HV Conservation Voltage Reduction Impacts Study

Chung Poon
System Planning Engineer
chung.poon@northernpowergrid.com

Phil Jagger
Smart Grid Development Engineer
phil.jagger@northernpowergrid.com

ABSTRACT

This project investigates the range of impacts of the Conservation Voltage Reduction (CVR) Programme on the Northern Powergrid (Yorkshire) High voltage (HV) distribution network. The CVR Programme informed the adjustment of the voltage regulation settings from nominally 11.3kV to 11.1kV at 91 primary substations in the Yorkshire licence area. The impacts of the CVR Programme were quantified with the use of statistical test methods. The results highlighted changes in apparent and reactive power demand. If the CVR Programme was to be scaled across the full Yorkshire licence area, the reduction in the energy consumed would equate to an estimated savings of £50 million for the HV & LV customer group in the license area.

1 BACKGROUND

The UK statutory limits for the voltage supplied to LV customers are 230V +10%-6% (216.2V to 253.3V) which were harmonised with the EU voltage limits. In reality, the UK LV voltages still nominally centred towards the top of the voltage range. However, the voltage on the LV network is actively regulated at the EHV/HV primary transformers by the On-Load Tap-Changers. This voltage setting is towards the higher end of the limits to account for voltage drop along the cables to the customers. Below Primary Substation level, for example, secondary distribution voltage regulation is not automatically controlled. These distribution transformers are usually equipped with Off-circuit Tap-Changers which can only be adjusted with the associated HV and LV networks de-energised. Hence, the LV network largely relies on the voltage regulation upstream at the EHV/HV primary substation transformers.

The primary goal of the Conservation Voltage Reduction (CVR) Programme is to release more voltage headroom to accommodate the Distributed Generation (DG) expected to be accepted and connected in the short to medium term. DG under a certain capacity can be connected to the LV network without first consulting the Distribution Network Operator (DNO) under Engineering Recommendation (ER) G83. This capacity limit is 3.7kVA or 16A for single phase installations. The effect of connecting generation on the network is a rise in the voltage supplied to the near-by customers (1). This means that DNOs will have to plan for increasing penetration of DG across its LV network, well in advance of any notification from the customer.

However, aside from managing increasing DG on the LV network, the CVR Programme may also bring other benefits. One such benefit is a reduction in power demand by the customers and in turn losses. This can be explained as follows; resistive loads such as heaters, will draw less power from a lower voltage because the real power consumed is directly proportional to the square of the voltage. Another possible benefit is the flattening of the load profile and a reduction of maximum demand (MD); because resistive load will take longer to draw the same amount of energy at a lower voltage. Finally, less reactive power flow from the EHV network would be required to maintain the reduced voltage. This means that the distribution network only needs to supply a smaller current to provide the same amount of real power to the customers. Therefore, the DNOs can not only reduce the losses from the network and defer on network infrastructure reinforcement, but the overall stability of the system is increased as the possibility of a voltage collapse is reduced (2).

All the benefits were hypothesised based on the assumption that load centres have a high concentration of resistive loads. Furthermore, modern buck-converters, commonly found in power supplies and phone chargers, will increase their current drawn as the voltage is reduced. These devices will not produce the benefits foreseen. The actual make-up of the load type at any substations is unknown, and hence the benefits from the CVR Programme could range from zero to the square of the voltage reduction depending on the load type.

2 SCOPE

This project investigates the magnitude of these changes brought about from the CVR Programme by interrogating the SCADA data from selected EHV/HV primary substations. The attributes that will be investigated are: MD, units of apparent power demand, the load-loss factor (LLF) and the units of reactive power flowed through the transformers at the EHV/HV primary substations. The LLF is used to quantify the flatness of the load-profile. A LLF of 1 means that the load profile is constant, and 0 would mean that all demand is consumed instantaneously. A typical LLF at HV level found in GB distribution networks is 0.2-0.25.

The statistical analysis will be carried out in two ways: (a) by detecting whether there is a statistically significant change in the attributes for a sample of substations, where voltage reduction has taken place, between a similar three-months period a year apart, before and after the voltage reduction and (b) by comparing the attributes from the substations in (a) against a control set of substations where no adjustments to the voltage regulation has been made. The analysis from part (a) will reduce the effects of confounding factors, such as regional and seasonal trends, on the results and part (b) will establish the magnitude of the benefits realised by the CVR Programme. The periods studied are equally spread across all months of the year between the substations to ensure a representative coverage of all seasons. A study by Shaddick et al., in (3), has previously highlighted a cause-and-effect relationship between real and reactive demand from a reduction in voltage settings. This project aims to confirm and extend the findings to cover other attributes.

3 DATA

The data from 69 substations, of which 31 had their voltage regulation settings reduced and 38 were from the control set with no change, were interrogated in this project. Only 31 out of the 91 substations in the CVR Programme were studied as the date range of data availability was a major limiting factor, as the Northern Powergrid Plant Information (PI) data archive only stored data from 22 October 2014 to 12 August 2017, which totalled 1026 days. Half-hourly apparent and reactive SCADA data were extracted from these substations for this period.

A total of over 4.7 million data points were processed.

The selection of the substation sample was done randomly, and then filtered for suitability based on the data availability and whether engineering work had been taking place, which may affect the results. It was found that many of the substations in the CVR Programme had reduced their voltage regulation settings before April 2015. This cut-off date was chosen such that there was sufficient data to test the attributes in a before-and-after comparison. The selection process is illustrated in Figure 1.

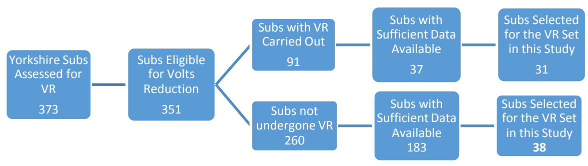

Figure 1-Flow chart of the CVR substation selection process

The resulting sample set is a mix of residential and commercial customers and is spread geographically across the Yorkshire license area. The date of the voltage change is provided by the responsible Control Engineer, and was independently verified by a second Engineer. The typical reduction in the voltage regulation is from 11.3kV to 11.1kV which is a reduction of 1.8%. A control set of substations were also selected from the list of substations that has not undergone the voltage settings reduction to establish a baseline of global trends, such as increasing penetration of DG and general reduction of consumer demand. The data sample dates used was replicated randomly from the voltage reduction data set.

4 METHOD

The analyses of the substation data attempts to establish a cause-and-effect relationship between the change in the voltage regulation settings and statistically significant changes in the attributes. The post-processing of the data extraction from the PI data archive includes: (a) a data smoothing routine, (b) selection of the relevant time periods and (c) calculation of the data attributes for these time periods, before the data attributes was suitable to be fed into the statistical models for comparison.

To address data quality issues from affecting the LLF results, a data smoothing routine was used to ensure that any data outages are estimated using standard forecasting techniques which examine the adjacent periods and the days before.

The time periods selected are based on the date of the reduction in voltage regulation settings. The two three-month periods centred on the six-months before and after the date of settings change are used for the analysis.

The calculation of the data attributes are purely based on the selected data without any external input. The MD is calculated as the 99.9th-percentile of the data, to eliminate the distortion of peaks in the data. The LLF is calculated as:

$$\text{LLF} = \sum_{n=1}^{m} \frac{D_n^2}{m \cdot \left(\max_{1 \le j \le m} (D_j) \right)^2}$$

, where: m is the number of data points in the data sample period and D_n is the apparent power demand at the n^{th} data point in the sample period.

The units of apparent and reactive power are derived from the demand data under the assumption that the demand is constant for each half-hourly period. The half-hourly data takes the maximum of that half-hour. Whilst this is a very conservative measure, it provides a good estimate to the units of VA and VAr flowing into the LV network. The maximum reactive power flow will also be studied.

In part (a) of the statistical analysis, a paired t-test is carried out for the data sets over each of these attributes. This will confirm any statistically significant changes in the attributes.

In part (b), a non-parametric t-test will be carried out against both data sets which have been standardised. This is so that the effects of the CVR Programme can be measured against baseline control set of substations. This will account for any potential external influence, such as long-term trends in the attributes.

5 Results

The first test comprised of comparing the data attributes for similar three-month periods a year apart, based upon the change in the voltage settings.

An example of the comparison made at a single substation that has undergone CVR is presented here, for a substation named Humber Road. The SCADA voltage measurements can be seen in Figure 2, which clearly shows the magnitude of the voltage reduction adjustment made in June 2015.

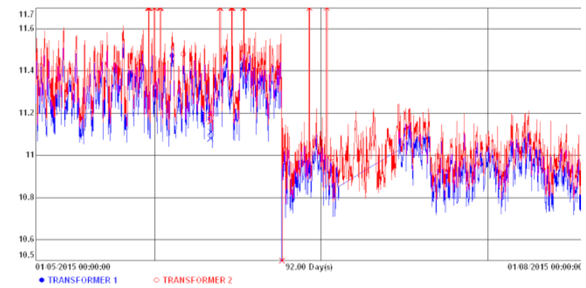

Figure 2-Voltage measurements at Humber Road substation

To make the comparison at this substation, the apparent and reactive power flow data recorded by the substation's transformers' SCADA system is extracted and then post-processed. As explained in the Method section, the data sample selection periods are three-months in duration and centred on six-months before and after the date of the voltage reduction. In this case, the comparison is done between the two data samples: (i) 1 December 2014 to 2 March 2015 and (ii) 1 December 2015 to 2 March 2016.

The apparent power demand data extracted can be seen in Figure 3. In the chart, the blue trend is the demand data for sample (i) pre-CVR, and the red trend is the demand data for sample (ii) post-CVR.

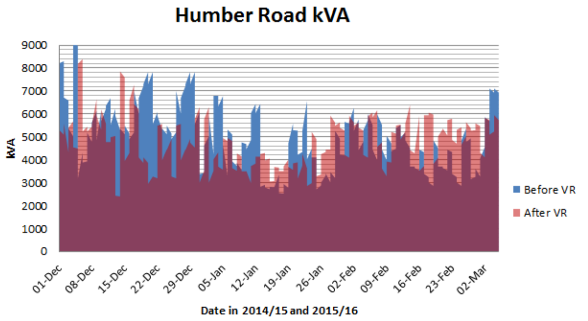

Figure 3 - Apparent power demand at Humber Road for the two sample periods

In the example of Humber Road, after CVR has occurred, it is can be seen from the chart that: (a) the maximum demand is lower, (b) the area under the curve which represents the total units of apparent power consumed is lower, and (c) the load profile appears to have more peaks and less consistent than the earlier sample. These trends are reflected in the data attributes calculated from the data samples which saw a 5% reduction in the MD, LLF and the units of apparent power consumed.

This verifies the integrity of the calculated attributes used to quantify the factors investigated in this project. The comparison seen at Humber Road is then repeated for all of the 31 substations in the Voltage Reduced (VR) set, as well as the 38 substations in the Control set.

5.1 Investigation Part A: Paired T-Test

The calculated attributes for each data set were input into two separate paired t-test, so that each data set was compared against itself, between the two sample periods. This test aims to establish whether there is a statistically significant change in the data attributes before and after CVR, and whether the same changes can be observed for the control set without a reduction in voltage settings.

The results from this statistical comparison are summarised in Table 1, which displays the average change in each data set for each attribute and the relevant statistical significance indicated by the *p*-value. The *p*-value is the probability of the set of variances observed by coincidence. An accepted *p*-value which connotes that the variance is deemed statistically significant is less than or equal to 0.05.

Table 1- Paired t-test results summary for all attributes for part (a) of the investigation and the mean change observed

Attribute \ Data Set	Voltage Reduced Set		Control Set	
	Avg. Change	***p***	**Avg. Change**	***p***
Max. Demand	- 4.4%	0.13	- 3.9%	0.02
LLF	- 7.5%	0.05	- 1.4%	0.27
VA Demand	- 7.2%	0.01	- 4.2%	0.11
Max VAr Flow	+76.1%	0.00	+95.6%	0.00
VAr Flow	-27.8%	0.09	+35.6%	0.00

The results show that there is sufficient evidence to indicate that both the units of apparent power consumed and the LLF decreased for the voltage reduction data set with statistical significance ($p \leq 0.05$). The average decrease is circa 7% for both data attributes. The decreased LLF connotes that the load profile is less uniform, and the decreased units of apparent power demand means that the LV customers are consuming less power as a result of the voltage reduction. These two trends were not seen in the control data set as $p > 0.05$.

On the contrary, there is also evidence to suggest that the peak reactive flow has increased substantially, regardless of the whether CVR has taken place, as this has been observed for both data sets. However, there was insufficient evidence from the selected sample of CVR data set to show that the maximum demand or the reactive power flow has changed due to the CVR Programme. More data, from a bigger sample size, is needed to confirm these trends which was seen in (3).

5.2 Investigation Part B: Non-Parametric T-Test

The goal of the second part of the investigation was to establish and quantify the impact of the CVR Programme on the different attributes over the baseline using the control set of substations that has not undergone CVR. This was carried out by taking the post-processed datasets (as used in part (a)), then standardising the data across the 69 substations using the z-score for each attribute, and finally input into a non-parametric heteroscedastic t-test. The CVR dataset was compared against the control dataset, unlike part (a). This form of the t-test was chosen as the variance was different between the datasets.

The result of the part (b) t-test is displayed in Table 2. A statistical significant change here (with $p \leq 0.05$) would represent that the relevant attribute has changed significantly post-CVR, more than the baseline change seen across the control dataset. The CVR average change displayed in the Table is real (*de-standardised*) change, based on from the average standardised variance seen in the CVR dataset less the baseline average standardised variance in the control dataset. This should be a more effective measure of the impact by the CVR Programme, as it considers the baseline changes due to regional or seasonal variance.

Table 2 - Non-parametric t-test results summary for part (b) of the investigation and mean change observed after normalisation for the global sample trend

	Voltage Reduced Set vs. Control Set	
Attribute	**VR Avg. Change**	**p-value**
Max. Demand	0.6%	0.20
LLF	-7.2%	0.06
VA Demand	-2.8%	0.04
Max VAr Flow	-19.3%	0.04
VAr Flow	-65.2%	0.00

Similar to the findings from part (a) of the investigation, there is evidence to show that the CVR Programme has reduced the apparent power demand by 2.8%, compared to the control baseline. Furthermore, the evidence has also shown that the CVR Programme is also responsible for reducing both the total units of reactive power flow and the peak reactive power flow by 65.2% and 19.3% respectively, compared to the control dataset.

It is also very likely that the LLF has decreased by circa. 7%, but this cannot be confirmed without a larger dataset as $p = 0.06 > 0.05$. However, there is insufficient evidence again to support claims that the CVR Programme has been effective in reducing the MD. The data could even be suggesting that the MD has increased slightly compared to the control counterparts. Either way, more data is needed to confirm whether there exists a change in MD due to the CVR Programme.

6 Conclusion

The analysis has shown that CVR Programme has the potential to provide significant benefit to both the DNO and the customers, in terms of reduced network reinforcement costs and savings from reduced energy consumption. More specifically, there would be an average reduction of 2.8% in energy demand, as a result of the 1.8% reduction in voltage delivered by the CVR Programme.

If the CVR Programme was to be scaled across the full Yorkshire licence area, the reduction in the energy consumed would equate to an estimated savings of £50 million for the LV customer group in the license area. This is based on the LV customer demand of 13.3 TWh in the Yorkshire license area (4) and based on the average tariff of 14.37p per kWh (5).

The quoted amount of savings may not be fully realisable due to operational restrictions and under-voltage issues which may prevent some substations in being included in the CVR Programme. There was insufficient evidence in this project to support the load profile flattening previously hypothesised. There was also not enough evidence to show a reduction in MD as seen in WPD's study.

Notwithstanding, there is still a very strong case to expand the CVR Programme across the license areas, to not only take advantage of the benefits seen in this investigation, but also for Northern Powergrid to support the development of a low-carbon economy in the long term.

7 References

1. *Analysis of Voltage Rise Effect on Distribution Network with Distributed Generation.* **Pota, M.A. Mahmud and M.J. Hossain and H.R.** s.l. : IFAC Proceedings Volumes, 2011, 18th IFAC World Congress, Vol. 44, pp. 14796 - 14801. 1474-6670.

2. *Concepts of Reactive Power Control and Voltage Stability.* **Akwukwaegbu I. O, Okwe Gerald Ibe.** 2, NIGERIA : Department of Electrical/Electronic Engineering Federal University of Technology Owerri Imo State, 2013, IOSR-JCE, Vol. 11. 2278-0661.

3. *THE IMPACTS OF A REDUCTION IN 11KV VOLTAGE SETTINGS IN SOUTH WALES.* **Gavin SHADDICK, Amelia GREEN, Matthew WATSON.** Glasgow : 24th International Conference on Electricity Distribution, 2017.

4. **Northern Powergrid (Yorkshire).** Northern Powergrid (Yorkshire) - 2017-18 CDCM Model. *Northern Powergrid.* [Online] 1 April 2017. [Cited: 11 August 2017.] https://www.northernpowergrid.com/asset/0/document/2110.xlsx.

5. **Energy Saving Trust.** Calculations. *Energy Saving Trust.* [Online] September 2016. [Cited: 14 August 2017.] http://www.energysavingtrust.org.uk/about-us/our-calculations.