SP ENERGY
NETWORKS

Flexible Networks
for a Low Carbon Future

Review of Experimental and Analytical Design and of Project Benefits

September 2015

1 Summary

The experimental design of the various elements of the ‘Flexible Networks for a Low-Carbon Future’ project have been reviewed, as have the claimed benefit of the project. Principal findings of the review are:

- The experiments and analyses conducted as part of the project have been appropriately designed, and that design is clearly set out in the project documentation.
- Although there were some inevitable limitations on availability of data or ability to make network interventions, these are appropriately acknowledged, and the results and findings respect these limits.
- The results and learning from the project are robust and reliable.
- The Successful Delivery Criteria for network capacity improvement have been achieved or exceeded for all three test areas.

2 Introduction

This report reviews the design of the various experimental and analytical activities within the SP Energy Networks (SPEN) ‘Flexible Networks for a Low-Carbon Future’ Tier 2 LCNF project. Proper experimental and analytical design is important in ensuring that claimed results and findings are robust, reliable and reproducible. While a poorly designed experiment may appear to give clear results, it may be difficult to determine how reliable they are. They may only be applicable to the particular circumstances of the experiment or the data which was analysed. Generalisation to other locations or times may be difficult.

It must be recognised that the experiments and analyses being undertaken are subject to constraints outside the control of the experimenters. The duration of the project is relatively short, particularly after accounting for the time necessary to procure and install measurement equipment, and it is confined to a small proportion of SPEN’s distribution network. Additionally, the experiments must be undertaken within the confines of an operational distribution network, which significantly constrains the nature, scale and duration of some of the interventions. Potential learning from robust experimental design has had be balanced against the network risk which would be incurred. Additionally, some experiments have depended upon the participation of customers, whose compliance cannot be compelled.

It is clear, therefore, that it is unreasonable to hold the project’s experimental and analytical activities to a standard of perfection. Rather, it is appropriate to ensure that the purpose and method of the experiments are clearly laid out, that any limitations are acknowledged, and that the conclusions fully exploit the analysis undertaken, but do not claim more than is appropriate in the light of the limitations.

In addition, the claimed benefits of the project in relation to increased network capacity have been reviewed in the light of the design of the experiments and interventions used to achieve them.

3 Experimental and Analytical Review

3.1 Work Package 1

Work package 1 is primarily concerned with the acquisition of power network measurement data from new and existing sources, and with the analysis of this data to better understand the behaviour of the network, and to develop new planning and operational tools. No specific experimental interventions were made as part of this work package. Instead, measurements made during the normal operation of the power system are analysed. This report therefore reviews the analytical processes applied and assesses the robustness of the conclusions drawn.

The four sub-work-packages or tasks making up work package 1 are:

- WP1.1: Improved use of primary substation data
- WP1.2: Improved secondary substation monitoring
- WP1.3: Improved operational tools
- WP1.4: Improved planning tools

These four tasks are quite closely interrelated, and similar analytical activities have been undertaken in more than one – for example analyses of patterns of imbalance at HV and LV. This review therefore considers the different analytical activities across the entire work package, rather than discussing each task in turn.

Principal analytical tasks within work package 1 are:

- Improved forecasting of peak load in comparison to existing methods, and characterisation of secondary substation load
- Statistical identification of suspect, erroneous or inconsistent measurements
- Characterisation of PV generation behaviour, impact on harmonics and capacity headroom
- Assessment of the level of HV and LV imbalance
- Investigation of the required sampling frequency of substation voltage

Each of these elements is discussed in the following sections.

3.1.1 Analysis and Forecasting of Load

This activity includes two analytical tasks, which are the forecasting of peak primary substation load[1], and the estimation of secondary substation load at the HV feeder peak[2].

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[1] “Flexible Networks – Improved Use of Primary Substation Data”, TNEI report 7640-05

The first of these involves the estimation of, and extrapolation from, a ‘synthesised peak demand’ figure calculated from a portion of the load duration curve. The method is clearly explained. The resulting forecasts are tested by comparison with forecasts given in the Long Term Development Statement (LTDS), and with the measured load peak. Because of a historical change in the way in which LTDS load forecasts are calculated and presented, only two sets of LTDS forecasts could be considered; the period of the forecast evaluation was constrained by the availability of measured data (the peak of the forecast year had not yet occurred). The comparison was undertaken for six primary substation groups.

The comparison method is explained, and results are clearly presented. Both the LTDS and proposed forecasting methods exhibit considerable variability in their success, which is a consequence of the year-on-year variability of peak demand. However, the results presented tend to suggest that the average error in the forecast produced using the new method is less than the error in the LTDS forecast.

The second task, the estimation of secondary substation demand, seeks to validate existing SPEN methods in this area, which are based on either transformer rating or maximum demand indicator (MDI) measurements. As before the method is clearly described and consists of comparing the measured substation load at the time of peak feeder load with the estimate. This evaluation considers 13 ground-mounted and 5 pole-mounted substations, supplied by two HV feeders at the winter 2013/14 feeder peak. This sample size is quite small, and although it appears that there is agreement between the estimate and measurement, it is difficult to assess the level of confidence in this assertion. Given the project timescale, and the relatively small number of pole-mounted substations which are monitored, the small sample size in these respects is probably unavoidable.

Understanding of the relationship between secondary substation and HV feeder load is also informed by work conducted by the University of Strathclyde[3]. This analysis investigated of the level of load diversity among secondary substations supplied by an individual HV feeder, A significant body of data was analysed, suggesting that the statistical properties of the results are likely to be reliable. It is notable, and acknowledged, however, that relatively little data is available for small, rural secondary substations, which are more likely to be pole-mounted. As the analysis is conducted on a per-feeder basis, pole-mounted and ground-mounted substations are not differentiated.

3.1.2 Identification of Suspect Measurements

A method is described of identifying measurement points which are suspect in terms of measurement error, or (for load measurements) which may relate to an abnormal network configuration. The method is tested on measurements made at primary[4] and secondary[5]

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[2] “Future Roadmap for Improvement of HV & LV Network Modelling”, TNEI report 7640-08

[3] “Technical Note on Investigation of Diversity in Secondary Substation Load”, University of Strathclyde report SP/LCNF-FN/TR/2015-001

[4] “Flexible Networks – Improved Use of Primary Substation Data”, TNEI report 7640-05

substations. It is based on a load forecasting method published in the academic literature[6] and relies on the statistical properties of the deviation of an actual measurement from an 'expected' measurement series based on historical data. The metric assumes that the deviations approximate to a normal distribution: while this is a reasonable assumption, it is not formally tested. Some examples are given, and the method is qualitatively assessed to perform well on load data, but less well when 'normal' data is subject to sudden random changes, such as tap changer activity in a voltage measurement series. Difficulties are evident in the identification of a source of verification data in relation to measurement errors or network reconfiguration, and therefore formal or statistical validation is considered possible.

3.1.3 Characterisation of PV

The characterisation of the behaviour and effects of photovoltaic generation involves a number of analytical tasks[7]: the development and testing of a PV generation model, determination of the relationship between PV/load balance LV and HV voltage behaviour, and assessment of the impact of PV on harmonic distortion[8].

The PV generation model is based on a combination of a minimum demand profile and a PV resource model. The methods of producing these components are described. The performance of the resulting model is demonstrated with respect to some examples of measured data, of which some show good correspondence and some less so. The differences are qualitatively explained with respect to apparent features which are not within the scope of the modelling exercise. The results of other comparisons are summarised, and the conclusions drawn appear appropriate.

The relationship between load, PV output and voltage behaviour is determined by calculating the correlations between LV current and LV voltage, and between LV voltage and HV voltage at the primary busbar. This calculation was made for the months of June and July 2014, when PV influence would be expected to be strongest. Unless there is a risk that the primary substation voltage itself is dominated by PV influence (and this is understood not to be the case), it can be concluded that this method is appropriate and should properly determine the relative strength of 'upstream' and 'downstream' influences on the voltage.

A further model validation of the voltage behaviour if the network model is carried out by assessing the correlations between measured voltage at customer premises and feeder phase current and secondary substation voltage. The analysis is limited by a relatively

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[5] "Technical note on trend-based quality assessment of measurement data", University of Strathclyde report SP/LCNF-FN/TR/2014-007

[6] Hill and Infield, "Modelled operation of the Shetland Islands Power System comparing computational and human operators' load forecasts", IEE Proceedings: Generation, Transmission and Distribution, 1995, pp555-559. doi: 10.1049/ip-gtd:19952248

[7] "Improved Characterisation of PV Capacity at LV", TNEI report 7640-10

[8] "Flexible Networks - Impact of Embedded PV Generation on Total Harmonic Distortion", TNEI report 7640-13

small sample size (six measurement points, with measurements taken for one day), and the timing of the installation of measurement equipment was such that the comparison could only be carried out under conditions of relatively low solar radiation in winter. The correlation values nevertheless support the stated conclusions.

The impact of PV on harmonic distortion in the distribution network is assessed by analysing THD measurements on two LV feeders at a single substation with contrasting levels of PV uptake for two days of high solar irradiance, and across the months of June and July 2014. The analytical methods are well-explained and appropriate. The time selections are likely to maximise the chance of identifying PV induced harmonics. It is acknowledged that the THD measurement is likely to be in current rather than voltage and that the actual influence of PV on power quality would depend both on this measurement and the network impedance upstream of the harmonic source. The report acknowledges that it is difficult to come to concrete conclusions based on the small sample size. These limitations are a consequence of the nature of the available measurement data.

3.1.4 Imbalance Assessment

Phase imbalance was assessed both in LV and HV feeders. LV imbalance analysis was undertaken by TNEI[9]. The methods used for calculating and quantifying phase imbalance are clearly explained. Measurements corresponding to the hundred highest load points annually are used in the analysis. The rationale for this choice is explained, and a sensitivity analysis in relation to this sample size has been undertaken in support. The report acknowledges that a relatively small number of feeders has been assessed: a total of 31 from 10 secondary substations. It is unclear how these feeders were selected, although it is stated that a variety of network characteristics are included. The conclusions appear reasonable, although those some classes of feeder (particularly rural feeders) are based on small samples as a consequence of available measurements.

The level of loss reduction and additional capacity headroom which could be achieved by rebalancing was also assessed. This analysis (which uses a simplified model of the results of rebalancing) uses a large sample of the monitored LV feeders over the complete winter 2013/2014. The methods used appear appropriate and the results reliable.

HV imbalance analysis was undertaken by the University of Strathclyde[10]. The analysis was based on current measurements taken at primary substations in the St Andrews and Whitchurch test areas and where available also used measurements from mid-feeder devices. The analysis covered one calendar year. The methods of data selection and analysis are described clearly and appear reasonable.

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[9] “HV and LV Phase Imbalance Assessment”, TNEI report 7640-07

[10] “Report on Assessment of Load Unbalance in HV Feeders”, University of Strathclyde report SP/LCNF-FN/TR/2014-005

Substation based measurements are presented as daily averages, and as averages by time of day across the year. While this reveals general patterns in the variation of unbalance in the feeders studied, the averaging may mask occasional events of significant unbalance. Nevertheless, the results clearly support the stated conclusions in terms of the levels and consistency of pattern of unbalance.

The report acknowledges significant problems in relation to the mid-point unbalance calculation, particularly in relation to the number of measurements made, and the difficulty of obtaining even approximately synchronised current measurements across the three phases. For this reason, although the results obtained appear reasonable, there must be some caution as to their reliability, as is acknowledged. It does not appear that a statistical treatment of the results could be usefully attempted.

3.1.5 Voltage Sampling Assessment

A comparison of different possible measurement intervals for secondary substation voltages was undertaken[11]. This analysis sought to statistically compare three possible measurement intervals, as well as an averaging-based approach reported by UKPN. The method by which substations for analysis was selected is explained and appears to give a representative sample. The statistical processes used for the comparison are stated and appear appropriate.

3.1.6 Work Package 1 Summary

The analytical methods applied in work package 1 are appropriate and make effective use of the available data. The conclusions drawn are robust, and acknowledge, where appropriate, limitations resulting from operational or data availability constraints. The results can be relied upon as providing a solid foundation for further experimental and analytical work in work package 2.

3.2 Work Package 2

Work package 2 includes a number of physical power system interventions, each of which is the subject of a specific sub-work-package or task:

- WP2.1: Dynamic thermal ratings
- WP2.2: Flexible network reconfiguration
- WP2.3: Energy efficiency
- WP2.4: Automatic voltage regulation

Some of these tasks have a degree of commonality with each other, and with elements of work package 1. In the following discussion, the elements of work package 2 are discussed individually, except that the related tasks 2.2 and 2.4 are discussed together.

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[11] "Technical Note on Substation Voltage Recording Intervals and Methods", University of Strathclyde report SP/LCNF-FN/TR/2014-004

3.2.1 Dynamic Thermal Ratings

Work package 2.1 consists of two parts: the development of real-time thermal ratings (RTTR) for two 33kV overhead line circuits, and the development of enhanced thermal ratings for primary transformers.

RTTR has been applied to two 33kV overhead line circuits in Fife[12]. This application has investigated and assessed a number of aspects of such a deployment, including:

- The algorithmic estimation of conductor temperatures
- The requirement for a sufficient number of weather stations
- Three alternative methods of attaching temperature sensors to conductors
- Correlation between load and real-time rating
- A 'graceful degradation' method to be used in case of unavailability of measurement data

Each of these is briefly reviewed in turn.

The algorithmic estimation of conductor temperatures is evaluated by comparison with actual temperatures measured by the installed transducers. The assumptions underlying this comparison, and the calculations of estimates are listed, and appear reasonable. The method of comparison appears reasonable and the results reliable.

The need for detailed weather monitoring using a number of weather stations was tested by calculating RTTR for the extreme cases of a full set of weather stations and a single weather station. This method illustrates the importance of more detailed monitoring, in line with the stated objective.

Alternative methods for attaching temperature sensors were evaluated by attaching six sensors to the three phase conductors on either side of a single pole. Four of these installations (all on one side of the pole plus one on the other side) were of a single installation type, with one of each of the other two. This method effectively controls for differences between phases and between sides of the pole. Results are shown for four of the sensors for a 48 hour period, and are compared with algorithmic estimates; it is clear that the conclusions are consistent with the results shown. Confidence can be placed in the comparison of the performance of the different means of attaching the sensor, and in the resulting recommendations.

The correlation between load and real-time rating is investigated by plotting the RTTR value at the time of peak combined daily load on the two circuits against the magnitude of the combined load for a considerable number of days. This approach is appropriate as an initial investigatory method, and the results indicate that more detailed investigation is unlikely to reveal useful addition detail.

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[12] "Work package 2.1: Dynamic thermal rating of assets – Cupar St Andrews RTTR system, Final Report", SP Energy Networks report, July 2015

The ‘graceful degradation’ algorithm is well explained, and the method of selection of parameters to the algorithm is set out and appears appropriate. The results presented support the parameter values chosen. It appears that the algorithm performs acceptably, and that confidence can be placed in its outputs.

The second element of the work package involves the application of enhanced thermal ratings to primary transformers based on a model specified by IEC standard 60076-7. There have been two principal experimental and analytical elements of this task: A condition assessment exercise, including estimation of the remaining life of a subset of the primary transformers in the three test areas under different loading conditions, and work to select parameters for the IEC model based on measurements of load and transformer temperature.

The condition assessment and life estimation work was conducted by DNV GL[13,14]. The measurements made and analytical methods used are clearly described, and the measurements themselves are clearly tabulated. The analytical methods applied appear appropriate (and limitations of some methods with respect to relatively recently built transformers are properly acknowledged), and the results and findings appear consistent with the known history of the transformers. While it would have been beneficial to assess any change in oil analysis results over a suitable time, the time constraints of the project have not permitted a suitable interval between tests, and the recommendation to re-test in the future is an appropriate substitute.

The model parameter estimation was undertaken by the University of Strathclyde and SP Energy Networks. Two analyses were undertaken on a single transformer: one under normal late autumn “loading conditions[15], and one under specially created high load conditions in winter[16]. The experimental interventions involved, measurements taken and assumptions made are clearly described. In both analyses, the period of the experiment was relatively short, and the volume of data available for analysis limited. The ability to obtain data at high transformer loads – above its nominal ‘nameplate’ rating – is limited by the expected effect on transformer life of operation at very high load, and by the acceptability to wider stakeholders within SP Energy Networks of the risks of such operation.

Problems with data collection resulted in the used of synthesised load and/or weather data in the analysis. Measures were taken to reduce the effect of these synthesised points on the analysis by avoiding sustained periods of synthesised load in the optimisation of

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[13] “Real Time Thermal Rating System – Phase I Asset Condition Assessment”, DNV GL report 14-2132.

[14] Meijer, de Wild, et al, “Dynamic Rating to Support Safe Loading of Transformers”, 23rd International Conference on Electricity Distribution, Lyons, June 2015, paper 0987

[15] “Technical note on initial assessment of IEC60076-7 model performance based on primary transformer measurements”, University of Strathclyde report SP/LCNF-FN/TR/2014-008A

[16] “Technical note on calibration of IEC60076-7 model performance based on primary transformer load test”, University of Strathclyde report SP/LCNF-FN/TR/2015-001A

parameters, and by requiring a period of measured load to 'condition' the model prior to optimisation.

The limited volume of available data prevents a division into 'training' and 'testing' data. The capabilities of the model in forecasting unseen transformer behaviour, particularly at high load, are therefore not exhaustively explored. In addition, some aspects of the transient thermal behaviour of the transformer are obscured by loss of data from the early part of the experiment.

An important limitation of the experiment is that no direct measurements of winding temperature are made. Such measurements are, by their invasive nature, at best very difficult to make on an in-service transformer without special provision having been made at the time of manufacture. As such, this limitation must be considered unavoidable, and is clearly highlighted in the discussion of the experimental results.

Overall, it is considered that the design of the experiment is as good as could be achieved, given that it is undertaken on an in-service transformer. Although a longer experimental period and/or a greater number of loading experiments would have been desirable, and would have allowed a more robust statistically based analysis of the results, it is not clear that this would have been operationally achievable.

Work Package 2.1 Summary

Both parts of the work package (overhead lines and transformers) have been based on well-established international standards which have been applied in the UK and abroad. Furthermore, well-designed experiments, which deal properly with deficiencies in data, have been conducted to verify that the standards are appropriate to the specific plant involved in the project. As such, there can be confidence in the increases in network capacity released through this work package.

3.2.2 Flexible Network Reconfiguration

Work package 2.2 consists of three parts. The first part involves the design, installation and commissioning of novel distribution automation systems[17]. This does not involve significant experimental or analytical activity, so it is not necessary to comment to any significant extent.

The second and third parts consist of the identification, analysis and selection of network reconfiguration in two of the project test areas, namely St Andrews in the north and Whitchurch in the south. The Whitchurch area analysis was led by TNEI[18], while that at St Andrews was led by the University of Strathclyde[19]. There are both differences and commonalities in the approaches adopted. The differences result in part (at least) from the

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[17] "Methodology & Learning report – Work package 2.2: Flexible Network Control" SP Energy Networks report, July 2015.

[18] "Whitchurch Load Automation Feasibility Assessment", TNEI report 7640-02

[19] "Evaluation of Headroom and Load Transfer Opportunities at St Andrews Primary Substation", University of Strathclyde report SP/LCNF-FN/TR/2014-001A

different network design and operation philosophies in the two areas, in particular the differences in the nature of a network group. As such, opportunities for intra-group transfers must be analysed at Whitchurch which are less relevant at St Andrews. The means of assessing substation and feeder loading patterns are similar, in that typical load profiles are constructed statistically from measurements. The options considered for when reconfiguration should take place are similar in both cases.

Identification of potential load transfers is well explained in both cases, although the methods are slightly different. At St Andrews, an approximate analysis of all measurement points over a single winter was undertaken while Whitchurch was assessed using maximum feeder load conditions and profiles. At the level of detail involved, and given that model-based analysis is subsequently undertaken, both methods seem reasonable: it is unlikely that options will be unreasonably excluded.

Evaluation of the feasibility and effectiveness of the potential load transfers is, in both cases, undertaken on the basis of network models. The construction of these models is explained in detail in work package 2.4 for the St Andrews model, including sources of data and assumptions. Validation from measured feeder voltage profiles is also covered. The apportionment of load to unmonitored secondary substations is based on the existing SPEN methods of estimating secondary substation demand whose validation was discussed in section 3.1.1.

Exhaustive practical validation of the performance of the Flexible Network Reconfiguration outcomes is difficult because of the potential for disruption to customers This would be tolerable in the event that a single reconfiguration was required to release capacity, but hard to justify to evaluate the many different reconfiguration options. However, the results shown give confidence that the expected performance can be achieved in practice.

3.2.3 Energy Efficiency

The work package is split into two main parts - being the modelling of demand, and the identification, assessment and application of energy efficiency interventions (including stakeholder engagement). In addition, experiments were undertaken to assess whether a reduction in load may be achieved by reducing the voltage at a primary substation.

The models are used to provide an understanding of the test area peak demand, and to identify interventions according to the load which is affected by the intervention. The method of constructing the models, the sources of data and the underlying assumptions are well explained[20], as are the conditions which the models are intended to represent. Potential future applications of the models and of the modelling approach are suggested and appear appropriate.

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[20] "Metholodgy & Learning report – Work package 2.3: Energy Efficiency", SP Energy Networks report, August 2015.

Results of the load modelling are presented for primary substations and are compared with measured load. Since the focus of the overall LCNF project is to increase capacity headroom at primary substations, the omission of secondary substations is reasonable. Differences between measured and modelled primary load are identified and possible reasons for these differences are advanced and justified.

The second major task within this work package is the assessment of the effectiveness of different energy efficiency interventions. The stakeholder engagement process is clearly explained, and well justifies the finding that large scale stakeholder engagement in a small area (at least without the benefit of initiatives like ESOS and EDR) is difficult. In terms of specific interventions, the results presented are estimates based either on statistics of load characteristics, or assessments of specific customer premises made by Scottish Power Energy Solutions. Although details of the individual assessments cannot, of course, be reported for reasons of customer confidentiality, the basis of these estimates is described and appears appropriate.

A significant limitation on the work, which is acknowledged in the various reports, is that a very small sample of intervention trials has been amassed, as a result of the difficulty of engaging customers. The reports also state, with good justification, that there are reasons to suspect that the sample may not be representative of the cost per unit of energy efficiency gain across the population of stakeholders whose participation had been hoped for. Nevertheless, the process adopted does provide useful and well-justified learning about the load modelling and stakeholder engagement processes, as well as some points of reliable data in relation to cost.

The third element of the work package consisted of two experiments and a review of data to determine the effect of a 3% reduction in primary substation voltage[21,22,23]. The purpose of the work was twofold: firstly to assess any change in substation load resulting from a reduction in voltage, and secondly to assess the tolerability of a permanent reduction in voltage to increase generation capacity headroom. The first of these objectives was addressed by two experiments in which the voltage at Ruabon primary substation was reduced by 3%, and the resulting change in load at the primary, and selected secondary substations was observed. In the second experiment, voltage at LV customer premises was also analysed. An analysis of measurements taken by Flexible Networks instruments during two earlier National Grid-led tests was also undertaken.

From the literature review, it is clear that the expected change in load is small – of the order of 1% in real power for each 1% reduction in voltage, with reactive power being

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[21] “Technical Note on Design of Ruabon Voltage Reduction Experiments”, University of Strathclyde report SP/LCNF-FN/TR/2014-002

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

[23] “Analysis of 2015 Voltage Reduction Experiment at Ruabon Primary Substation”, University of Strathclyde Report SP/LCNF/TR/2015-008

somewhat more sensitive. Given the finding that a typical power factor is around 0.98[24], it is likely that the change in load in response to voltage adjustment will be similar to the underlying short-term random variability of the measured load. The effect will be further reduced by the process of averaging inherent in the power measurement process used. As such, even with careful identification of control measurements, while a single voltage reduction experiment might identify a voltage-induced reduction in load, it is unlikely to be able to reliably quantify it. The second experiment therefore adopted a more sophisticated statistical approach involving year-to-year comparison of intervention and control periods, which revealed that there was a significant load change which varied from HV feeder to HV feeder. The size of the intervention and control data sets indicates strong confidence in this result.

The acceptability of a voltage reduction for generation capacity headroom was tested in the first experiment by maintaining the 3% reduction until a complaint of low voltage was received from a customer. This analysis was verified in the second experiment by projecting measured LV customer voltages back to the winter peak period by comparison with measured secondary substations behaviour under two different assumptions. The results of the first and second experiments are compatible in relation to this area.

3.2.4 Integration of Voltage Regulators

Work package 2.4 consists of three main elements. Firstly, an analysis was undertaken to identify the most suitable location for the AVR (discounting site-specific factors such as wayleaves etc.) on the basis of network modelling[25]. The construction of the models, including data sources and assumptions is well described, as are the influences of particular factors such as large loads and generation. The model is validated by comparing the modelled voltage profile (at monitored secondary substations) with positive results. The allocation of load to unmonitored secondary substations uses a method developed by SPEN, whose validation is more fully discussed in section 3.1.1. In general, it appears that the analysis is well-designed, and likely to deliver trustworthy results.

The second element of the work package involves the design and implementation of the physical AVR installation and the associated control systems. This does not involve any significant analytical or experimental activity.

The final element of the work package is assessment of the actual effect of the AVR by switching the existing NCPs in the feeder to move load between St Andrews and Anstruther and measuring the voltage downstream of the AVR. These measurements will then be compared with simulation results to further validate the assessment. From discussions with TNEI and SP Energy Networks, it appears that the design of this experiment is satisfactory and will yield reliable results.

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[24] “Future Roadmap for Improvement of HV & LV Network Modelling”, TNEI report 7640-08

[25] “St Andrews Series Voltage Regulator Location Study”, TNEI report 7640-01

4 Applicability to Other DNOs

It is considered that the learning resulting from the project, and the methods which have been applied are highly applicable to other GB DNOs. The challenges which the project addresses – increases in LV-connected generation and uncertain but potentially rapid and significant future load growth related in part to low-carbon technology – are of wide concern within the electricity supply industry and effective approaches to these issues can be expected to be of general interest.

The plant targeted by the interventions included in the project is in common use by other DNOs. The primary transformers and 33kV overhead lines which are the subject of the Dynamic and Enhanced Rating intervention are typical of those in use by other DNOs. Application to primary transformers of differing ages and capacities has been demonstrated, and the substantially same approach as was trialled here has also been shown to be appropriate to 132kV overhead lines[26].

Although the particular design and operational approaches applied in the SP Manweb network introduce a certain amount of complexity to the design and assessment of Flexible Network Control schemes, the overall approach has been generalised to perform equally well in that network and also in the more typical conditions of the SP Distribution network. Furthermore, the suitability of the method for less usual situations such as single-transformer primary substations will enhance its applicability to DNOs having such sites. As such the diversity of the trial areas used can be said to have enhanced the generality of the method. Learning on the selection, design and implementation of advanced telecontrol schemes will be of independent value.

The project’s learning outcomes in relation to enhanced monitoring of primary and secondary substations are likely to be widely applicable. Many other LCNF, NIA and NIC projects have sought to increase the level of monitoring of distribution networks. However, in selecting a suitable monitoring approach, an optimal level of monitoring detail and coverage must be identified in order to make the best use of available investment. The recommendations for selection, installation and management of such monitoring, assessment of improved network understanding which may be gained through it, and interventions which are facilitated by it will contribute to the selection of suitable monitoring strategies by DNOs for “Business As Usual” application.

5 Assessment of Delivered Capacity Benefits

The Successful Delivery Criteria for the project specified the achievement of a 20% increase in capacity headroom in each of the three test areas. At St Andrews and Whitchurch, this increase would be to accommodate increased load, while at Wrexham the increase would allow installation of additional small-scale generation with specific emphasis on domestic-scale PV. In all three cases, it is claimed that this level of capacity

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[26] “Implementation of a real-time thermal rating system on the 132kV network in North Wales” SP Energy Networks report, July 2013

increase has been achieved. These claims are assessed for each of the three test areas in turn in the following sections.

5.1 St Andrews

The actual level of capacity headroom increase achieved by each of the interventions applied is stated to be as follows:[27]

Intervention	**Capacity Headroom Increase**
Dynamic Rating	14%
Flexible Network Control	6%
Energy Efficiency	<1%
Voltage Optimisation	0%
Total	**20%**

The interventions for the St Andrews test area are independent: there is, for example, no requirement for network reconfiguration in order to take advantage of dynamic ratings. The contributions are therefore assessed individually.

The calculation of increased capacity from dynamic rating depends on the ability of lower-rated equipment to support the limiting current in non-dynamically-rated equipment. The limiting plant items are considered to be certain 33kV cable sections supplying St Andrews, with a rating of 24MVA, which is not altered by the project.

The limiting factor under "Business As Usual" approaches is the 21MVA rating of the two primary transformers. The application of dynamic rating to these transformers is based on an internationally-applied[28] thermal model specified by an IEC standard[29]. The modelled thermal behaviour of the transformers at St Andrews has not yet been directly validated by experiment. However an experiment in the Whitchurch test area (see below) suggests that the model parameters applied result in pessimistic estimates of transformer temperature under high load conditions. There can thus be high confidence that the stated transformer dynamic rating is available in practice.

A second element of the dynamic rating intervention at St Andrews concerns the 33kV overhead lines supplying St Andrews primary substation. As before, the methods used are based on established international standards[30,31]. The results given are based on extensive testing over the course of approximately 11 months, and show that the dynamic overhead line rating has been, on average, 7% above the current winter rating during the winter

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[27] "Case Study: Management of Network Capacity: St Andrews Trial Area", SP Energy Networks Report, August 2015.

[28] Jalal, Rashid and van Vliet, "Implementation of Dynamic Transformer Rating in a distribution network", IEEE International Conference on Power System Technology, Auckland, Oct. 2012. doi: 10.1109/PowerCon.2012.6401328

[29] IEC 60076-7

[30] IEC 61597

[31] CIGRE Working Group 22.12

season. Since the winter rating is above that of the limiting plant, there can be strong confidence that dynamic overhead line rating will contribute to the delivery of the stated outcome.

The increased capacity ascribed to Flexible Network Control has been derived from loadflow studies of the St Andrews 11kV network under peak conditions. The value claimed is further localised to the individual network sections considered for control. The level of uplift attributable to each of these sections has not been individually validated, but the methods used to construct the analytical model underlying them, and the associated assumptions, have been clearly described and effectively validated, as discussed earlier. It is therefore clear that the stated increase in network capacity from this intervention has been demonstrated.

Results from the work on energy efficiency indicate that this intervention applied is likely to contribute, at most, a few hundred kilowatts to the increase in available capacity. The methodology supporting the expected capacity increase is robust, and the stated contribution from this intervention is available.

International experience and experimental testing in the Wrexham test area[32] suggest that voltage optimisation may result in a reduction in power demand, and may provide some benefit in terms of sustained current reduction in constraining plant (other LCNF projects[33] have shown evidence of short-term benefits in this regard). However, the Wrexham experiment also showed that this benefit may vary significantly according to local conditions. As such, it is reasonable that the project claims no benefit from this intervention in relation to St Andrews.

In summary, it is clear that there can be strong confidence that the 20% target level of capacity headroom increase for the St Andrews test area has been achieved.

5.2 Whitchurch

The actual level of capacity headroom increase achieved by each of the interventions applied is stated to be as follows:[34]

Intervention	**Capacity Headroom Increase**
Dynamic Rating	10%
Flexible Network Control	11%
Energy Efficiency	0%
Voltage Optimisation	0%
Total	**21%**

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[32] Literature review

[33] CLASS

[34] "Case Study: Management of Network Capacity: Whitchurch Trial Area", SP Energy Networks Report, June 2015.

There are some relationships between the first two interventions, in the sense that they address group capacity limits under N-1 conditions. Since the network is designed on the basis of single-transformer primary substations, switching will be required following a first outage in order to restore supply to the affected section of network and to make use of the increased capacity delivered by Dynamic Ratings or Flexible Network Control. Nevertheless, the benefits reported for each intervention are distinct and do not overlap. As such, they are assessed individually below.

As at St Andrews, the ultimate constraint on the capacity increase that can be achieved by Dynamic Rating is imposed by plant which is not dynamically rated – in this case switchgear and cables connecting to the transformer. The increased capability of the transformers has been assessed using the same model as for St Andrews, with parameters adjusted to the rating and cooling methods of the Whitchurch area transformers. An experiment[35] has been conducted on the Liverpool Road transformer to assess the suitability of this model and its parameters at high load. The results of this experiment suggest that the parameters used to configure the model are somewhat conservative in comparison to observed thermal behaviour. There can therefore be strong confidence that the claimed benefits have been realised.

The claimed benefits of Flexible Network Control are based on an analysis of network power flows under different N-1 conditions, and different intra-group supply restoration switching strategies following the proposed reconfiguration actions. This analysis is performed under worst-case loading conditions. Constraints on the ability to transfer load within the group are considered in selecting the reconfiguration actions. As for St Andrews, the level of capacity increase attributable to each of the individual network sections which may take part in reconfiguration has not been practically verified, but the calculation approach described can be regarded as an acceptable substitute, since its assumptions and models have been validated as previously described. The claimed benefits have been achieved.

As for St Andrews, energy efficiency and voltage optimisation are not claimed to contribute to the stated capacity headroom increase.

In summary, it is clear that the 20% target level of network capacity improvement has been achieved in the Whitchurch test area.

5.3 Wrexham

At Wrexham, the increase in network capacity relates to the accommodation of more photovoltaic generation than has hitherto been acceptable, through the better understanding and relief of voltage constraints. The actual level of capacity increase is stated to be as follows:[36]

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[35] "Technical note on calibration of IEC60076-7 model performance based on primary transformer load test", University of Strathclyde report SP/LCNF-FN/2015-004A.

[36] "Case Study: Ruabon Multiple Domestic PV Connections", SP Energy Networks report, September 2015.

Intervention	Capacity Headroom Increase
Improved Network Analysis	38%
Voltage Optimisation	90%
Total	**124%**

These interventions are independent of one another.

The Improved Network Analysis intervention involves the generation of a generic residential load profile, of which the minimum daytime demand (MDD) is important in determining the net output of domestic PV and its consequential effects on voltage. The MDD value is consistent with recent international analysis of smart meter data from Ireland[37]. Network modelling has been undertaken to quantify the expected increase in voltage for different levels of PV deployment, and also to consider the effects of phase imbalance[38]. The modelling has been satisfactorily validated using voltage measurements taken at LV customer premises.

Detailed analysis of observed overvoltages at secondary susbstations has shown that these exceedences do not generally take place at times of significant PV output, and that this behaviour is unexceptional among the complete population of secondary substations in the Wrexham and Whitchurch test areas. As such, it is concluded that they are not related to existing PV installations, and that overvoltage is unlikely to prevent achievement of the stated 38% increase in capacity headroom.

The 90% claimed increase in capacity headroom from Voltage Optimisation is consistent with the analysis carried out in support of the Improved Network Analysis intervention. Practical experiments in the Wrexham test area[39] have shown that reductions in primary substation voltage propagate effectively to secondary substations and to LV-connected customers.

In summary, it is clear that the target 20% level of network capacity improvement has been significantly exceeded in the Wrexham test area.

6 Discussion and Conclusions

Proper design of experimental and analytical methods is important in ensuring that the results of the various modelling exercises, data analyses and practical trials are robust, reliable and repeatable. They can also contribute to an understanding of the accuracy of

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[37] H.-Â. Cao, C. Beckel and T. Staake, “Are domestic load profiles stable over time? An attempt to identify target households for demand side management campaigns”, 39th Annual Conference of the IEEE Industrial Electronics Society, Vienna, Nov. 2013, pp4733-4738. doi: 10.1109/IECON.2013.6699900.

[38] “Improved Characterisation of PV Capacity at LV”, TNEI report 7640-10.

[39] “Analysis of 2015 Voltage Reduction Experiment at Ruabon Primary Substation”, University of Strathclyde report SP/LCNF-FN/TR/2015-008.

the results and the range of circumstances and conditions within which they can be applied.

The experimental design of the project has two main externally-imposed constraints. Firstly, the relatively short duration of the project, especially after accounting for the time needed for acquisition and installation of monitoring equipment. The second constraint reflects the fact that experimental interventions are made on a live, in-service, distribution network, and are thus constrained by the operational requirements of the power system, and by the requirement to balance potential learning which could be gained from experiments against the risk to asset health and security of supply.

Within these boundaries, the experimental and analytical design is satisfactory, as is their presentation in the project documentation. In a number of analyses and experiments, the sample size is relatively small, which restricts the ability of the experiment to accurately determine some results, or to report meaningfully on their accuracy. However, this is an inherent limitation resulted from the constraints on the project, and is acknowledged and commented on appropriately. The stated results and claimed benefits are compatible with these limitations.

In general, it can be said that the experimental and analytical design of the project is appropriate to the objectives of the project and that its results and the learning produced are reliable and reproducible within the limits which are claimed for them in the project documentation. The Successful Delivery Criteria in relation to network capacity improvement have been achieved or exceeded for all three test areas.