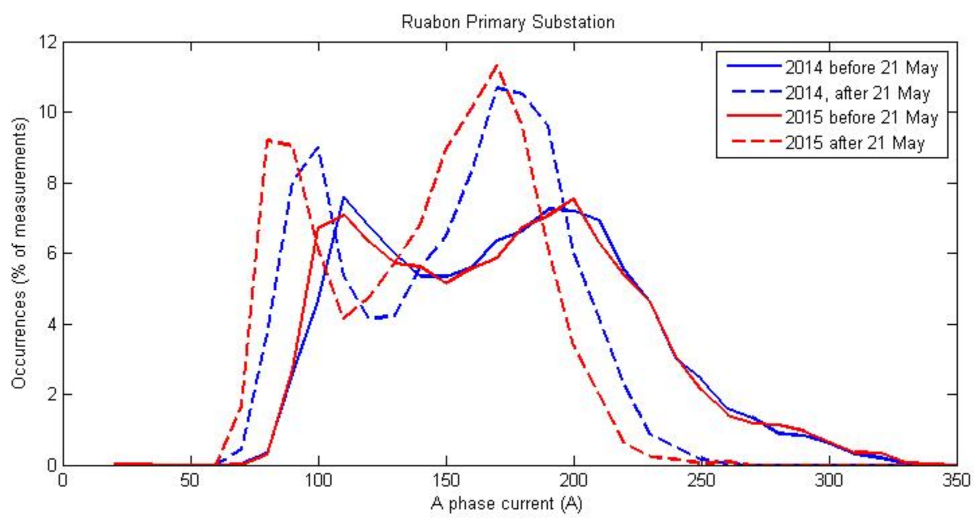


Figure 5: Statistical distribution of measured current flow through Ruabon primary transformer

Again, Figure 5 shows good agreement between the 2014 and 2015 distributions for the period before 21 May. For the period after 21 May, the 2015 distribution, although of a similar shape, is displaced towards lower current in comparison to the 2014 distribution. The difference in mean current for this period is 10.1A, or 6.7% of mean 2014 load for the period. As for the active power, the reduction in the absolute maximum current is much smaller – across the three phases, the difference between 2014 and 2015 in maximum current for the period is 6A or less. The 98th percentile current, however shows a reduction of 11–13A (5.2–5.8%), depending on phase, again suggesting that there is a significant and genuine reduction in peak current.

From the foregoing, it is clear that, in comparison to the same period in 2014, there has been a significant reduction in load at Ruabon primary following the voltage reduction on 21 May 2015. However, it is not certain that this load reduction is related to the voltage change. It may be that the underlying load was naturally lower, or that the output of PV generation was higher because of increased capacity or sunnier weather.

[2] "Flexible Networks – Improved Use of Primary Substation Data", TNEI report 7640-05, January 2015.

As previously discussed, it proved impossible to identify a suitable primary substation to use as a control for the behaviour of load in spring and summer 2014 and 2015. Secondary substation measurements were therefore investigated, as discussed in section 5.3.1.

5.1.3 Weather Influences

Weather data was investigated to determine whether changes in ambient temperature or PV output might explain the observed differences in load. Measurements of average ambient temperature and solar radiation intensity were retrieved via iHost from the weather station at Ruabon for the same periods in 2014 and 2015. The statistical distribution of these two quantities was calculated for the periods before and after 21 May in each year. Solar radiation data was restricted to the period from 0600–2000 daily.

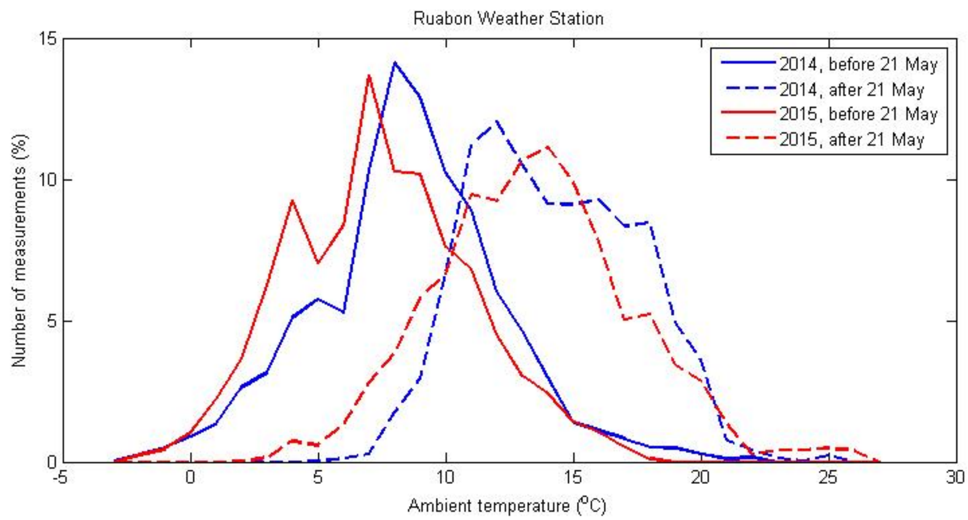


Figure 6: Statistical distribution of measured ambient temperature at Ruabon

Figure 6 shows that 2015 was slightly cooler than 2014, both before and after the day of voltage reduction. The difference in average ambient temperature between the two years was 1.1ºC before 21 May and 1.2ºC afterwards. It is considered unlikely that this reduction in ambient temperature is causally related to the observed reduction in load.

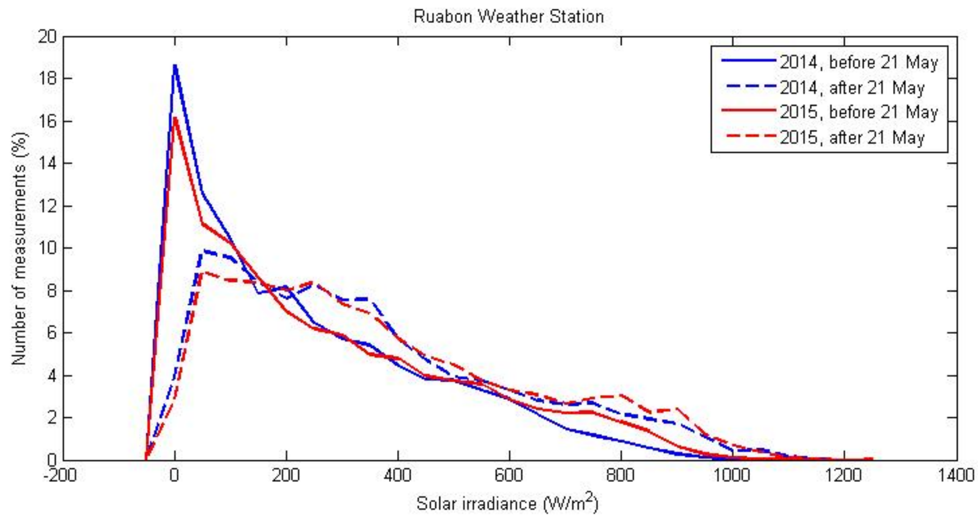


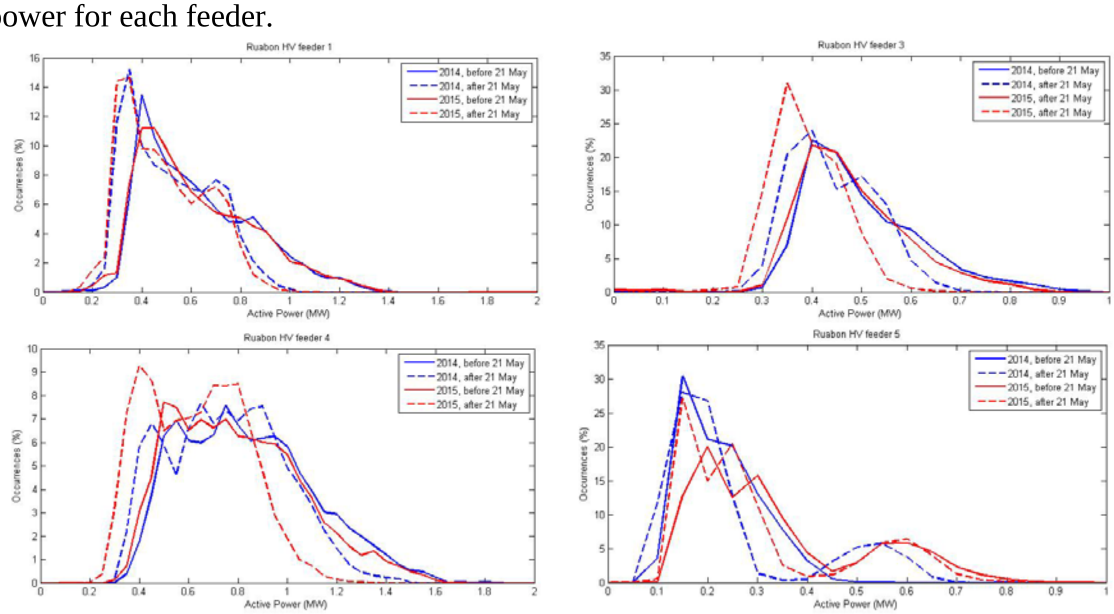
Figure 7: Statistical distribution of solar radiation intensity at Ruabon

Figure 7 shows that solar radiation in 2015 was very similar to that in 2014. The difference in mean solar radiation intensity from 2014 to 2015 was 34W/m^2 before 21 May, and 16W/m^2 afterwards, with the 2015 mean being higher in both cases.

In summary, it is considered unlikely that the observed reduction in load in the period after 21 May is a result either of weather effects or of increased output from small-scale PV generation connected to Ruabon primary.

5.1.4 Feeder Analysis

Statistical distributions of active power load and current were calculated for each of the monitored HV feeders leading from Ruabon primary substation, to determine whether the observed reduction in load is evenly distributed. Figure 8 shows the distribution of active power for each feeder.



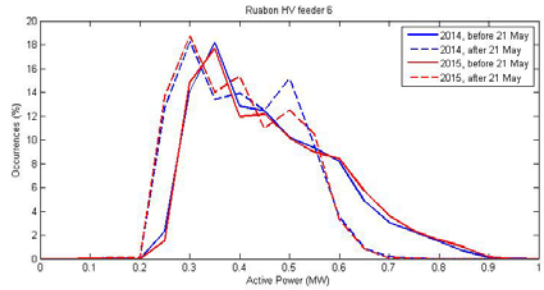


Figure 8: Statistical distributions of active power measurements for monitored Ruabon feeders

In most cases, there is close correspondence between the load prior to 21 May in the two years considered. Feeder 5, however, appears to have been more highly loaded in 2015. It is also noticeable that since May 2014, feeder 5 has had two distinct regions of load value: the reason for this is unknown. For feeders 1 and 6, there is a small reduction in load under reduced-voltage conditions after 21 May in comparison to the previous year. The difference in mean load for that period is 24kW and 6kW respectively, being 4.6% and 1.5% of mean 2014 load for the period. Feeders 3 and 4 experience a larger reduction of load, with mean load for the period after 21 May reducing by 55kW (12.4%) and 122kW (16.2%) respectively.

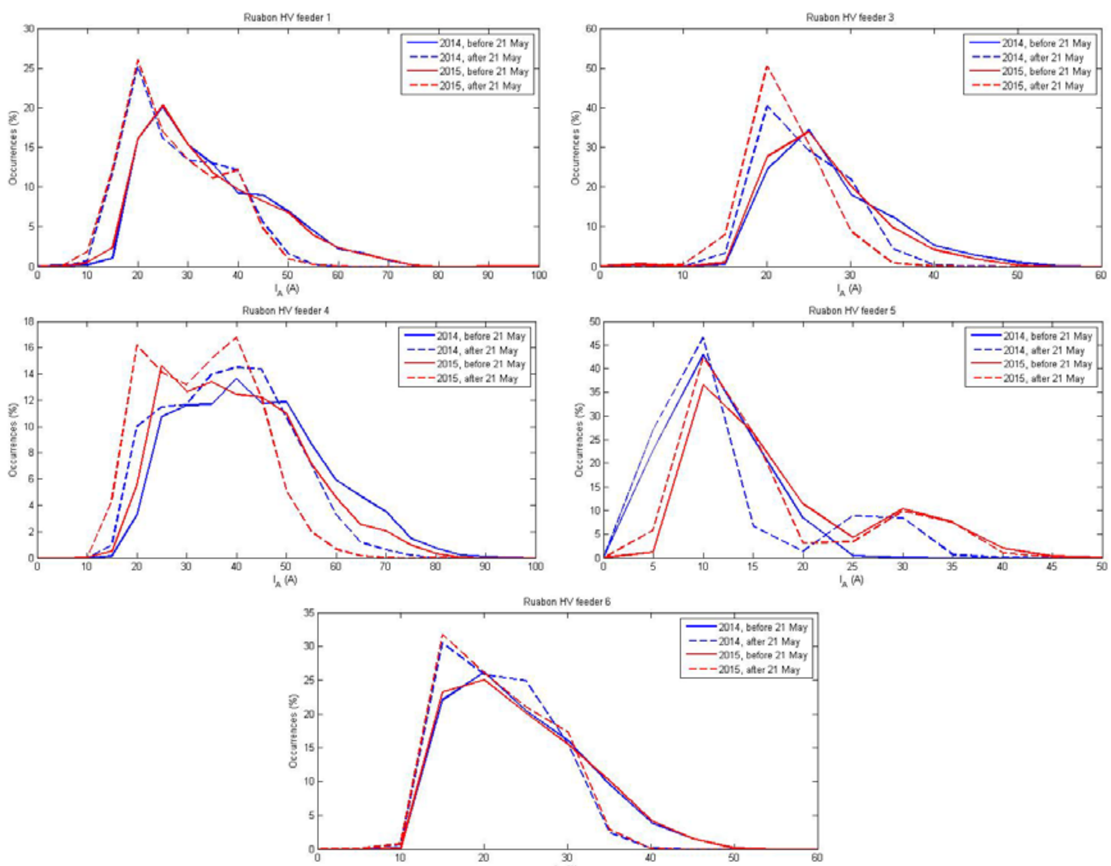


Figure 9: Statistical distributions of A-phase current measurements for monitored Ruabon feeders

In general, the current distributions shown in Figure 9 follow the same pattern as the active power distributions. With the exception of feeder 5, the current distributions for the period before 21 May are similar in both years (although the current in feeder 4 was slightly lower in 2015). The voltage reduction does not appear to cause a noticeable change in feeders 1 and 6 (2.6% reduction and 0.3% reduction respectively, which are similar to the changes in pre-21 May current). Feeders 3 and 4 show a larger change. After allowing for the difference in current before 21 May for the two years, the reduction after that date is respectively 5.5% and 5.8%.

Thus, it can be seen that the reduction in overall primary load is not distributed evenly among the HV feeders. Some feeders experience a significant reduction in load current, while others are largely unaffected. One feeder experienced both an increase in load, and a change in the shape of its distribution over the period of interest; however, given that the change in shape occurs in 2014, it is suspected that a change in the nature of the load has occurred which is unrelated to the experiment.

5.2 Temporal Behaviour

The current and active power measurements were aligned according to the day of the week, and measurement by measurement differences calculated. For example, measurements at 01:00 on Monday 3 March 2014 were subtracted from those at 01:00 on Monday 2 March 2015. Points at which either or both measurements were not available were discarded. The calculation is designed so that negative results will indicate a lower load in 2015. Figure 10 shows the distribution of active power differences, while Figure 11 shows the distribution of A-phase current differences.

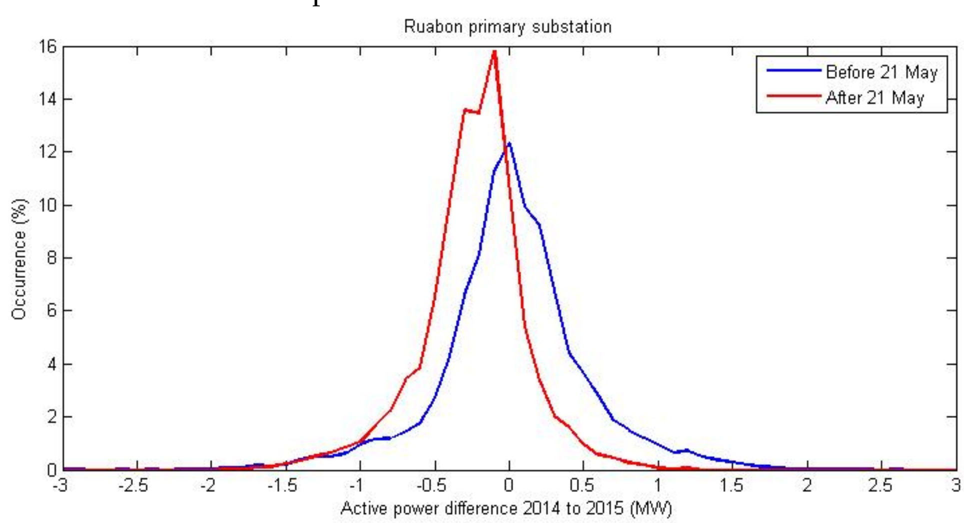


Figure 10: Statistical distribution of active power difference from 2014 to 2015

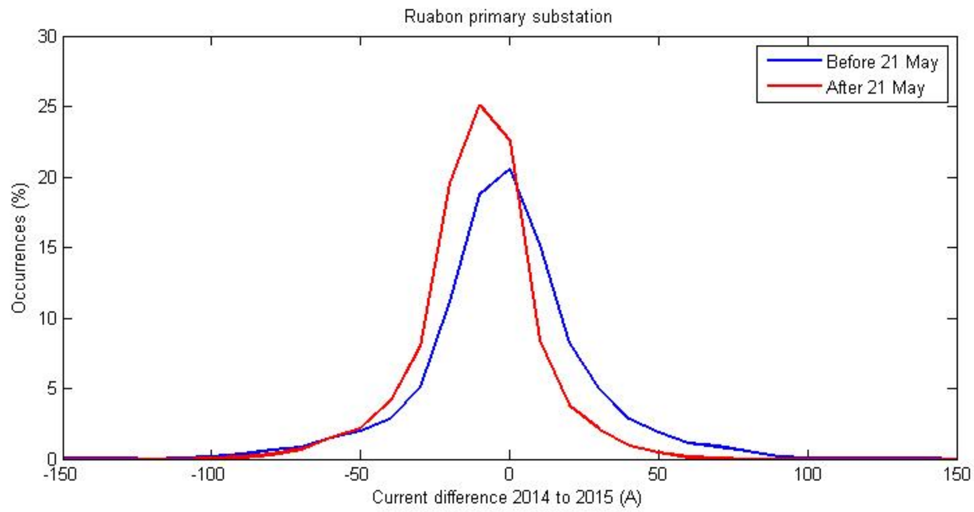


Figure 11: Statistical distribution of A-phase current difference from 2014 to 2015

The mean difference in active power was 22kW (higher in 2015) before 21 May and 241kW (higher in 2014) after 21 May. The mean current differences are 0.9A before 21 May and 9.8A after 21 May, in both cases higher in 2014. These values are consistent with the results shown in section 5.1.2.

To determine whether voltage reduction is particularly effective at certain times of day (by, for example reduced curtailment of PV generation), the average difference was calculated for each 10-minute measurement interval, considering the periods before and after the voltage reduction. The resulting difference profiles are shown in Figure 12 and Figure 13:

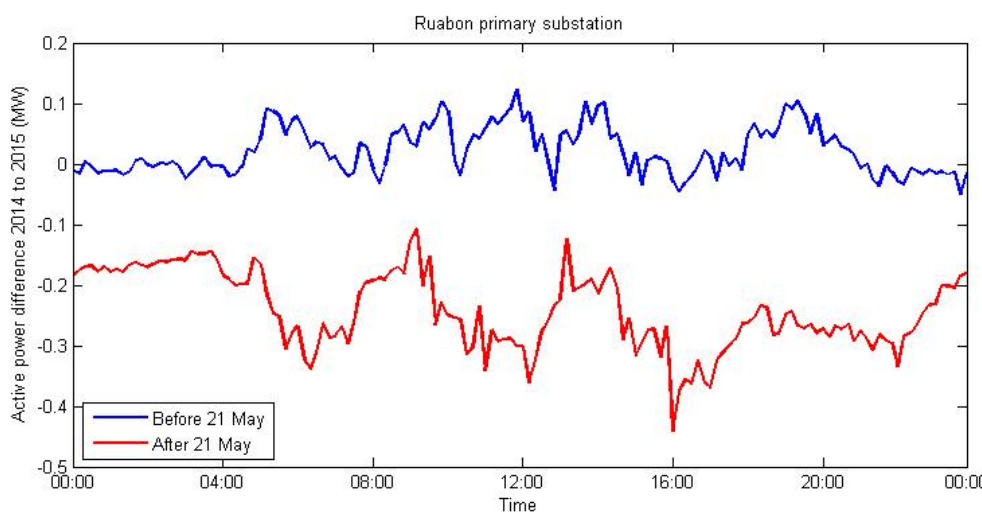


Figure 12: Profiles of average differences in active power

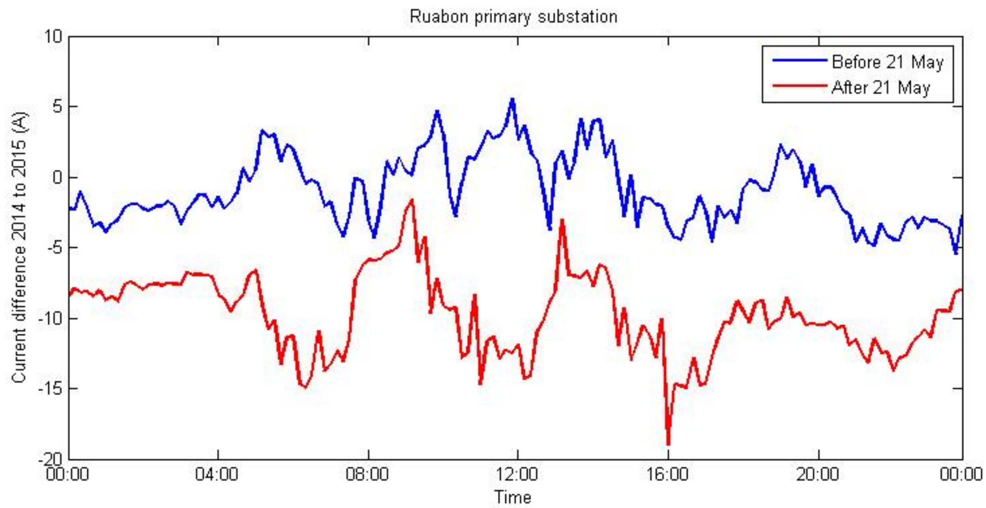


Figure 13: Profiles of average differences in A-phase current

Figure 12 and Figure 13 show that the reduction in active power is relatively low overnight, but increases from around 05:00. The reduction is fairly small through the morning peak but then increases until early afternoon. The reduction increases from mid-afternoon until the evening peak (which will be less pronounced since the reduction occurred in late spring) following which the reduction then falls to its overnight level.

The daytime variation in the current difference is larger than that in the active power, when compared to the overnight behaviour. This may indicate that the voltage is lower during the day (so that larger variations in current are required for a given power change), or that the load power factor is poor – previous studies have shown that reactive load is more influenced by voltage reduction.

The overall shape of the difference profile is not strongly suggestive of any obvious cause of the load reduction. If reduced PV curtailment was an important factor, the effect would be strongest during the middle part of the day, or would increase at the morning peak, as rising load offset PV output and reduced curtailment. The variability during the day, the relatively low overnight benefit and the variation among feeders suggest that the voltage reduction affects some specific types of load more strongly than general 'base load'. Nevertheless, it is clear that some reduction in load is achieved throughout the day, although at some times the reduction in current is rather small.

5.3 Secondary Substation Behaviour

5.3.1 Aggregate Behaviour

As previously noted, it was impossible to identify a suitable primary substation to use as a control to distinguish between the influence of voltage and other factors on the load behaviour. An attempt was therefore made to compare aggregate monitored secondary substation load at Ruabon to that in the Whitchurch test area. Active power at substations in each test area was summed. The following substations were excluded from the analysis as a result of significant gaps in the measurement record during one or more of the periods of interest:

- Ruabon test area: Cae Gabriel, Film Cap, Leisure Centre, Tesco Well Street
- Whitchurch test area: Alkington Road No.2, Belton Farm, Business Centre, Civic Centre, Cold Store, Heatley Court, St Johns Flats 2

In the Ruabon test area, 22 secondary substations were considered; 33 were considered in the Whitchurch test area. Measurement instants which did not have active power measurements for all of the included substations in the test area were excluded from the analysis. The total number of measurement points analysed in each time period was:

Test Area	2014		2015	
	Before 21 May	After 21 May	Before 21 May	After 21 May
Ruabon	10517 (91.3%)	10530 (88.0%)	10416 (90.4%)	17041 (72.1%)
Whitchurch	7871 (68.3%)	7311 (61.2%)	8646 (75.1%)	5333 (44.6%)

The calculated distributions of aggregate secondary substation active power in the two test areas are shown in Figure 14:

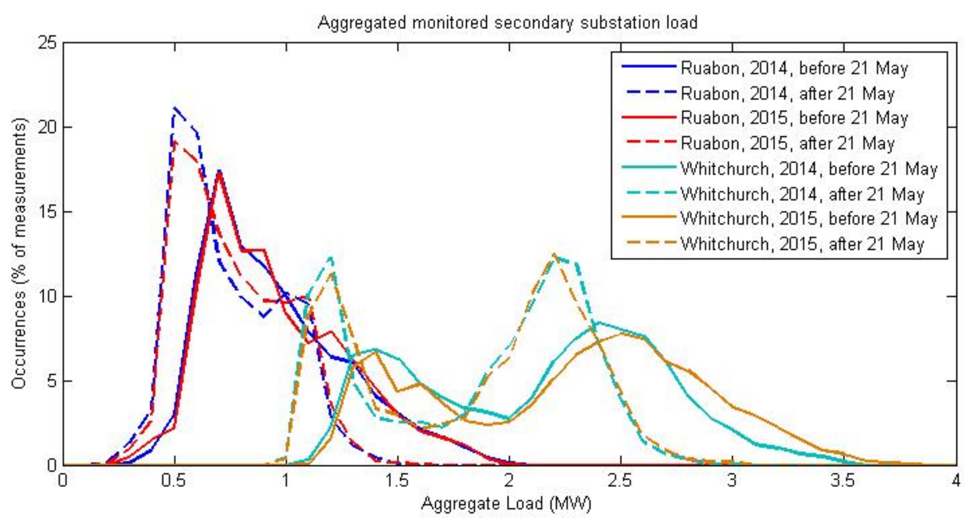


Figure 14: Statistical distributions of aggregate secondary substation active power

The reduction in primary substation active power shown in Figure 4 is not readily apparent in Figure 14. Indeed, it is arguable that there is a slight increase in post-21 May active power from 2014 to 2015 in the Ruabon test area. It was previously observed that load behaviour in response to the voltage reduction varies between HV feeders, and it is likely that there is also variation among secondary substations, which will be investigated in the following section. It appears that the particular selection of secondary substations studied is not collectively representative of the overall behaviour of load at Ruabon primary. It should be noted that the monitored secondary substations at Ruabon are connected to Feeders 1, 4 and 5, of which only Feeder 4 was found to show a strong reduction in load. Not all of the secondary substations on each feeder are monitored.

On the basis of this further analysis, it cannot be conclusively determined that the observed change in load is linked to the applied voltage reduction, rather than some other source affecting load more generally in the geographical area.

5.3.2 Individual Behaviour

Figure 15, Figure 16 and Figure 17 show summary voltage statistics for the monitored secondary substations fed from each of the three monitored Ruabon 11kV feeders. Substation names are as shown in Table 1. In general, higher numbered substations are further from the primary substation.

Feeder 1		Feeder 4		Feeder 5	
No.	Name	No.	Name	No.	Name
1	Plas Bennion	1	Idwal Plas Madoc	1	Bodlyn
2	Council Houses	2	Dinas	2	Leisure Centre[3]
3	Afoneitha Est No.1	3	Peris Plas Madoc[4]	3	Plas Madoc
4	Afoneitha Road	4	Hampden Way		
5	Hall Street	5	Cae Glo		
6	Cae Gabriel	6	Chapel Street Rhosymedre		
7	Pont-Yr-Avon	7	Brook Street		
8	Hill Street	8	Park Road I.E		
9	Bro Awelon	9	Film Cap[5]		
		10	Rock Road		
		11	Tesco Well Street[6]		
		12	Well Street		
		13	Plas Kynaston		
		14	Fford Offa		

Table 1: Key to secondary substation charts

[3] No 2014 measurements for period after 21 May
[4] Investigation by SP Energy Networks and Selex (the substation monitor vendor) has found that the substation monitor at this location was miscalibrated throughout the period of the study.
[5] No active power measurements recorded
[6] HV customer with voltage measurements only for 2014. Not shown in graphs.

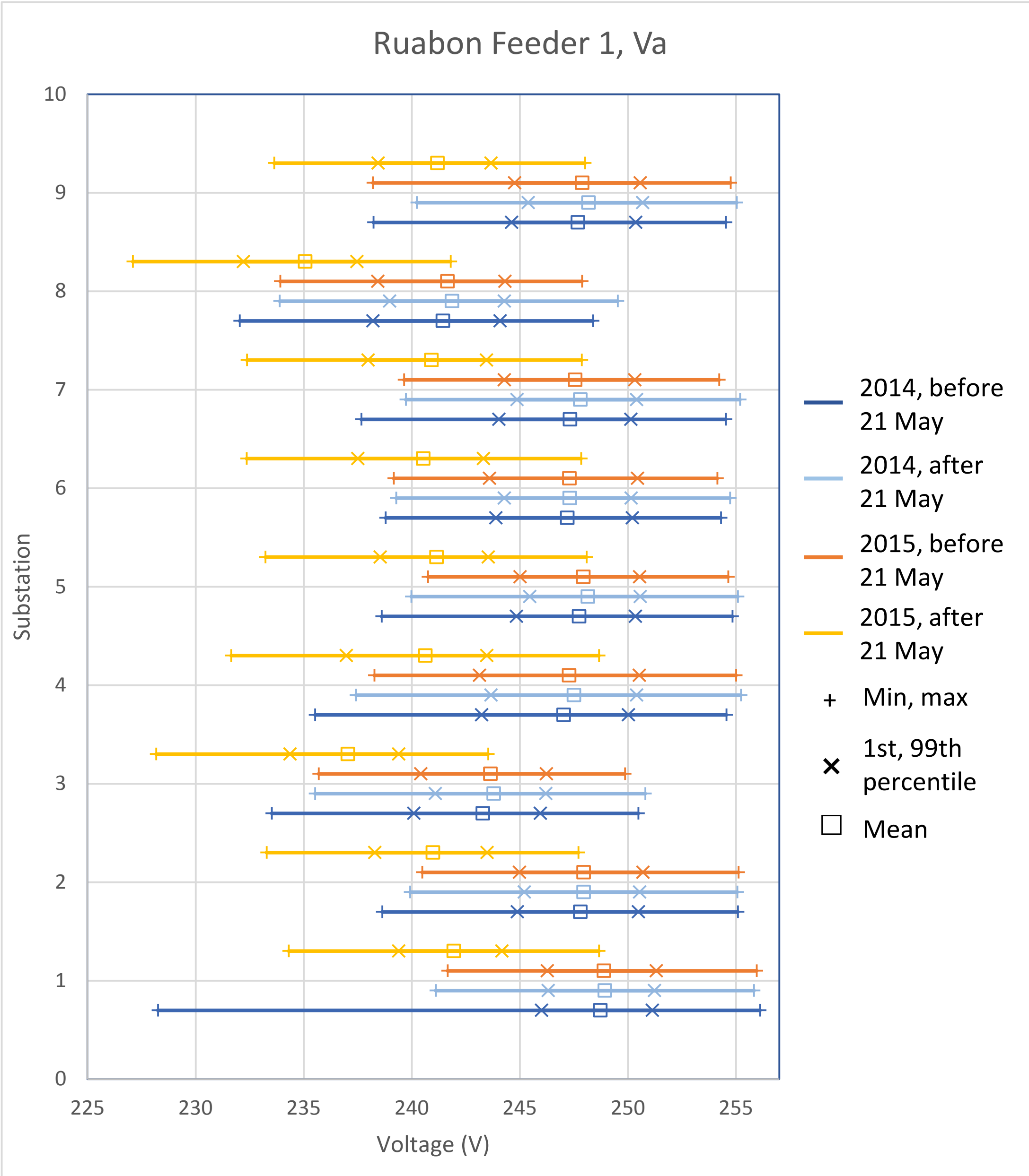


Figure 15: Statistical summary of secondary substation voltages, Ruabon 11kV feeder 1

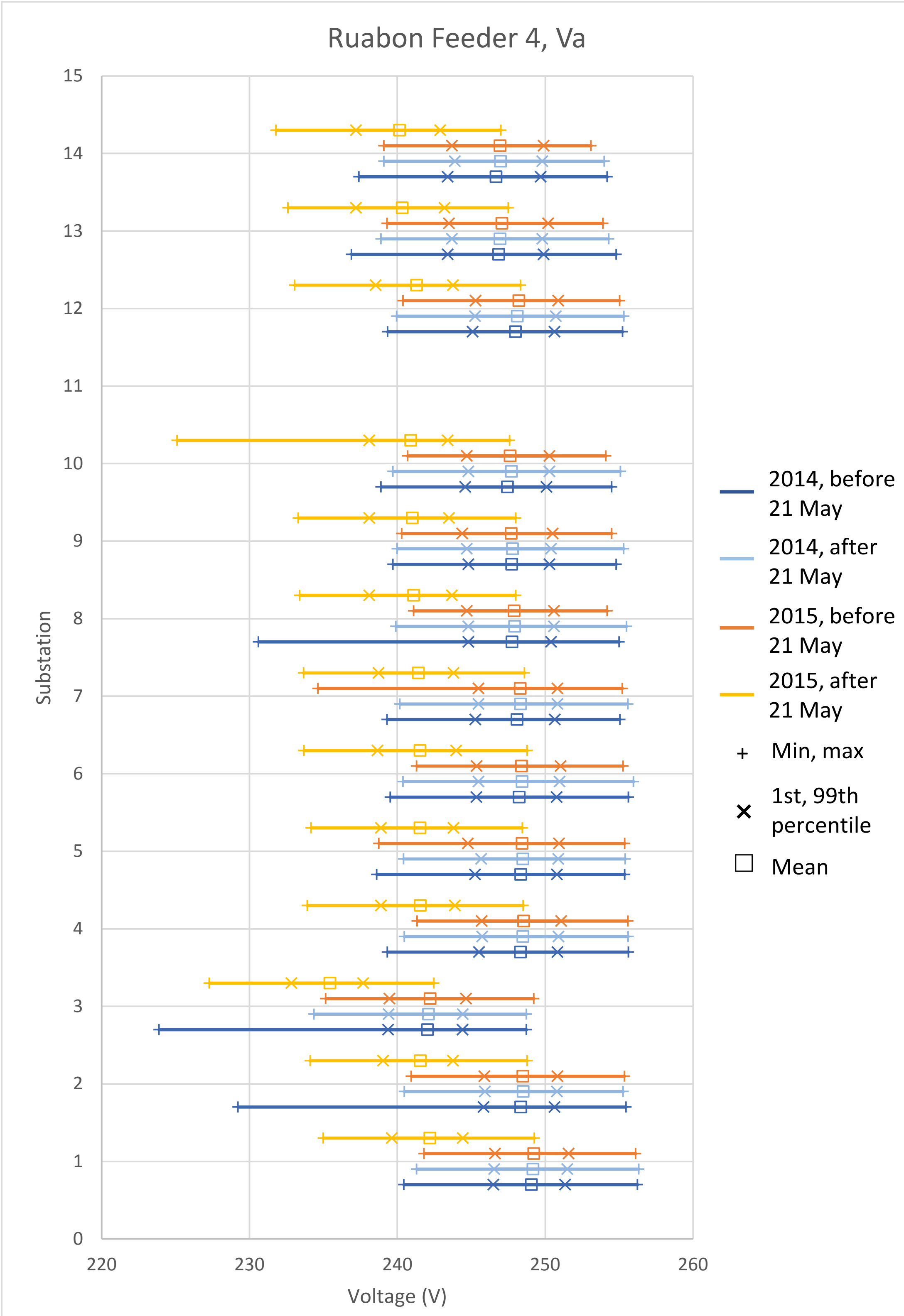


Figure 16: Statistical summary of secondary substation voltages, Ruabon 11kV feeder 4

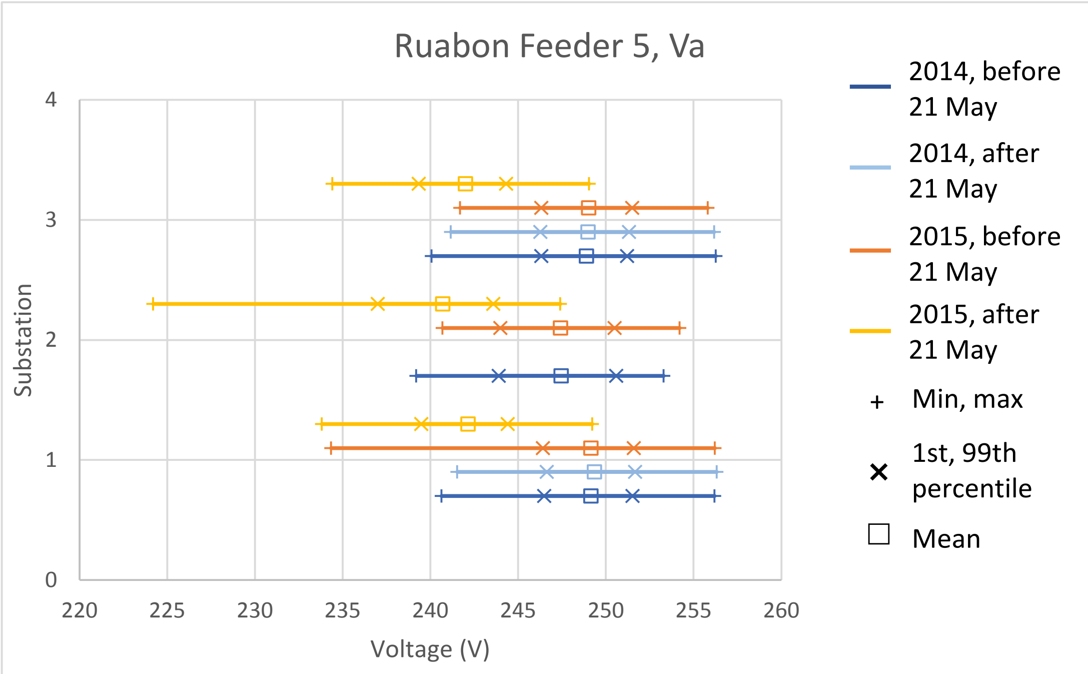


Figure 17: Statistical summary of secondary substation voltages, Ruabon 11kV feeder 5

In the data underlying the graphs, voltage measurements below 200V were removed on the basis that they are likely to relate to voltage dips unrelated to the experiment. It can be seen that all secondary substations experience the voltage reduction, and that the relationship between the mean, maximum and 1st and 99th percentile voltages is not significantly affected by the reduction. At a number of substations, the minimum voltage is displaced quite significantly from the 1st percentile voltage, particularly in the period before 21 May 2014. This may be a consequence of a minor voltage dip, rather than a sustained or regular phenomenon. Nevertheless, no substation experiences a voltage below the statutory minimum of 216V under ‘normal’ conditions.

The miscalibration of the substation monitor at Peris Plas Madoc (substation 3 on feeder 4) is clear. In comparison to the gradual decline in mean voltage along the length of the feeder, it appears that the reported voltage at this location is 6 – 7V lower than expected. The reported voltage behaviour is consistent across all three ‘normal’ voltage periods, and the recorded behaviour following the voltage reduction is consistent with the adjacent secondary substations. It is considered unlikely therefore that this miscalibration will introduce a significant error in the assessment of load and voltage behaviour following the voltage reduction.

Figure 18, Figure 19 and Figure 20 show a similar statistical summary of the total active power at each secondary substation.

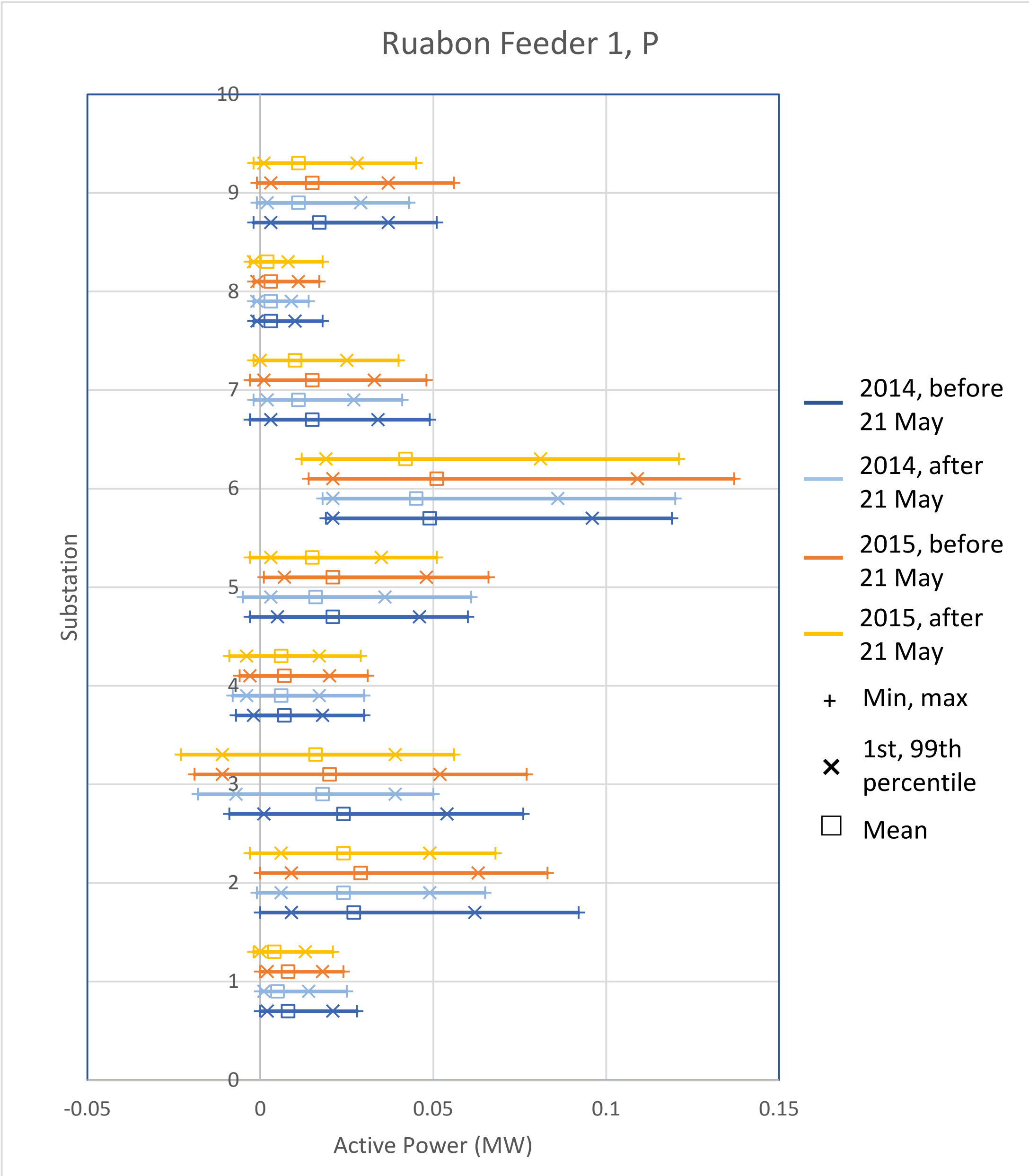


Figure 18: Statistical summary of secondary substation active power flow, Ruabon 11kV feeder 1

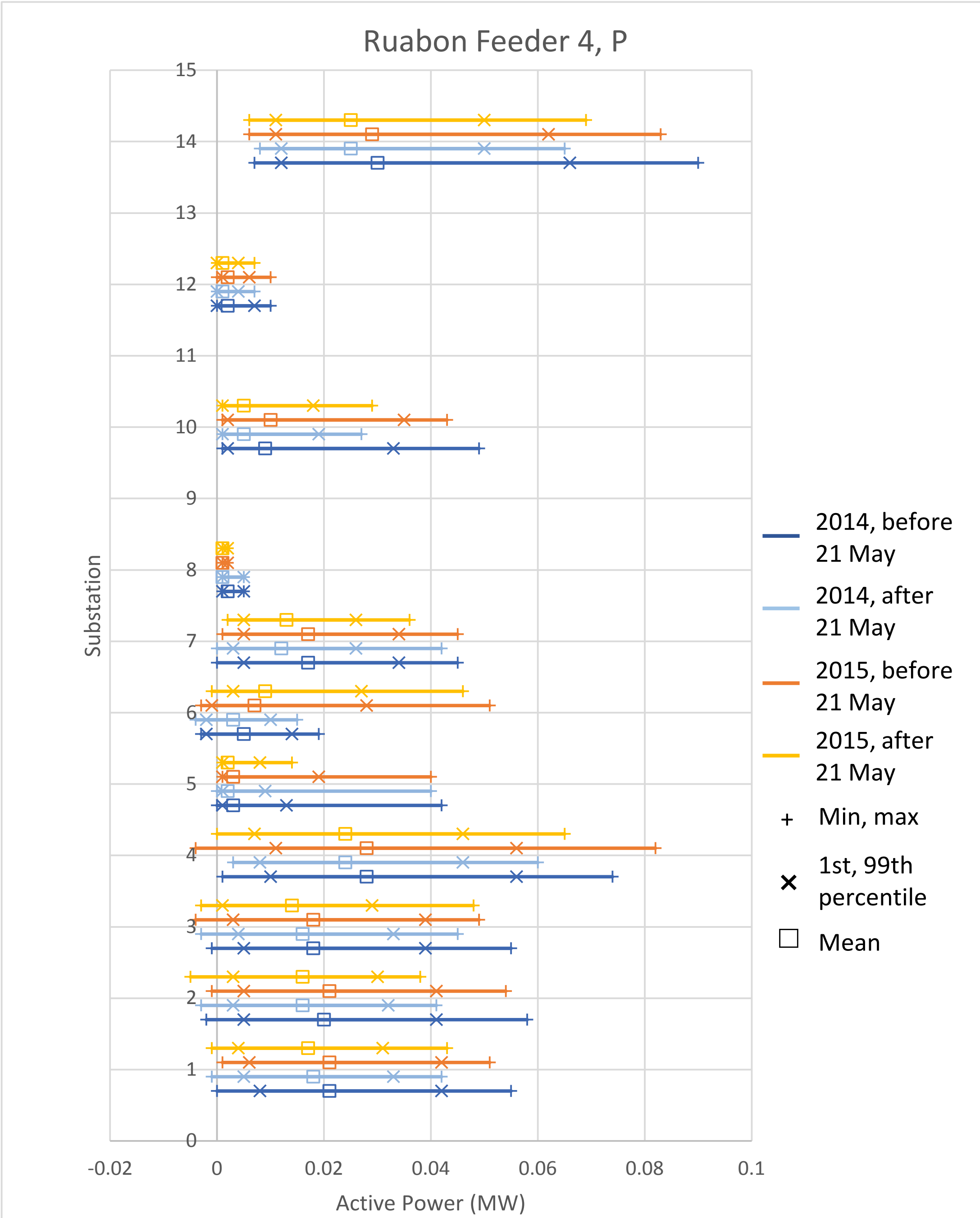


Figure 19: Statistical summary of secondary substation active power flow, Ruabon 11kV feeder 4

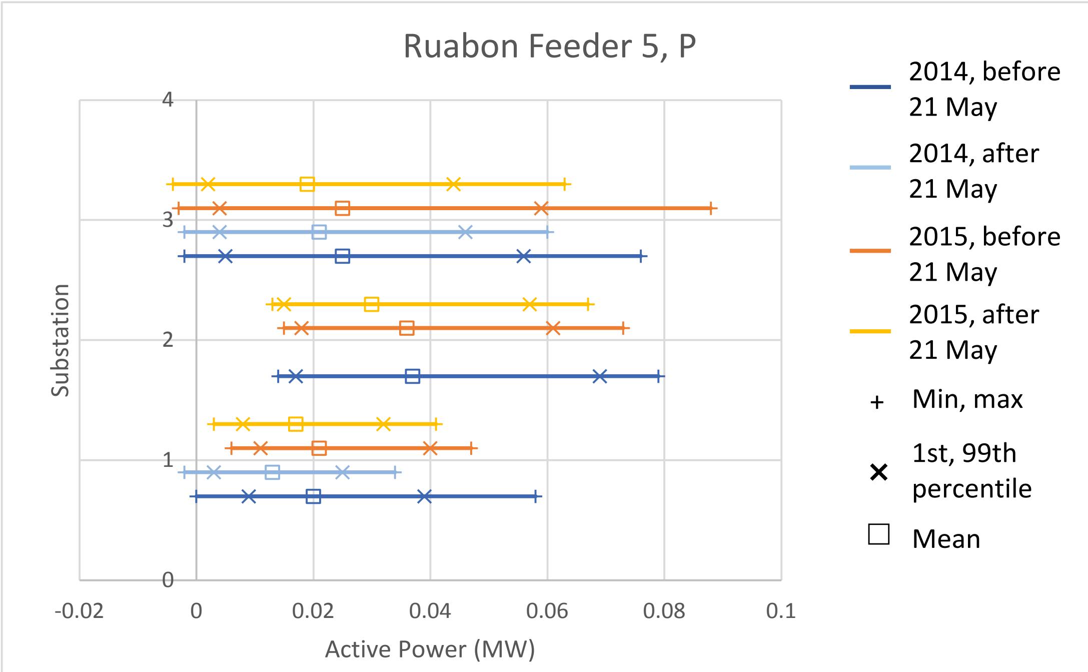


Figure 20: Statistical summary of secondary substation active power flow, Ruabon 11kV feeder 5

It is not clear from the charts above that there is a general reduction in the active power load at the secondary substations shown. In most cases, the change appears to be relatively small. The percentage change from 2014 to 2015 in mean active power for the period after 21 May is shown in Table 2 below.

Feeder 1		Feeder 4		Feeder 5	
Name	ΔP (%)	Name	ΔP (%)	Name	ΔP (%)
Plas Bennion	-18.9	Idwal Plas Madoc	-5.7	Bodlyn	+20.3
Council Houses	+1.0	Dinas	-5.4	Leisure Centre[7]	-
Afoneitha Est No.1	-9.3	Peris Plas Madoc	-16.6	Plas Madoc	-7.0
Afoneitha Road	+7.6	Hampden Way	-2.0		
Hall Street	-4.7	Cae Glo	-6.6		
Cae Gabriel	-7.0	Chapel Street Rhosymedre	+234		
Pont-Yr-Avon	-9.7	Brook Street	+15.9		
Hill Street	-11.3	Park Road I.E	-18.4		
Bro Awelon	-3.5	Film Cap[8]	-		
		Rock Road	+0.9		
		Tesco Well Street[9]	-		
		Well Street	+17.2		
		Plas Kynaston	-		
		Fford Offa	-1.3		

Table 2: Percentage change from 2014 to 2015 in mean active power for period after 21 May

[7] No 2014 measurements for period after 21 May
[8] No active power measurements recorded
[9] HV customer with voltage measurements only for 2014. Not shown in graphs or tabulated

Some secondary substations do experience a significant percentage reduction in load. Others, however, see an increase. It should be noted that, in a number of cases, the mean active load is a low multiple of the 1kW resolution of the substation monitor.

Figure 21, Figure 22 and Figure 23 show a similar statistical summary of the secondary substation currents.

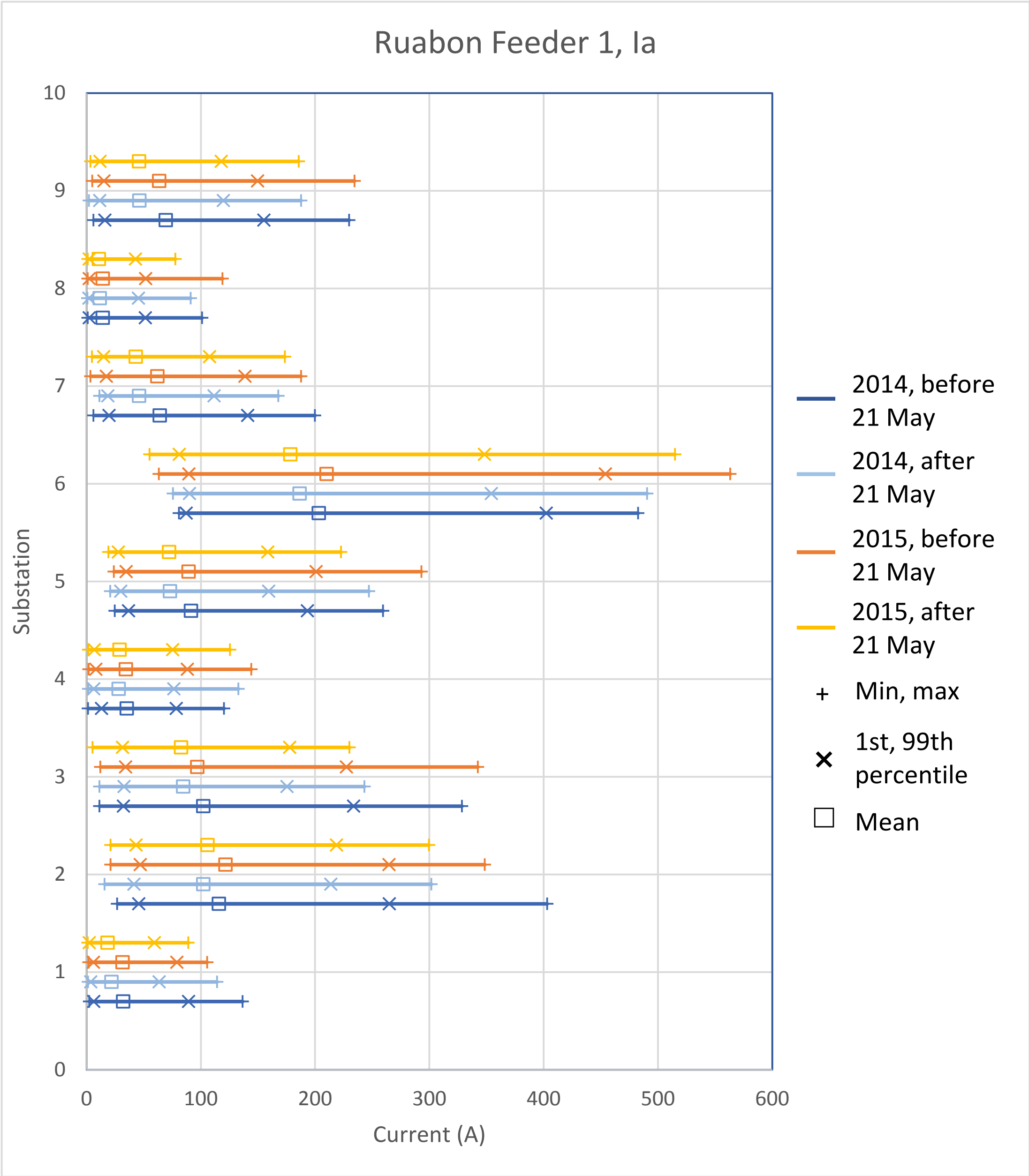


Figure 21: Statistical summary of secondary substation currents, Ruabon 11kV feeder 1

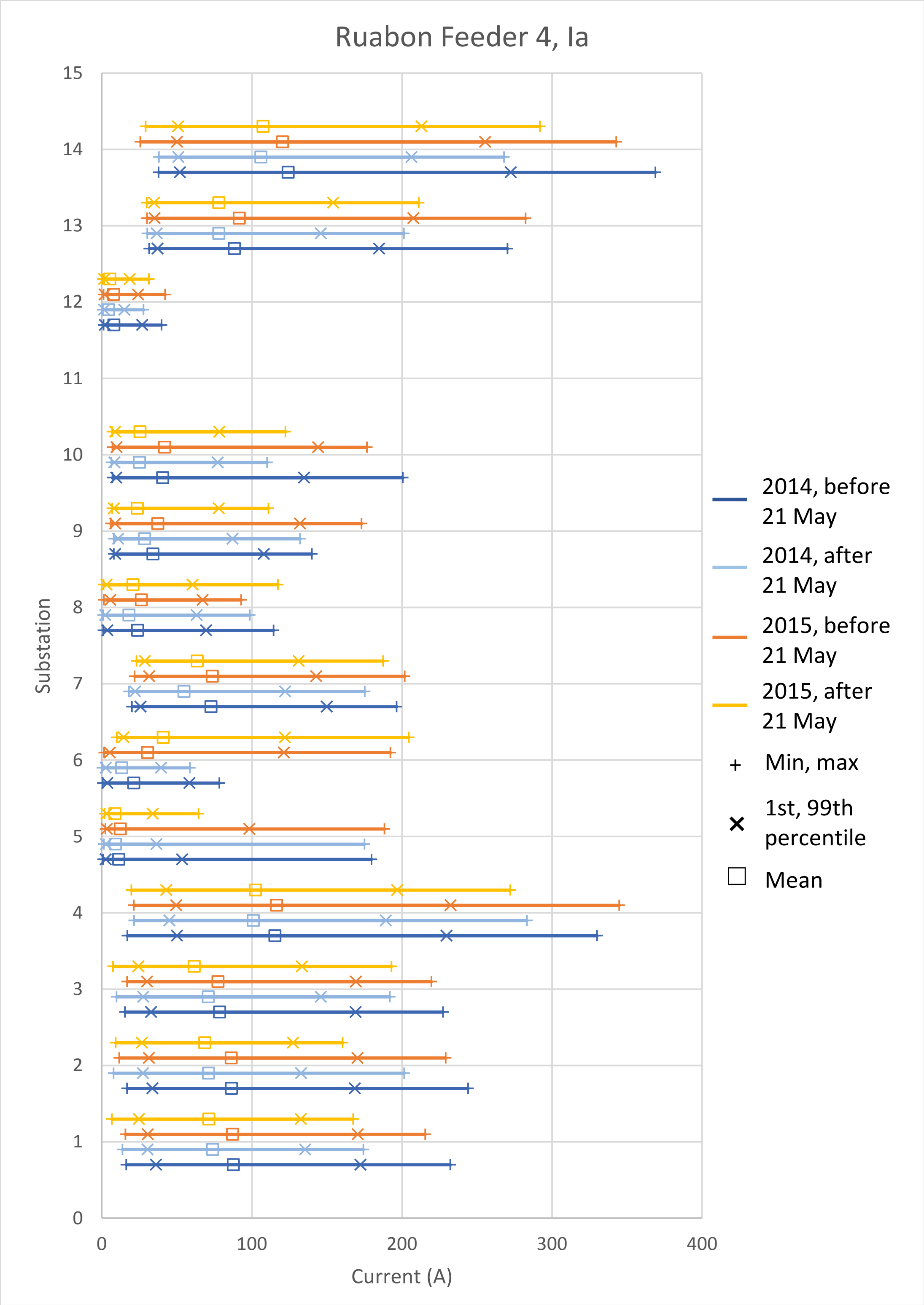


Figure 22: Statistical summary of secondary substation currents, Ruabon 11kV feeder 4

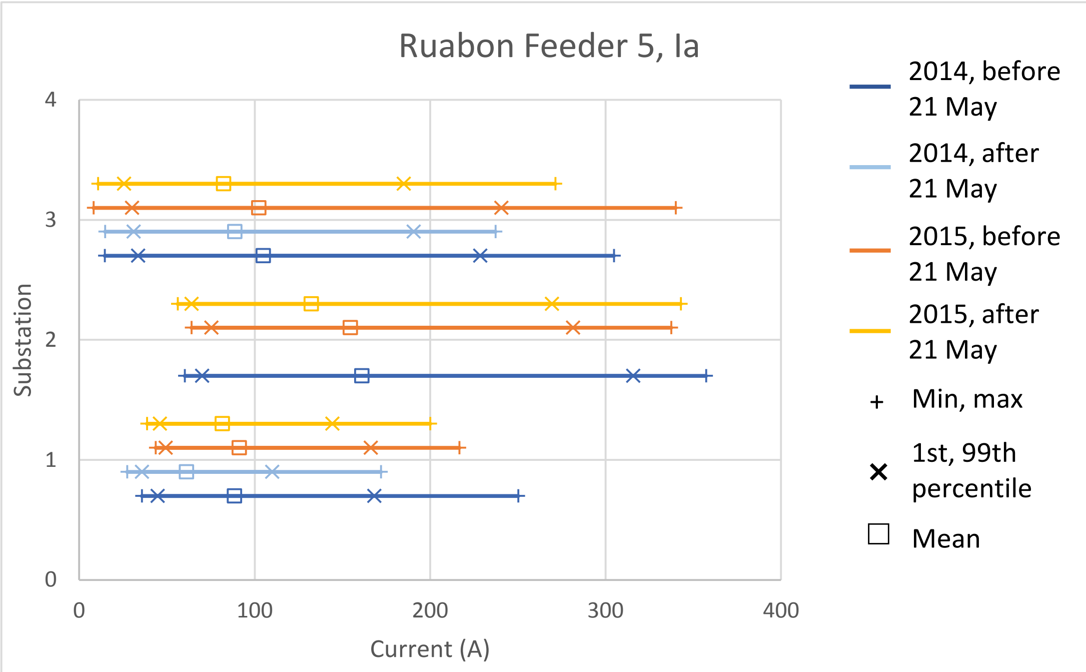


Figure 23: Statistical summary of secondary substation currents, Ruabon 11kV feeder 5

As for the active power, it is not clear from these statistical summaries that there is a general reduction in secondary substation load. Table 3 shows the percentage change from 2014 to 2015 in mean current for the period after 21 May.

Feeder 1		Feeder 4		Feeder 5	
Name	ΔP (%)	Name	ΔP (%)	Name	ΔP (%)
Plas Bennion	-15.7	Idwal Plas Madoc	-3.4	Bodlyn	+21.0
Council Houses	+3.5	Dinas	-3.5	Leisure Centre[10]	-
Afoneitha Est No.1	-2.1	Peris Plas Madoc	-13.1	Plas Madoc	-3.7
Afoneitha Road	+2.6	Hampden Way	+1.3		
Hall Street	-1.0	Cae Glo	-5.6		
Cae Gabriel	-4.4	Chapel Street Rhosymedre	+208		
Pont-Yr-Avon	-6.6	Brook Street	+16.3		
Hill Street	-5.3	Park Road I.E	+14.6		
Bro Awelon	-0.5	Film Cap[11]	-16.9		
		Rock Road	+1.6		
		Tesco Well Street[12]	-		
		Well Street	+18.6		
		Plas Kynaston	+0.1		
		Fford Offa	+1.4		

Table 3: Percentage change from 2014 to 2015 in mean active power for period after 21 May

[10] No 2014 measurements for period after 21 May
[11] No active power measurements recorded
[12] HV customer with voltage measurements only for 2014. Not shown in graphs or tabulated

The changes in current are generally consistent with the previously tabulated changes in active power, bearing in mind the 3% voltage reduction. However, as in the case of the active power, Table 3 shows that there is considerable variability in the change in load between 2014 and 2015. It is not clear to what extent these changes are the result of the voltage reduction, and to what extent they are the result either of other changes in the load fed from each secondary substation, or of random variation.

No general conclusions can be drawn from the analysis of secondary load. Although some changes are observed, their magnitude and direction varies considerably across the set of monitored secondary substations.

6. Voltage at Customer Premises

As previously stated, voltage information was gathered from eight LV monitoring devices located at customer premises. The location of these devices is unknown, and they are referred to in this report by the last two digits of their serial numbers. No data was available from a ninth device (device 34).

These devices record the LV phase voltage at 1 minute intervals, and generally began recording in December 2014. At the time of analysis, data was generally available until the end of 9 August 2015. One device (device 37) appears to be connected to a three-phase supply but only A-phase voltages are available for the period of interest here.

6.1 Observed Behaviour

The voltage reduction is shown in Figure 24:

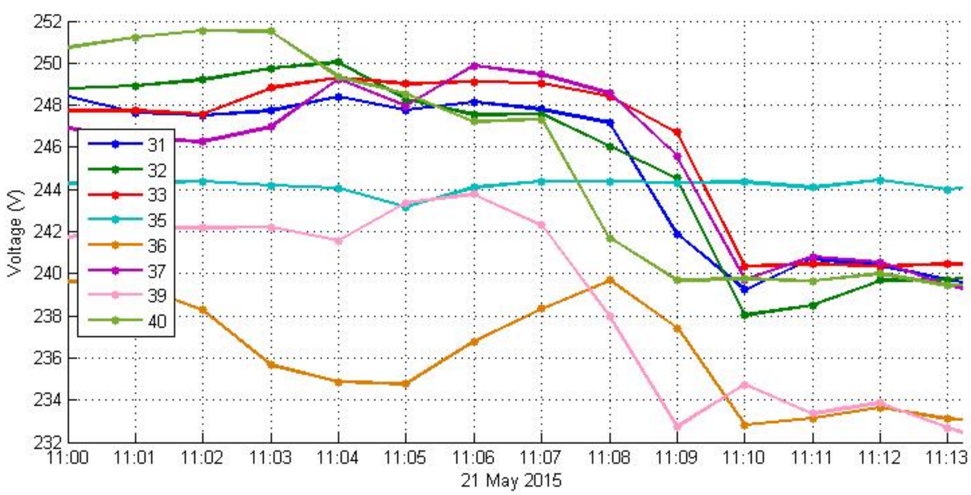


Figure 24: Measured customer voltages around time of voltage reduction

It can be seen that there is an offset of slightly over two hours between the time at which the voltage reduction is recorded at the primary substation and at the LV monitors. There are also offsets of one minute between some of the monitors. These are considered to be the result of variations in the clock settings of the various monitors. The timestamps on the LV monitor measurements were corrected to align the voltage step observed at the LV monitors with that observed at the primary substation.

As before, the data was divided into three periods:

- Before the voltage reduction: 2 March to 20 May
- The day of the voltage reduction: 21 May
- After the voltage reduction: 22 May to 9 August

Two significant, isolated voltage dips, each of approximately 1.5 hours duration were observed in the data:

- At monitor 33 on 22 April, with voltage varying between 70V and 180V
- At monitor 35 on 17 June, with voltage varying between 215V and 230V

No corresponding dips were observed at other LV monitors. These were considered to indicate either measurement error, or an isolated voltage dip in the LV system, and were excluded from subsequent analysis.

The number of available voltage measurements in each period for each of the LV monitors was as shown in Table 4, which also shows the percentage of possible measurements which was recorded:

Monitor	Before reduction		Day of reduction		After reduction	
	Samples	%	Samples	%	Samples	%
31	112860	97.97	1440	100	96554	83.81
32	115079	99.89	1440	100	113699	98.70
33	113970	98.93	1440	100	113699	98.70
35	115080	99.90	1440	100	97168	84.35
36	44766	38.86	1440	100	57539	49.95
37	93896	81.51	1440	100	108945	94.57
39	115080	99.90	1440	100	79028	68.60
40	112376	97.55	1440	100	103620	89.95

Table 4: Completeness of LV customer voltage measurement series

With the exception of monitor 36, coverage of the period of interest is generally good or excellent. Data from monitor 36 is characterised by a number of large gaps in the period before the voltage reduction; no data is recorded after 1 July 2015. Monitor 39's data has a large gap in the period after the voltage reduction.

The changes in voltage observed by the LV monitors at the time of the voltage reduction were tabulated, as shown in Table 5:

Monitor	Before Reduction (V)	After Reduction (V)	Change	
			(V)	(%)
31	247.16	239.24	7.92	3.2
32	246.04	238.03	8.01	3.3
33	248.40	240.35	8.05	3.2
35	244.38	244.32	0.06	0.2
36	239.68	232.80	6.88	2.9
37	248.57	239.72	8.85	3.6
39	242.31	232.72	9.59	4.0
40	247.31	239.69	7.62	3.1

Table 5: Voltage reductions recorded by LV monitors

All but one of the LV monitors experienced a voltage reduction of 3–4% on the morning of 21 May 2015. Monitor 35 did not experience a significant voltage change at the time of the voltage reduction. Inspection of the complete series of measurements made by this monitor, as shown in Figure 25, reveals that no voltage reduction was observed during the period analysed. It is thus concluded that monitor 35 is not supplied from Ruabon primary substation, and can be used as a control to determine the effect of the voltage reduction on the pattern of Ruabon-area customer voltages.

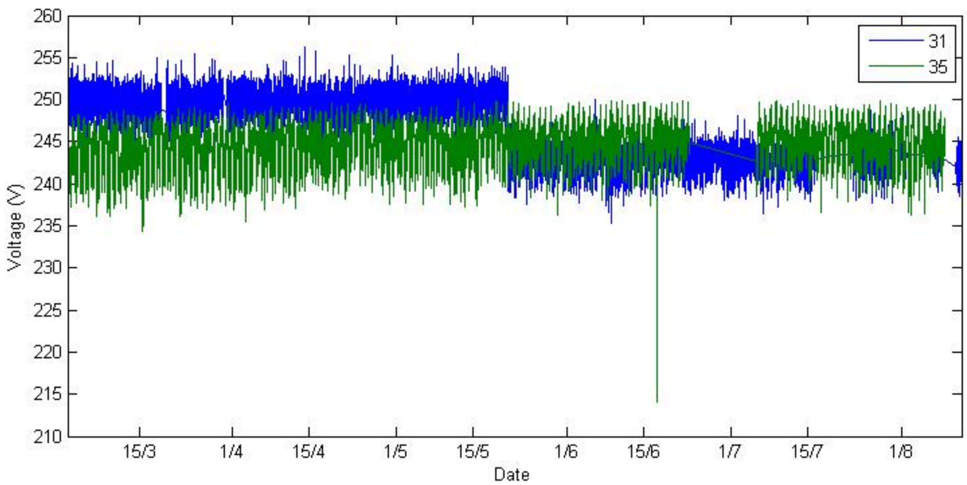


Figure 25: Measured voltage at monitors 31 and 35

6.2 Statistical Behaviour of Voltages

Summary statistics of the measured voltages were calculated for the periods before and after the voltage reduction, and are shown in Figure 26 and Figure 27. Precise values are tabulated in the appendix.

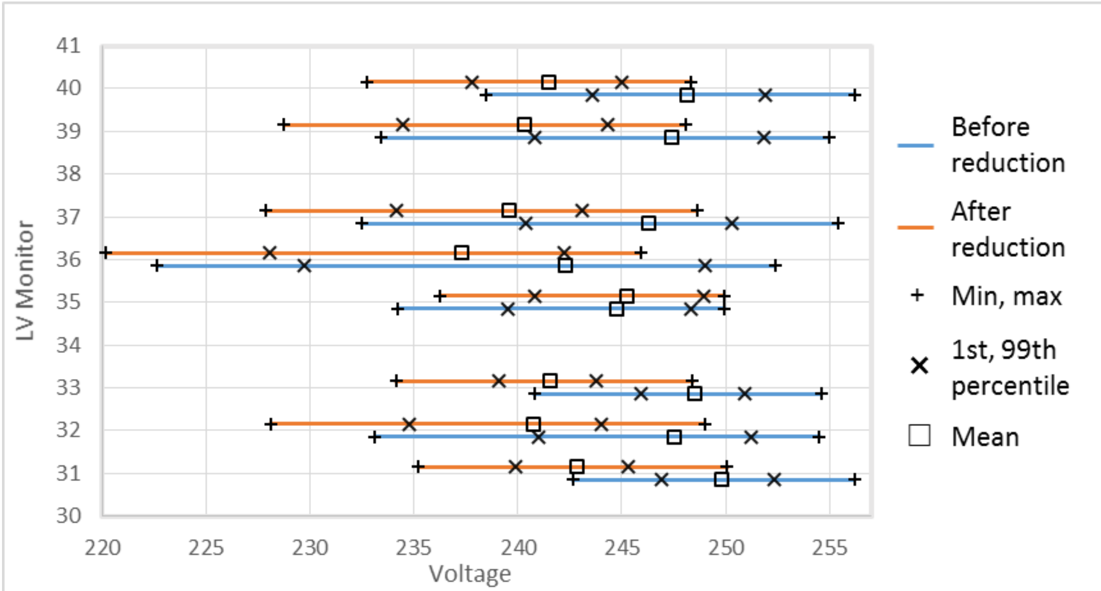


Figure 26: Statistical summary of LV monitor measurements

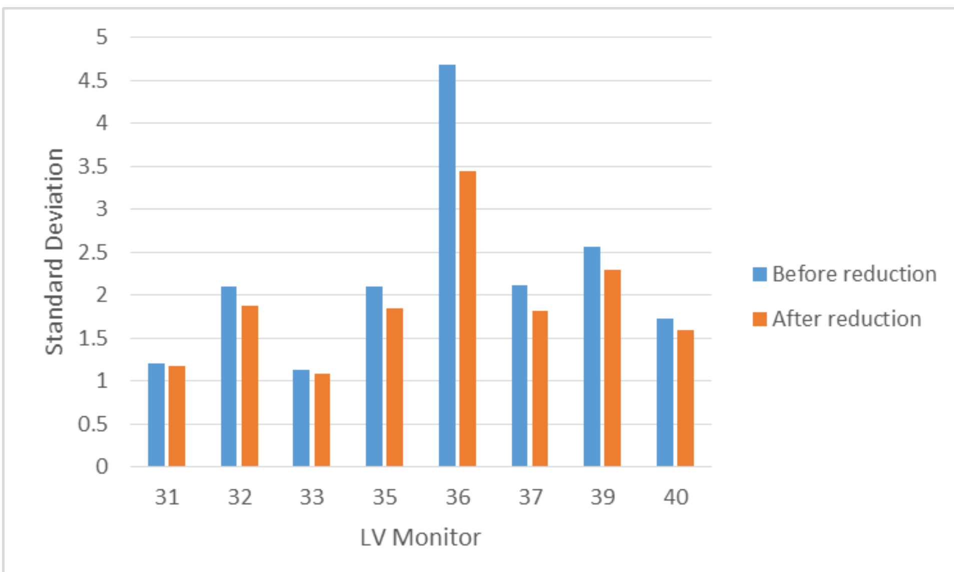


Figure 27: Standard deviation of LV monitor measurements

It is clear from Figure 26 that all LV monitors except monitor 35 experience a sustained and significant reduction in voltage. The reduction in mean voltage varies between 6.6 and 7.2V, which is slightly smaller than the observed instantaneous voltage reductions. The small upward movement in the mean voltage at monitor 35 between the two periods suggests that there may be an underlying rising trend in voltage as load reduces between from the early to mid-spring period before the reduction to the late spring and summer period afterwards.

The chart of standard deviations shows that the measured voltages are rather less variable after the voltage reduction than before it. Since this behaviour is also observed in monitor

35, it is likely that this results from the underlying voltage behaviour, and is not a result of the voltage reduction. Monitor 36 shows a much larger reduction in variability than others. Examination of Figure 26 shows that this monitor has the largest range between minimum and maximum voltage and also between 1st and 99th percentile. In addition, the minimum and 1st percentile voltages show a much smaller response to the voltage reduction than for other monitors.

From Table 4, it will be noted that this monitor has significantly fewer voltage measurements in the periods before and after the voltage reduction; furthermore, not data is available after 1 July. However, restricting the analysis of other Ruabon-area monitors to the period before that date showed little change in the standard deviation, or in the separation between the 1st percentile and mean voltages. It is therefore concluded that these characteristics of the voltage behaviour at monitor 36 are not likely to be an artefact of the lack of measurements after 1 July.

From the results presented, it is clear that, for the period of the voltage reduction, the measured voltages do not closely approach the statutory minimum, and 1st percentile voltages are generally above and at worst slightly below the nominal voltage.

6.3 Winter Peak Considerations

The LV monitor with the lowest mean, minimum and 1st percentile voltages is monitor 36. It is therefore considered that this monitor is most likely to experience below-statutory voltage conditions if the voltage reduction was maintained through the winter. Figure 26 shows that the minimum and 1st percentile voltages at this monitor are closer to the mean following the voltage reduction than before it. Two hypotheses can be suggested:

1. This reduction in spread is a consequence of the voltage reduction and would be repeated if the voltage were reduced at other times of year
2. The reduction in spread is a consequence of the load behaviour at the particular time of year, and the mean, 1st percentile and minimum voltage would retain their separation if the voltage was reduced at other times of year

To assess the effect of these hypotheses, additional data was used to calculate the voltage distribution at monitor 36 for the two-week period from 14 February 2015 to 1 March 2015. This period includes the lowest voltages measured by monitor 36 in the period for which data is available. Prior to 14 February, monitor 36 had only recorded voltages for four days during the Christmas holiday period.

To test the effects of the two hypotheses above, the calculated voltage distribution was modified in two ways:

1. The mean, 1st and 99th percentile, minimum and maximum voltages were adjusted by the same percentage change as shown in Figure 26.
2. The entire distribution was adjusted by the same percentage change observed in the mean voltage in Figure 26.

The results of this exercise are shown in Figure 28 below:

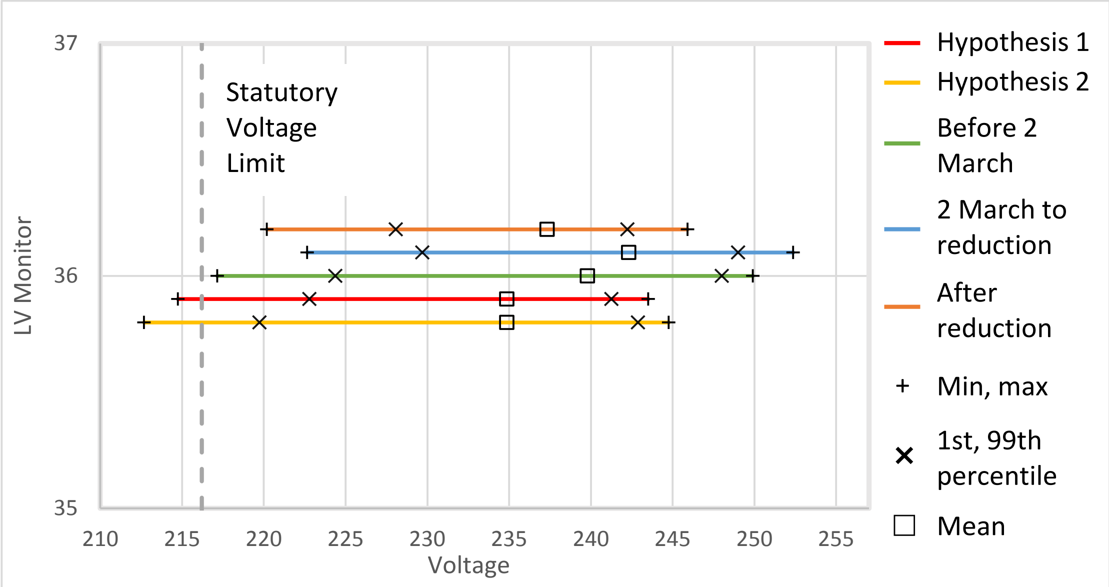


Figure 28: LV Monitor voltages under different voltage behaviour hypotheses

It can be seen that, at its lowest, the voltage at monitor 36 is already close to the statutory minimum voltage of 216.2V (230V – 6%): the minimum recorded value was 217.15V, and it seems likely that the voltage fell below the minimum during the unmonitored part of the winter. Regardless of which hypothesis is considered, it is expected that a 3% voltage reduction at the primary substation would place the minimum voltage at this monitor outside the statutory limits. Under hypothesis 1, the minimum voltage is 214.7V, while under hypothesis 2 it is 212.7V.

Given that lower, but unobserved voltages may have been experienced at this monitor location, it seems unlikely that any year-round reduction in primary substation voltage could be applied without placing this customer outside the statutory voltage limits. Additional voltage support could be provided to overcome this problem, either by LV rearrangement or reinforcement, by secondary transformer tapping, or by voltage optimisation at the customer's premises.

Alternatively, seasonal voltage reduction would be likely to provide much or all of the anticipated additional PV generation capacity since:

- PV output will be lower in winter.
- The higher winter load will absorb additional PV output in the LV and HV networks.
- The lower winter voltage will reduce or eliminate PV output constraints due to overvoltage.

7. Discussion and Conclusions

It is clear from the analysis of primary substation load that, in comparison to the previous year, a clear and consistent reduction in load took place following the voltage reduction. The magnitude of this load reduction was such that the current in the primary transformer was significantly reduced. The average reduction in active power was around 8.5%, while the average reduction in current was around 5.5%. The reduction in power is consistent throughout the day; at some times of day, the reduction in current is small.

It cannot, however, be conclusively shown that this load reduction was directly caused by the voltage reduction. However, year-on-year changes in weather conditions or PV output appear unlikely to be a principal cause. It is possible that coincidental but unrelated changes in specific loads at Ruabon or in the wider geographical area have occurred.

Considerable variability is observed in the extent to which load in individual HV feeders and secondary substations reduces. Some show very significant reductions, while in others the load is essentially constant. In some cases, the load increased from year-to-year despite (or perhaps because of) the voltage reduction. It is possible that this results at least in part from the nature of the load supplied from these feeders and substations.

It is difficult to generalise from this single experiment to the wider application of voltage reduction to primary substations in general. Depending on the nature of their loads, the demand reduction may vary significantly from the results observed here. This is, in effect, a consequence of a small sample size in terms of HV feeders, and in particular a single primary substation. Therefore, no change is made to the previous recommendation that a 'default assumption' should be made of a 1% active power reduction for each 1% voltage reduction. This experiment shows that larger reductions are possible, but not that they are likely.

Consideration of the voltages recorded by LV monitors at customers' premises show that statutory voltage limits at those premises may form a barrier to year-round application of voltage reduction. Given the small sample size, it is not possible to estimate the extent of this constraint – where the problems are few and localised, mitigation measures may be effective in resolving them, and would permit permanent voltage reduction via a simple change in policy rather than more complex seasonal approaches.

This experiment has shown that an extended voltage reduction trial, together with statistical analysis of the results, is effective is identifying load reductions which are not immediately obvious from inspection of time-series data. Although ENW's CLASS project has shown that high-frequency monitoring can detect sudden load changes consequent on voltage reduction directly from the time-series, longer-term reductions are more relevant to the capacity headroom improvements sought by Flexible Networks. Reliable monitoring at the primary substation is effective in characterising the effect of voltage reduction: it is considered that extensive secondary substation monitoring is of little extra benefit, except to the extent that there are voltage or load concerns at those substations. Targeted monitoring of voltage at customers' premises is, however, useful in determining whether infringement of statutory voltage limits may constrain the application of voltage reduction.

The experiment has also shown the importance of good experimental design and data management. The problems in determining the extent to which the observed load reduction is caused by the voltage change stem from the inability to identify a suitable control for the experiment. This is, in turn, partly caused by data collection problems at other substations a year before the experiment.

Nevertheless, given the relative simplicity and effectiveness of the experiment, it can be strongly recommended that it be repeated at other primary substations following the conclusion of the Flexible Networks project. However, careful planning in advance must be undertaken to ensure that suitable data is and will be available from existing sources such as PI and that appropriate additional monitoring is put in place and managed so that suitable comparison data is available for analysis.

Appendix: Selected Statistics

Primary Substation Statistics

Ruabon Primary												
2014												
Quantity	Before 21 May						After 21 May					
	Min	2%	Mean	98%	Max	Std Dev	Min	2%	Mean	98%	Max	Std Dev
V_A (V)	6162	6326	6382	6438	6567	28.2	6194	6325	6383	6438	6572	29.0
V_B (V)	6176	6325	6390	6448	6578	30.5	6205	6335	6398	6455	6594	31.0
V_C (V)	6172	6325	6392	6454	6594	31.4	6177	6325	6389	6449	6592	31.3
I_A (A)	75	93	174.3	286	340	50.5	69	81	151.8	223	262	41.0
I_B (A)	65	83	162.7	267	317	48.4	63	73	142.9	211	243	40.3
I_C (A)	76	96	172.6	281	335	48.0	71	83	151.8	222	258	39.9
P (MW)	1.378	1.730	3.243	5.315	6.324	0.936	1.305	1.508	2.835	4.178	4.839	0.770
Q (MVAr)	0	0	0.140	0.577	1.049	0.150	0	0	0.228	0.749	1.158	0.190
2015												
Quantity	Before 21 May						After 21 May					
	Min	2%	Mean	98%	Max	Std Dev	Min	2%	Mean	98%	Max	Std Dev
V_A (V)	6210	6328	6384	6441	6554	28.8	6036	6148	6205	6259	6374	27.5
V_B (V)	6214	6328	6393	6452	6576	31.1	6044	6151	6213	6267	6372	29.3
V_C (V)	6231	6334	6398	6461	6563	31.7	6055	6151	6216	6275	6396	30.4
I_A (A)	20	93	173.4	290	339	51.8	67	76	141.7	210	263	39.4
I_B (A)	22	85	164.4	275	321	50.1	62	70	133.8	200	249	38.2
I_C (A)	20	98	174.7	289	334	49.9	70	79	142.8	209	261	37.8
P (MW)	0.396	1.757	3.264	5.470	6343	0.968	0.931	1.388	2.588	3.827	4.783	0.715
Q (MVAr)	0	0	0.107	0.545	1.194	0.149	0.041	0.044	0.164	0.545	0.896	0.128

Ruabon Weather Statistics

Ruabon Weather Station												
2014												
Quantity	Before 21 May						After 21 May					
	Min	2%	Mean	98%	Max	Std Dev	Min	2%	Mean	98%	Max	Std Dev
Amb. Temp (ºC)	-2.54	0.76	8.55	16.83	22.32	3.69	5.43	8.45	14.22	20.26	25.48	3.22
Sol. Rad. (W/m^2)	0	0	234.9	763.9	1113.7	217.1	0	0	198.8	882.9	1160.8	251.9
2015												
Quantity	Before 21 May						After 21 May					
	Min	2%	Mean	98%	Max	Std Dev	Min	2%	Mean	98%	Max	Std Dev
Amb. Temp (ºC)	-2.26	0.76	7.45	15.18	18.06	3.56	2.41	5.98	13.46	21.63	26.44	3.85
Sol. Rad. (W/m^2)	0	0	268.9	836.7	1097.6	241.5	0	0	215.1	902.1	1245.5	264.2

LV Monitor Statistics

Monitor	Before Reduction						After Reduction					
	Min (V)	1% (V)	Mean (V)	99% (V)	Max (V)	Std Dev	Min (V)	1% (V)	Mean (V)	99% (V)	Max (V)	Std Dev
31	242.65	246..94	249.80	252.36	256.19	1.21	235.24	239.88	242.82	245.33	250.08	1.18
32	233.12	241.02	247.56	251.23	254.52	2.10	228.12	234.77	240.78	244.04	249.00	1.87
33	240.81	245.91	248.52	250.90	254.61	1.13	234.14	239.08	241.55	243.76	248.40	1.09
35	234.30	239.55	244.73	248.35	249.96	2.10	236.25	240.84	245.25	248.94	249.93	1.85
36	222.66	229.70	242.31	249.01	252.37	4.68	220.18	228.07	237.33	242.23	245.92	3.44
37	232.49	240.36	246.32	250.32	255.41	2.12	227.85	234.18	239.56	243.08	248.63	1.81
39	233.43	240.82	247.41	251.86	254.97	2.57	228.76	234.44	240.30	244.31	248.06	2.30
40	238.46	243.58	248.16	251.91	256.22	1.73	232.74	237.77	241.51	245.03	248.35	1.59