SP ENERGY NETWORKS

Flexible Networks for a Low Carbon Future

Technical Note on Modelling of Load

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Executive Summary

The "Flexible Networks for a Low Carbon Future" Tier 2 LCNF project aims to increase available distribution network capacity headroom through a number of innovative interventions, including the optimisation of network voltage to reduce network demand, whilst also creating additional headroom for the connection of embedded generation. This technical note concentrates on the load modelling aspects of the project. To gauge the likely effectiveness of this intervention, we have reviewed methods of modelling load, and investigated practical UK and international experience of the response of load to controlled changes in network voltage.

Historically, it was assumed in the UK that a 3% reduction in voltage would reduce demand for electricity by 5%. Recent observations of the behaviour of load in response to changes in network voltage, and knowledge of the changing mixture of loads (for example, the growth in low-energy lighting) have led this assumption to be challenged. Model-based and experimental studies have been conducted in the UK and internationally in order to investigate load behaviour.

Demand is often modelled in detail using one of two models – the "ZIP" model divides the load into three parts which behave in different (but fixed) ways in response to a change in voltage, while the "exponential" model attempts to fit a single exponential equation to the behaviour. Various authors have used these approaches to construct "bottom-up" models of aggregated demand, but it is not clear how well these correspond to actual distribution network behaviour

We have also reviewed a number of experiments which have been conducted in the UK and internationally to evaluate the response of electricity demand at a substation to a deliberate change in network voltage. Two of these experiments affected sections of network which we are monitoring as part of the Flexible Networks project and have therefore been analysed in more detail. These results provide useful knowledge about the behaviour of load, which is summarised in the learning points below.

Learning Points

As a result of this review, we have identified a number of key learning points:

- A reduction in voltage will generally result in a reduction in active power demand.
- This reduction will be larger over the short term than in the long term
- The reduction achieved will depend on the types of load present, and therefore:
    - can vary between different parts of the distribution network
    - can vary between different seasons, and different times of day
    - can vary according to the ambient temperature

- In the absence of local knowledge of experimental results, a reduction of 1% in active power demand in response to a 1% voltage reduction is a reasonable estimate
- Reactive power demand will generally be reduced by a larger factor than active power demand

This report contributes to work package 1.4, forms part of Strathclyde deliverable DU1.4.1 and fulfils actions 25 and 26.

Recommendation

On the basis of these learning points, it is recommended that SPEN should model network loads on a constant current basis, except where knowledge of particular load behaviour dictates otherwise. In IPSA model, this can be achieved through use of the ZIP load model, configured to act as a constant current load.

TNEI may wish to consider enhancing IPSA to make more advanced load features, such as load profiles and reliability available for the ZIP load model.

1 Introduction

The modelling of distribution system load (whether at secondary substation level, primary substation level or GSP level, etc) is important to assessing both the adequacy of network capacity and the response of load to interventions (such as voltage management) intended to influence its behaviour. Additionally, load modelling can be applied to the prediction of the transient and dynamic behaviour of the power system, although models directed towards that application are not considered here. Historically, assumptions had been made on the expected response of demand to a voltage reduction. Observed changes in behaviour, and an awareness of changes in the nature of load (for example, the replacement of incandescent lighting) has led these assumptions to be questioned, and experiments to be undertaken to better understand this behaviour.

This report reviews published work on the characterisation of load, considering both the composition of aggregated loads, and their response to changes in voltage. Some recent experiments on load behaviour in the UK power system and internationally are also discussed.

2 Aggregated Load Models

Fundamentally, the load on the distribution system is made up of a very large number of individual devices associated with industrial, commercial, domestic premises, etc. Each of these devices will exhibit a particular temporal pattern in its demand for real and reactive power, and that demand will change in response to changes in supply characteristic (voltage being of particular interest) in a way which is dependent on the nature of the device. Broadly speaking, three classes of response can be outlined:

- Constant impedance – in which current falls in proportion to reducing voltage (and thus power reduces rapidly)
- Constant current – in which current is independent of supply voltage, and thus power is reduced in proportion to the reduction in voltage
- Constant power – in which power is independent of supply voltage, and thus current increases as the voltage reduces. This relationship between voltage and current is sometimes referred to as “negative impedance”. It should be noted that consumed power may actually increase as a result of greater losses resulting from the increased current.

A load model combining these characteristics is often referred to as a “ZIP model” in reference to the conventional symbols for the three constant quantities:

$$P = P_0 \left[Z_P \left(\frac{V}{V_0} \right)^2 + I_P \left(\frac{V}{V_0} \right) + P_P \right]$$

where V_0 and V are the nominal and actual voltage, P_0 is the active power at nominal voltage, and Z_P, I_P and P_P are the proportions of the load which behave respectively as constant impedance, constant current and constant voltage, and sum to 1.

Alternatively, an exponential load model may be used:

$$P = P_0 \left(\frac{V}{V_o} \right)^n$$

where *n* (which is usually not an integer) is a constant describing the load's behaviour, and other symbols have the same meaning as in the ZIP model.

Various authors (for example [1,2,3,4]) have constructed feeder and substation-level models by aggregating load models for individual appliances to represent households of different types, and then aggregating these households to represent feeders and substations. It is unclear, however, how well these aggregates represent the actual behaviour of sections of UK distribution networks.

An alternative, empirical approach is based on evaluating the response of power system load, measured in bulk at a substation or feeder end to a deliberate short-term or long term reduction in voltage. A useful metric – the percentage reduction in load for each 1% voltage reduction – can then be derived. A number of such experiments have been carried out in the UK and internationally, and are discussed in the following sections.

3 Historical Work in the UK

In the mid-1980s, the CEGB reported on a series of experiments at 30 transmission substations in order to evaluate the relationship between voltage and real and reactive power demand [5]. A total of 55 experiments were considered, conducted in four geographical areas over a period of approximately five years. The reported work aims to use these experiments to validate a model of voltage to load relationship, and to derive typical parameters for the model.

The modelling approach adopted attempts to divide the total real and reactive power demand between static load, motor load and (for reactive power only) iron saturation load. Rules of thumb are provided for the proportions of these in loads of different types (domestic, commercial, light/heavy industrial). A polynomial expression is then used to represent the real and reactive power response of the load types to voltage change using the typical parameters previously derived.

Graphs showing these results are also presented. To summarise the results, it appears that for real power, a generally linear response can be expected for modest voltage reductions, with domestic load being most responsive at approximately 1.8% power reduction for a 1% voltage reduction, while heavy industrial load is least responsive at roughly 0.6%. For reactive power, the picture is more complex, since the response is much less linear, and also depends on power factor, with high power factor domestic loads being most responsive, and low power factor industrial loads least responsive.

4 Work Led by National Grid

Historically, it had been assumed that a 3% reduction in voltage would result in a 5% demand reduction, and that two such reductions could be applied to give a total of 10%. These assumptions began to be called into question in 2006/2007, with the result that tests were conducted with two DNOs in summer and autumn of 2008 involving the instruction of a 3% voltage reduction at 9 sites, primarily serving domestic, industrial or commercial customers (referred to as the Phoenix Exercise). Achieved voltage reductions varied between 2% and

4.3%, while observed load reductions ranged from 2.6% to 5.1% (see Figure 1). The average reduction obtained was 3.4%.

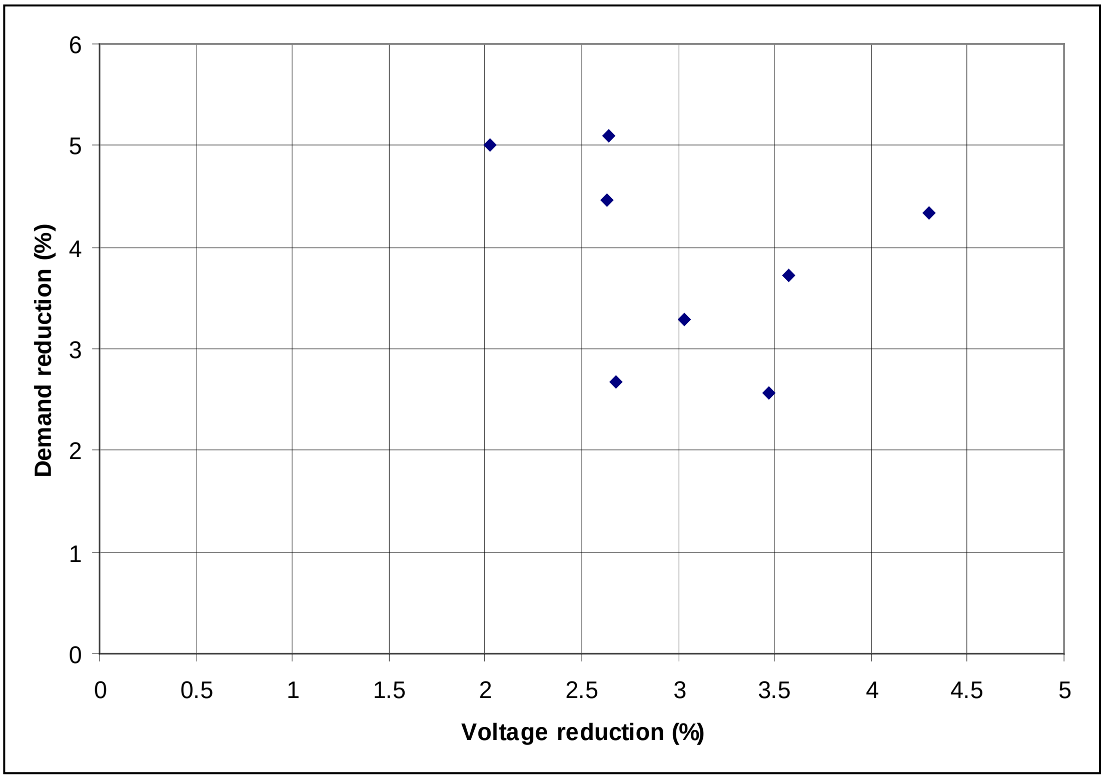

Figure 1: Exercise Phoenix voltage reduction results

As a result of this test, a report [6] was presented to the Grid Control Review Panel noting (*inter alia*[1]) that a 3% voltage reduction might more realistically be expected to result in a 3% reduction in demand (i.e. 1% demand for 1% voltage).

A further series of tests, referred to as *Operation Juniper*, were conducted in autumn 2013, in which 13 DNOs implemented 3% voltage reductions for 50 minutes each on separate dates. Results according to (anonymised) DNO are presented in [7], and show that achieved demand reduction ranged from –1.2% (i.e. demand increased) to 2.0%, with an average of 1.1% after 5 minutes; and from 0% to 2.7%, with an average of 1.5% after 10 minutes. Over the 10 minutes after the end of the test, demand recovered by between –1.0% (i.e. demand reduced) and 2.5%, with an average of 1.2%. Although a 3% voltage reduction was instructed, the *actual* range of voltage reduction achieved is not documented.

4.1 Operation Juniper: Scottish Power Activity

On separate dates in October 2013, stage 1 (3%) voltage reductions were applied in the SP Manweb (SPM) and SP Distribution (SPD) areas as part of Operation Juniper [8].

In both cases, the voltage reduction was held for approximately 50 minutes, following which the normal voltage target was restored. Voltage reduction was applied initially at Grid substations and then (following a short delay) at primary substations. The voltage reduction

[1] A more serious concern was the actual implementation time of the demand reduction.

was not applied at certain substations, either because of customer considerations, or because of lack of VR capability at the substation.

The SP Energy Networks report on the exercise [8] shows SPD-wide and SPM-wide active power demand, plotted at 1-minute intervals for the period of the test, and the corresponding period of the previous day. For SPD, an initial active power reduction of 2.6% is reported for a 3% instructed voltage reduction (this appears to be measured from a peak coincident with the application of the voltage reduction), with an average reduction over the course of the test of 0.7% of demand. For SPM, the initial active power reduction is reported as 2.1%, with about half this reduction being sustained beyond the initial load reduction. For SPD, the demand reduction reported by National Grid was similar to the average reduction observed by SP; for SPM it was somewhat less: the reasons for this difference are unclear. It should be noted that the results presented do not consider the response of reactive power, which, as discussed earlier, might be expected to be larger. Although the actual voltage reduction achieved is not reported, these results suggest that a 1% voltage reduction might be expected to give an active power demand reduction of slightly under 1%.

The response of the substations in the test areas to the Juniper voltage reduction was investigated. The substation monitor at Ruabon primary was not operational at the time of the SPM test. Clear voltage reductions were observed at all remaining substations except for two. At Leuchars, there was a clear voltage increase of about 1% for the duration of the test (see Figure 2). At Whitchurch, the start and end of the test are marked by brief voltage excursions in the opposite sense to that expected (see Figure 3; effect confirmed from secondary substation measurements), but the voltage is otherwise unchanged during the test. The recorded voltage at St Andrews shows evidence of tapchanger operation during and after the test, and the achieved level of voltage reduction was generally less than that at other substations.

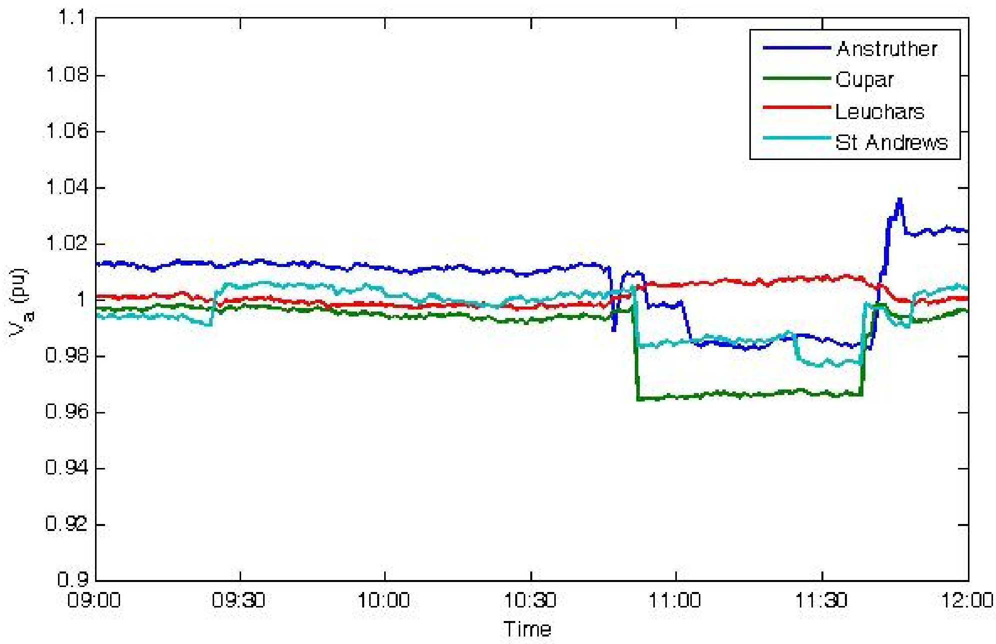

Figure 2: Juniper voltage reduction in SPD Flexible networks test area

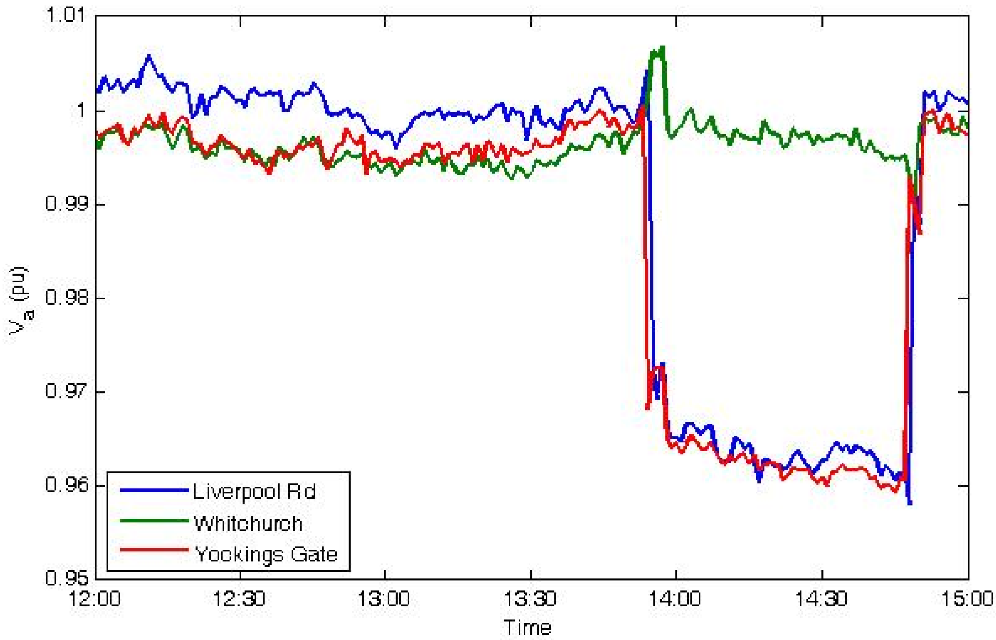

Figure 3: Juniper voltage reduction in SPM Flexible Networks test area

Real and reactive power measurements for the primary substations concerned were investigated, with particular focus on those for which a clear, sustained voltage reduction was achieved. Figure 4, for example shows the A-phase current, real power flow, reactive power flow and power factor for transformer 1 at Cupar, together with the A-phase voltage for reference. Figure 5 shows the same quantities for Liverpool Road. In both cases, I, P and Q are normalised to their maximum value on the day of the test.

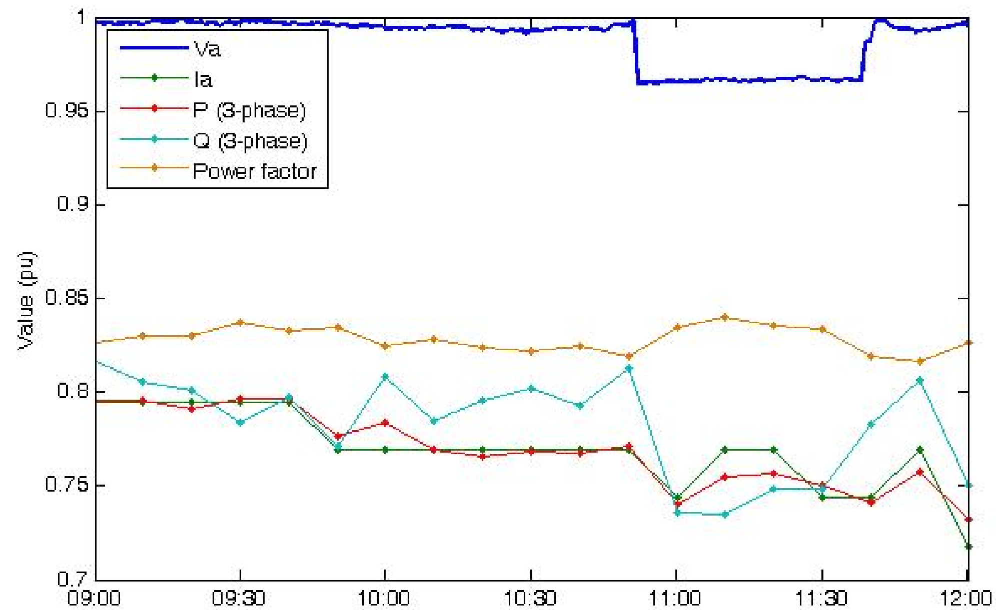

Figure 4: Load at Cupar during Juniper voltage reduction

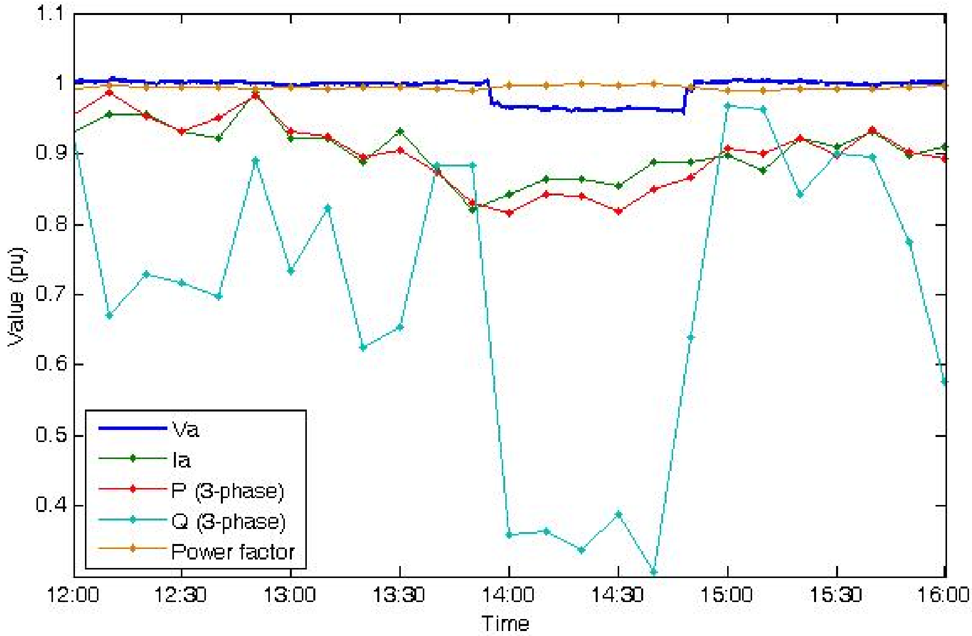

Figure 5: Load at Liverpool Road during Juniper voltage reduction

Some difficulties arise in relation to the 10-minute sampling interval of the current and power: current measurements are instantaneous, whereas power measurements are averaged over the preceding 10-minutes. The power measurements immediately after the application and removal of the voltage reduction are therefore a mixture of 'reduced voltage' and 'normal voltage' load, dependent on the point in the sampling period at which the reduction was applied. Nevertheless, it is clear that there is a response to the voltage reduction.

The most significant response is, as expected from the earlier CEGB work, in the reactive power which reduces markedly in both cases shown. At Cupar, real power also shows a definite immediate reduction, followed by a partial recovery. At Liverpool Road, real power shows what might be a small reduction, followed by a recovery to a slightly higher level than before the voltage reduction. In both cases, there is an increase in real and reactive power on removal of the voltage reduction.

The following table summarises the effect for the substations at which a sustained voltage reduction was observed:

Substation	Voltage reduction (%)	Real power			Reactive power		
		Immediate reduction (%)	Sustained reduction (%)	Recovery (%)	Immediate reduction (%)	Sustained reduction (%)	Recovery (%)
Anstruther	2.5	21	19	0	57	53	11
Cupar	3	4	1.5	2	9.5	7.5	3
St Andrews[2]	2/1	2/4	2	0	6.5/8	4.5	4.5
Liverpool Road	4	1.5	–1.5	2	58	54	69
Yockings Gate	3.5	2	0	1.8	20	7.5	12.5

Table 1: Response of primary substation loads to application and removal of voltage reduction

It seems likely, given the disparity between reduction and recovery observed at Anstruther that there is a change in the characteristics of the load at the time of the test, either coincidentally, or in response to the reduction in voltage. The actual response of the load is probably significantly less that that shown. Local knowledge on this point would be valuable in interpreting the results, and in the design of any future experiments.

It should be recognised that the magnitude of the real power reductions and increases shown is, in some cases, similar in magnitude to the apparent variability of the real power. Furthermore, it is possible that at least part of the reduction observed is a consequence of a general downward trend in the load at the time of the experiment – as might be suggested by the lack of real power increase in response to the increase in voltage in some cases. There is no ‘control group’ of substations at which the load unmodified by voltage reduction is observed. Finally, it must be borne in mind that the results shown relate to a single test at each substation, and are thus dependent on the particular combination of loads being supplied at that time. Nevertheless, the fact that load reductions are observed in all cases suggests that a genuine relationship between load and voltage exists.

5 LV Network Templates

Although the main focus of the WPD LV Network Templates LCNF Tier 2 project was the development of models characterising the behaviour over time of aggregated LV loads, it resulted in the gathering of a significant volume of voltage data from the LV network. As a result, WPD found that there was voltage “footroom”, in that the vast majority of voltage measurements were within required limits, and most out-of-limit values were overvoltages [9]. As a result, WPD calculated that a 0.1kV reduction in voltage at the 11kV primary busbars, would be expected to result in a reduction in peak demand of 15.7MW across their South Wales distribution network. It should be noted that this calculation is based on an

[2] At St Andrews, there is a voltage reduction of approximately 2% at the beginning of the test, followed by a further reduction of 1% shortly before the end. The two figures shown for immediate reduction refer to these two reductions. There is insufficient time between the second reduction and the removal of the reduction to determine a sustained response.

assumption of 1% reduction in demand for a 1% voltage reduction (from the National Grid work mentioned above) rather than any independent experiments.

6 Ruabon Experiment

In January 2014, an experiment was undertaken at Ruabon primary substation as part of a wider WPD-led piece of work to determine the effects of a reduction in the lower bound of the statutory +10% / –6% voltage limits. At Ruabon, a 3% voltage reduction was applied on the morning of 9th January, and was held until the afternoon of 30th January. The voltage reduction was removed in response to a customer complaint of low voltage (although upon investigation voltage at the customer's premises was found to be within statutory limits).

Voltage, current and power measurements were retrieved from Ruabon primary substation and for monitored secondary substations in the area, which are located along three 11kV feeders fed from Ruabon primary. Measurements were retrieved for the period 1 December 2013 to 28 February 2014, to allow comparison of load before, during and after the period of the experiment. The days of application and removal of the voltage reduction were inspected in detail, and average weekday load current profiles were compared across three comparable periods in December, January and February.

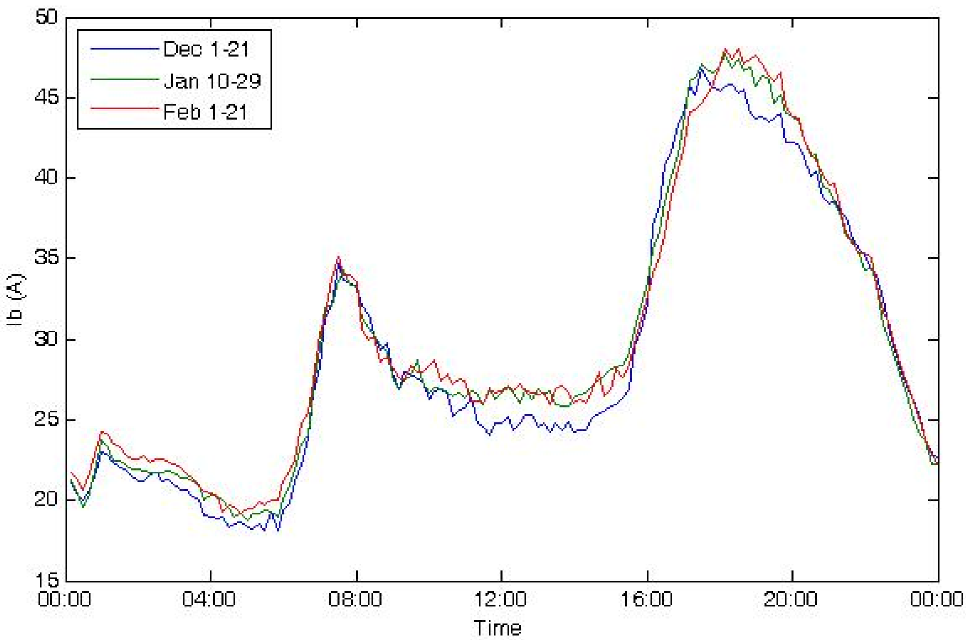

Figure 6: Average weekday B-phase current at Ruabon primary for three-week periods

Figure 6 shows the average weekday current profiles for three three-week periods in December, January and February. The period used to calculate the January profile corresponds to the period of voltage reduction. It can be seen that there is no clear difference between the January profile and the February profile. Similar plots were constructed for the three Whitchurch-area primary substations to investigate whether any variations could be detected which might reflect a deviation at Ruabon from a regional pattern (for example, if January were colder than February, then the similar pattern shown in Figure 6 might reflect an effective reduction in January load). Although some suggestions of this were found, there was little consistency between the three substations at Whitchurch.

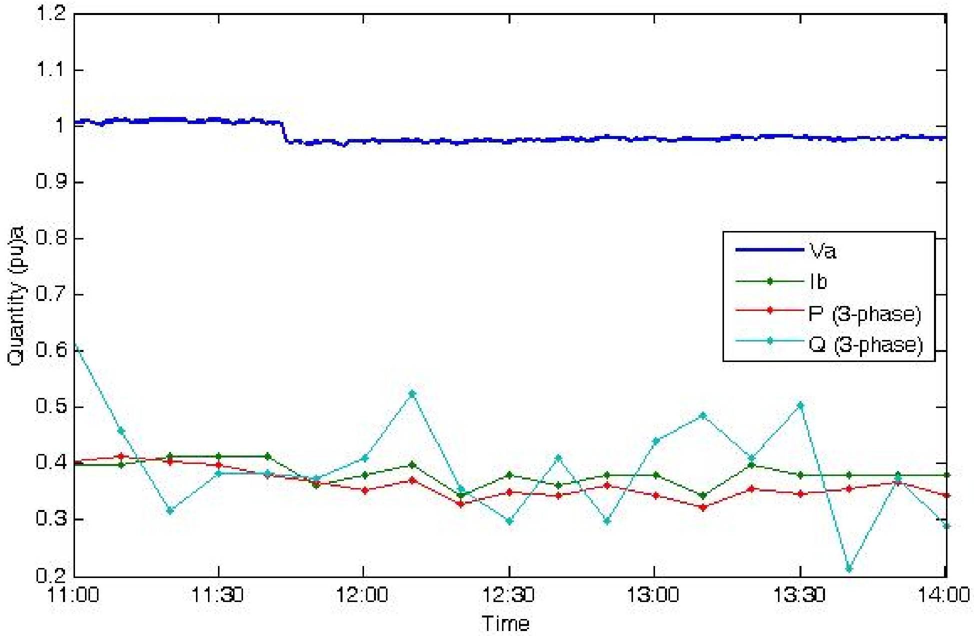

Figure 7: Ruabon load at application of voltage reduction

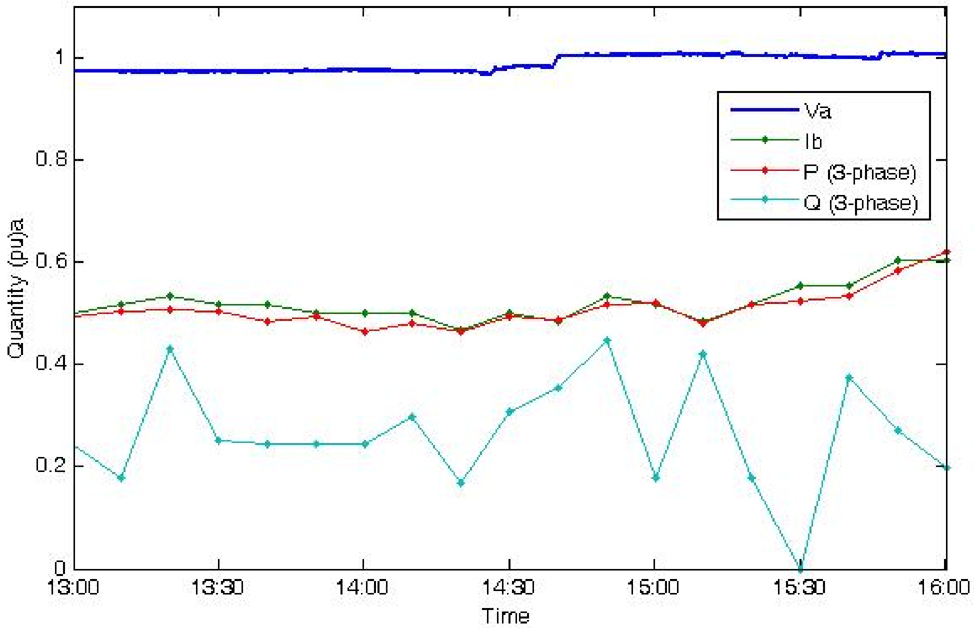

Figure 8: Ruabon load at removal of voltage reduction

Figure 7 and Figure 8 show the real and reactive power flow in the transformer at Ruabon primary substation at, respectively, application and removal of the voltage reduction. The recorded voltage is also shown to provide a reference to the point of application or removal of the voltage reduction. Instantaneous current, and 10-minute average active and reactive power are normalised to their highest value over the three-month period considered (it should be noted that Ruabon power factor was always above 0.98, and generally above 0.995 for this period).

From the two graphs, it does appear that there is a change in active power and current at the point of the voltage step. Upon voltage reduction, the 10-minute average active power measurement is in a generally falling trend of about 3% every 10 minutes, which appears unaltered by the voltage reduction. The instantaneous current measurement however shows a sharp drop of about 12.5% between measurements, around two thirds of which is recovered over the following twenty minutes. It is possible that the response of the active power is being masked to a degree by the averaging process.

At the end of the experiment, the voltage increase occurs in two steps: the increase in active power at the first is approximately 6%, and 5% at the second. Current follows a similar pattern, with a slightly larger initial increase as a result of the increase in reactive power which occurs at the same time.

These results suggest that there may be some change in load associated with the change in voltage at Ruabon. It is however difficult to quantify the magnitude of the reduction on the basis of the measurements available.

7 CLASS

Electricity North West is currently conducting the Tier 2 LCNF-funded Customer Load Active System Services (CLASS) project. CLASS seeks to demonstrate the ability to manage system voltages for the purpose of demand reduction at the time of system peak, mitigation of overvoltage risk at time of peak embedded generation and minimum load, and the provision of system balancing services [10].

Although no results from the CLASS trials have been published to date, some model-based analysis of the behaviour of load connected to an ENW primary substation has been published by academics associated with the project [2]. This work used data on the typical characteristic of different residential appliances, together with a UK National Statistics on household composition and a high resolution domestic energy demand model to construct per-household aggregate ZIP models of the of the residential load supplied from the substation; industrial and commercial load (which, except at the evening peak, is larger then the residential load) was assumed to be fixed. These models were then used to predict the response of the load to changes in primary substation voltage.

The analysis presented in the paper shows that the response of the overall substation load to a 5% voltage reduction varies between 0.17% and 3.24% depending on the time of day, with an average of 1.75% (or 0.03%, 0.65% and 0.35% per 1% voltage reduction). Since these values neglect any response in the significant industrial and commercial load, the authors also give results for the residential load in isolation, which correspond to a minimum load reduction of 0.39% per 1% voltage reduction, with a maximum of 1.13% and a daily average of 0.93%.

8 Other Recent Work

In addition to the UK-based work discussed above, similar experiments have been carried out in countries, particularly in North America. Some of these are briefly reviewed here. In general, because of the changing nature of load over time, only more recent studies are discussed. In addition, it must be borne in mind that the composition of load may vary between studies, and from UK conditions – for example, in warmer climates, air conditioning load may be much more prevalent.

8.1 Distribution Efficiency Initiative

In 2007, the Northwest Energy Efficiency Alliance (NEEA) reported on the results of its three-year Distribution Efficiency Initiative (DEI) project [11] undertaken in the north-western United States. This project studied the response of demand to two classes of voltage reduction intervention: voltage reduction through the installation of devices in individual dwellings (the "Load Research Project"); and voltage reduction at the substation (the "Pilot Demonstration Project") – the substations considered were broadly equivalent to UK primary substations.

The Load Research Project involved the installation of voltage regulators in 413 homes, of which 395 were included in the analysis of one year of data. On alternate days, these devices controlled (in almost all cases reduced) the voltage to a constant value of 115.5V. On other days, the voltage was left unchanged. An average voltage reduction of 4.3% was achieved. A reasonably wide range of change in energy consumption was found, with 19% achieving an average reduction in demand over the year of more than 1% for a 1% voltage reduction, while in 17% of cases, the average demand increased in response to the voltage reduction. There was also considerable variability across the 11 participating utilities. Overall, the reduction was estimated to be 0.57±0.06% per 1% voltage reduction. The study found that voltage reduction was most effective in homes with non-electric space or water heating. Similarly it was found to be most effective during the summer months. Overall estimated reduction in reactive power demand was estimated at 2.9±0.1% per 1% voltage reduction.

The Pilot Demonstration Project considered nine substation-based voltage reduction schemes spread across seven substations operated by six utilities. Of these, voltage control at one was effected by per-feeder in-line voltage regulators; at the remainder, transformer tapchangers were used with or without remote voltage measurements. In some cases, improvements such as phase balancing and installation of reactive compensation were also made. Data was collected over an aggregate period of almost three years, although only one scheme was in operation throughout this period, and not all were in operation simultaneously.

An average voltage reduction of 2.3% was achieved at the substation, and across the nine schemes average demand reduction varied between 0.3% and 0.86% per 1% voltage reduction. More variation was observed on individual feeders, which in a few cases exhibited a small increase in average demand of up to 0.1% – in these cases the achieved voltage reduction was generally less than 1%. In most cases, voltage reduction was least effective in reducing demand in the winter months, but was found to be most effective during the night. As for the Load Research Project, this suggests that electric heating reduces the effectiveness of voltage reduction. Reduction of the one-hour peak hour demand was found to be greater than the overall average, ranging between 0.55% and 1.1% per 1% voltage reduction.

8.2 Hydro Quebec

In 2008, Hydro Quebec[12] reported on the results of a voltage reduction study undertaken at a 6-feeder 26.4kV substation, feeding mainly residential load with a small amount of commercial load also present. The substation was operated on alternate days at normal and reduced voltage. Consideration of the achieved long-term power reduction showed a wide variation of results, from approximately 0.3% power reduction per 1% voltage reduction to around 0.95% for the 50 days presented graphically in the paper.

Further analysis, however, showed a strong relationship between the degree of load reduction achieved and the ambient temperature. At low temperatures (<–10ºC), the load reduction per 1% voltage reduction was very small, close to 0.1%. At high temperatures, however, the response was very much better, with 0.9% load reduction being achieved at temperatures above 20ºC. This indicates the important effect of thermostatically controlled heating load, whose long-term response is poor, since, under given ambient conditions the same amount of energy is required to maintain the required temperature.

8.3 PCS UtiliData

Wilson [13] summarises a total of 10 CVR schemes supplied by PCS UtiliData to North American utilities, one of which is represented in the NEEA study above. These schemes include both single and multiple substation applications, and serve a variety of loads ranging from small town residential/commercial to large industrial loads. In all cases, the scheme's commissioning was followed by a 3- or 12-month test period, in which CVR was applied on alternate days.

Results from only two of these schemes (and only for certain feeders) are presented in detail the paper, and appear to suggest rather larger reductions in active power demand than in other studies, with reductions of between 1.9% and 2.4% for a 1% voltage reduction. Reductions in reactive power were between 2 and 3.6 times the active power reduction. It is possible, given the small quantity of data presented, that these are the most favourable results from the set of schemes described.

8.4 BC Hydro

In 2010, BC Hydro [14] reported on its experiences of managing substation voltages for, *inter alia*, demand regulation. At that point, their approach had been deployed at three substations, with a primary objective of reduction in energy demand. It was found that energy reduction (i.e. long-term average active power reduction) of about 0.7% per 1% voltage reduction was achieved, which is consistent with earlier test results published by BC Hydro in 1995 [15]. A secondary objective is the reduction of peak load through short-term response to voltage reduction, although the 2010 paper does not provide a numerical measure of the effectiveness of this response. The 1995 paper, however, reports a short term reduction in active power of between 1% and 1.5% per 1% voltage reduction.

8.5 EPRI

Sunderman [16] reported briefly in 2012 on an analysis by EPRI of the results produced by a commercial CVR system installed by an unnamed utility on the feeders of a rural 13.2kV substation. The network used voltage regulators connected to each feeder at the substation to control the line-end voltage, with a reduction of 3.7% applied when CVR was in effect. Measurements were obtained over a calendar year from March 2010 to March 2011. Over part of this period, CVR was in effect on alternate days.

EPRI estimated that the average reduction in active power for a 1% reduction in voltage ranged from 0.4% to 0.7%, depending on the feeder. As a result of operational issues, the 95% confidence intervals were found to be quite wide, ranging (for the feeder with the most statistical confidence) from 0.16 to 1.19 about an average of 0.7%. This result was reproduced through modelling.

Through modelling, and the study of SCADA data, it was found that one of the feeders at the substation studied suffered from low voltage at times of peak demand. As a result, because the line-end voltage is targeted by the CVR system, and controlled by individual voltage regulators, this feeder was found to exhibit a rise in active power under CVR.

8.6 ESB Networks

ESB Networks [17] reported in 2012 on a voltage reduction trial then being conducted in two 20kV test areas within their network, one in the Dublin urban area and one in the rural west of Ireland. Both test areas were dominated by domestic load, with little commercial and minimal industrial load. Reductions in active and reactive power were evaluated separately, with reactive power being found to be much more responsive to voltage reduction than active power. Since the networks concerned operated at close to unity power factor, the authors suggest that the reduction in reactive power consumption is mainly associated with distribution transformers. Also, given the high load power factor, it is likely that the reduction in active power is more significant in terms of apparent power (and thus current) behaviour.

ESB Networks found that average reduction over 6 months in the reactive power was between 6% and 6.6% per 1% voltage reduction (depending on the network), whereas active power reduced by between 0.58% and 0.98%. More detailed results, aggregated fortnightly, are presented for one of the test networks. These show considerable variation in the effect of voltage reduction on active power, varying between 0.25% and almost 2% for each 1% voltage reduction. Reactive power shows more consistent behaviour, with a general upward trend through autumn into winter. This is consistent with the hypothesis of distribution transformer involvement, since these would be expected to become more heavily loaded over this period.

9 Conclusions

The various experiments and studies summarised above agree in suggesting that a reduction in demand can be expected in response to a reduction in voltage. Unsurprisingly, the actual reductions observed or predicted in each case vary significantly, from less that 0.5% per 1% voltage reduction to 2% or more, and depend on the mixture of loads in use at the time, which itself is dependent on the season. Short-term peak lopping or overload relief actions appear generally more effective than long-term energy reduction response. As an initial estimate, it seems reasonable therefore to suggest that a figure of 1% reduction in real power for a 1% reduction in voltage might be assumed in the absence of more detailed knowledge or experimental results.

10 Recommendations on Load Modelling

Since,

$$I = \frac{S}{V}$$

a 1% reduction in apparent power load for a 1% reduction in voltage implies a constant current load. This will not fully capture the additional sensitivity of reactive load to voltage, and is likely to be slightly conservative in its representation of load behaviour. It is therefore recommended that, in the absence of more detailed knowledge about the behaviour of specific loads, a constant current load model should be used by SPEN to represent loads in network models. This will represent an improvement in accuracy over conventional constant power load modelling. For studies specifically considering the response of the network immediately after a voltage reduction, particular consideration should be given to the modelling of load on the basis of available historical data.

In IPSA, two options exist for the modelling of constant current load. A specific “Constant Current Load” model will represent only a constant current load, while a “ZIP model” represents a load as a combination of constant impedance (Z), constant current (I) and constant power (P), each of which may account for up to 100% of the configured load. For reasons of flexibility in accommodating local knowledge of the behaviour of particular loads use of the ZIP model is recommended. A ZIP load is added to an IPSA model by adding a Universal Machine model to the node to be loaded, as shown in Figure 9. This is then configured as shown in Figure 10. It should be noted that any measured loads must be corrected to real and reactive power at nominal voltage before entry: it is likely that measured loads are recorded at a different voltage at the busbar where they are modelled. If disparate real and reactive response characteristics (perhaps as a result of local knowledge) are required, then these should be represented separately using two ZIP loads.

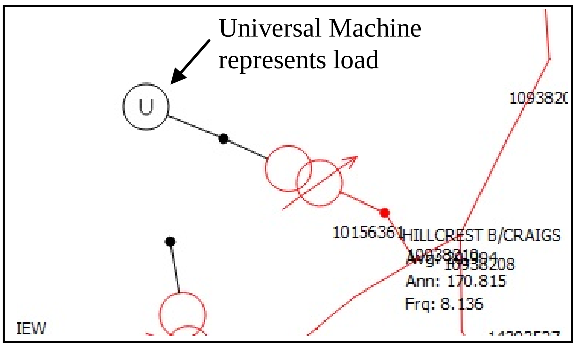

Figure 9: Universal machine added to IPSA network model

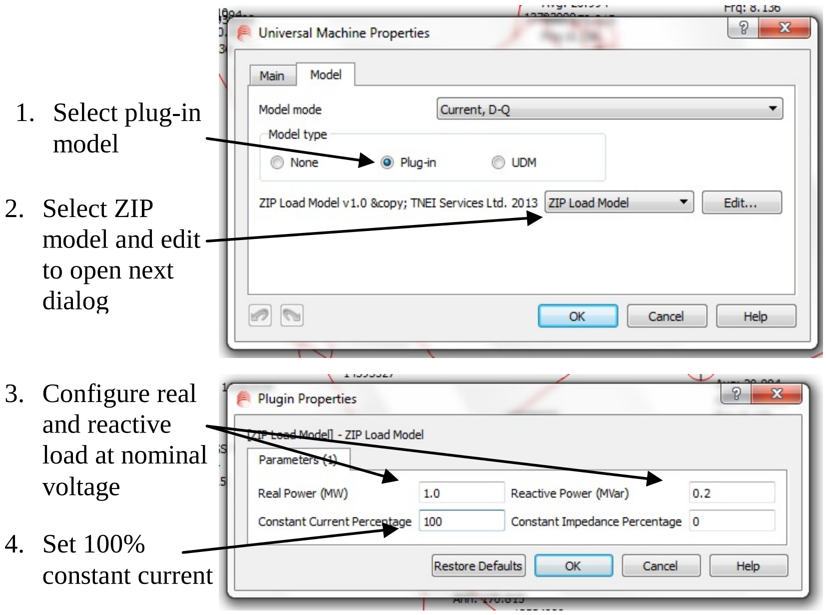

Figure 10: Configuration of universal machine as constant current load

Two limitations apply to the use of ZIP loads in place of conventional loads in IPSA models. The ZIP load does not allow the configuration of a load profile (which allows a number of different load conditions, such as the half hours of a day, to be simulated in a single study), or record the number of customers represented by the load for reliability analysis. These features have been recently introduced to IPSA, and it is not clear that they are used to any significant by SPEN. A workaround for the reliability limitation would be to add a conventional load of

0 MVA with the appropriate number of customers adjacent to the constant current load, but representation of constant current load profiles would require enhancement of IPSA by TNEI.

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