1. Introduction

In April 2011, Ofgem approved an Electricity North West Limited (ENWL) project under Tier 1 of the Low Carbon Network Fund, "Voltage Management on Low Voltage Busbars (ENWLT1002)", with an agreed budget of £500,000. The project aims were to trial solutions with the potential to help voltage management on LV networks and to provide operators with an understanding of the potential for alternative methods to cope with the changing nature of demands. Solutions to be trialled included; network monitoring, sub-station voltage regulation using on-line tap change distribution transformers, harmonic filters, power factor correction, and in-line LV voltage regulation. powerPerfector was chosen as the provider for the in-line LV voltage regulator and this brief paper summarises the technology, the project objectives, the trial of the voltage regulator, recommendations and the scope for other trials.

2. The powerPerfector Plus

2.1 General Overview

powerPerfector Plus is a 3-phase low voltage technology that provides immediate automatic and autonomous dynamic voltage control to reduce the input voltage whilst maintaining the output voltage above a user-defined minimum level. Whilst the powerPerfector Plus appears to be similar to an autotransformer (there is no separate secondary winding), it differs in its construction and operational characteristics (it provides a very low impedance path for fault currents). The technology was designed as an energy efficiency product that has a design life in excess of 50 years, an efficiency of more than 99%, and a very low fault impedance. The technology was designed specifically as an energy saving device with no moving parts and, when installed in non-domestic properties, the installation of the unit provides a number of power quality benefits. Electricity savings for non-domestic properties are typically 10%.

2.2 How the powerPerfector Plus Works

The powerPerfector Plus optimises the LV system voltage to a user-defined Minimum Output Voltage (MOV) using a patented thyristor-based Automatic Voltage Controller (AVC) that is connected in parallel to the standard powerPerfector.

The AVC has five optimisation settings that change the output voltage level relative to the input voltage level. One setting increases the input voltage level (boost), one setting does not change the input voltage level, and three settings reduce (buck) the input voltage level. The powerPerfector Plus can be set to change optimisation settings manually or automatically.

In automatic mode the technology operates as follows;

- the user sets the MOV at a level between 374V and 392V (this level can be adjusted when the technology is online);
- the AVC constantly samples the output voltage level to ensure the AVC is at the appropriate optimisation setting to maintain the output voltage at or above the MOV;
- if a change in optimisation setting is required, the AVC will only be triggered if the need for the change still exists at the end of a 4-10 second period (avoids hunting);
- if the voltage is below the MOV at any time, the AVC will be triggered to cause the optimisation setting to increase the output voltage level to or above the MOV;
- if the voltage is above the (MOV + the voltage equivalent of one optimisation setting), the AVC will be triggered to cause the optimisation setting to reduce the output voltage level whilst maintaining it at or above the MOV; and

- once the AVC is triggered to change the optimisation setting, the change will happen in less than 2 micro-seconds and is seamless to the supply.

In the unlikely event of a failure of the AVC module, the unit defaults to a 0.0% optimisation setting. The AVC can then be 'hot swapped' using the integral manual bypass arrangement without the need for any interruption to the supply.

The powerPerfector Plus has the ability to be IP addressable and the main functionality can be controlled remotely (auto or manual state, enable or disable a timer function, and remote monitoring of voltage, current, and power levels (amongst others).

The description in this section 2.2 applies only to the powerPerfector Plus. Other in-line LV voltage regulators may have different functionality and will work differently.

3. Project Aims and Objectives

3.1 Project Aims

To trial solutions with the potential to help voltage management on LV networks and to provide operators with an understanding of the potential for alternative methods to cope with the changing nature of demands.

3.2 Project Objectives

- Demonstrate the buck and boost capabilities of the powerPerfector Plus and verify whether a minimum output voltage is maintained;
- Construct a circuit representation of the powerPerfector Plus to allow network modelling to be undertaken;
- Determine the powerPerfector Plus capability to manage and control voltage in two LV domestic feeders;
- Test the technology at various MOV settings whilst monitoring the far point voltages.

4. In-line LV Voltage Regulator Trial

4.1 General Overview

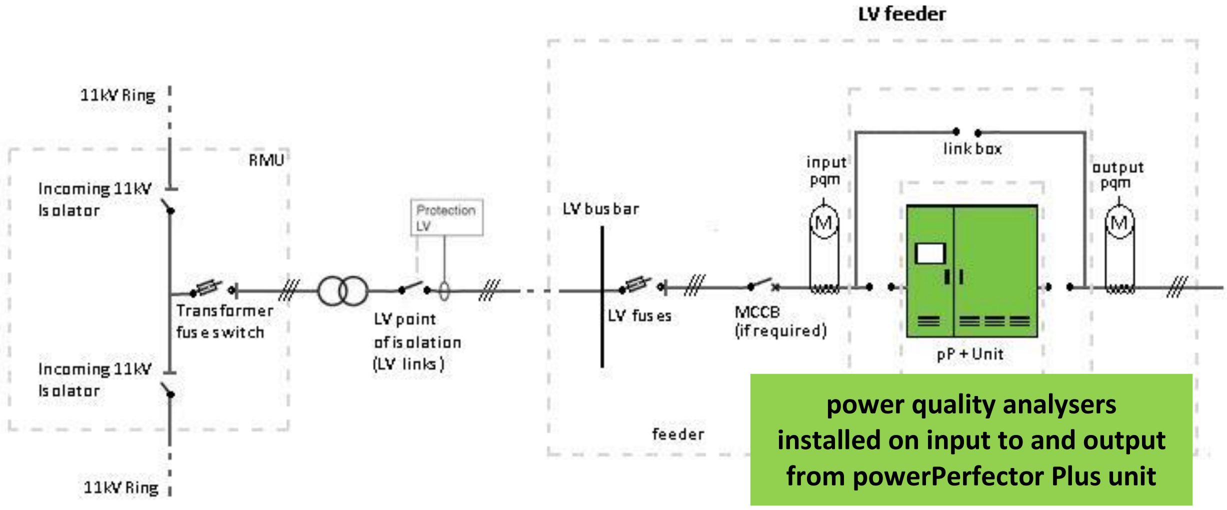
ENWL identified a number of domestic LV feeders for evaluation and summary details of the two selected for the trial are provided in Table 1 below.

Table 1 – Details of the Feeders Selected for the In-line LV Regulator Work Packages

LV Feeder	Golborne Secondary S/S Edge Green Lane	Droylesden Secondary S/S Greenside Lane
Number of Domestic Customers	38	50 (135 after LV links inserted)
Domestic PV Installations	number required	1 (1 after links inserted)
Unit Rating (provided for fully loaded feeder)	350 kVA	350 kVA
Optimisation Range Settings	+4%, 0%, -4%, -8%, -12%	+2.7%, 0%, -2.7%, -5.4%, -8.1%
Installation Date	8 August 2012	25 October 2012

The circuit diagram showing the location of the powerPerfector Plus is provided in Diagram 1.

Diagram 1 – Circuit Diagram of the powerPerfector Plus location in the Feeder



4.2 Work Packages

There were two specific work packages;

Work Package 1 (WP1)

- Vary the output voltage of the in-line LV voltage regulator to demonstrate the buck and boost functionality;
- Manchester University to construct a circuit model of the in-line LV voltage regulator; and
- Verify the Manchester University circuit model of the in-line LV voltage regulator.

Work Package 2 (WP2)

- Additional domestic load was added, all without any PV installations by installing LV links on the feeder.
- Vary the output voltage of the in-line LV voltage regulator to demonstrate the buck and boost functionality whilst monitoring the mid-point and far-point voltage for the Greenside Lane feeder during this phase (this information was used to develop working assumption for the Edge Green Lane feeder); and
- Validate the Manchester University circuit model of the in-line LV voltage regulator.

The in-line mid-point and far-point monitoring and metering devices were developed between WP1 and WP2.

5. Results

The power quality analysers were installed on the input and output of both feeders for more than 14 months in the case of the Edge Green Lane feeder and more than 12 months in the case of the Greenside Lane feeder. WP2 also collected data at the mid-point and far-point of the Greenside Lane feeder. Due to the installation configuration used, it has only been possible to evaluate the voltage control and management characteristics of the in-line LV voltage regulator, but not to consider power quality improvements or savings evaluation.

A selection of the data has been used to provide the charts in this section. In all of the charts in this section;

- the **black** trace is the input voltage to the powerPerfector unit;
- the **red** trace is the output voltage from the powerPerfector unit; and
- the **blue** trace is the import and export power (kW).

Chart 1 – Edge Green Lane, Demonstration of Buck Mode (WP1)

For this period, the MOV was set to 220V and the chart demonstrates the MOV was maintained with a varying input voltage. The step reductions in output voltage occur when the input voltage increases to the point where there is a change of optimisation setting (buck mode).

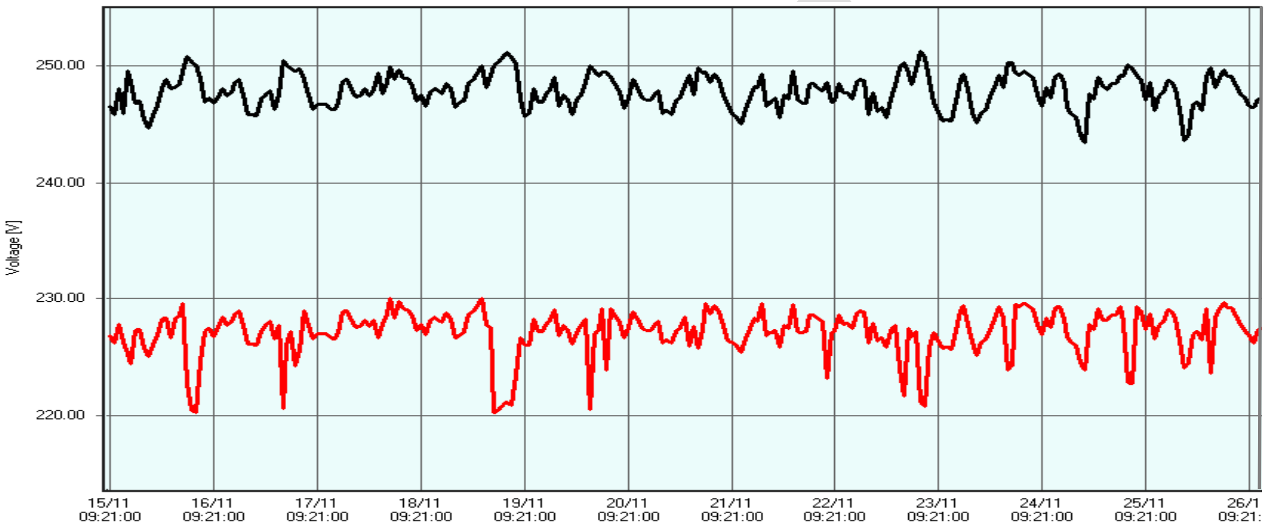


Chart 2 – Edge Green Lane, Demonstration of Boost Mode (WP1)

For this period, the MOV was set to 243V and the chart demonstrates the MOV was maintained with a varying input voltage. The step increases in output voltage occur when the input voltage reduces to the point where there is a change of optimisation setting (boost mode).

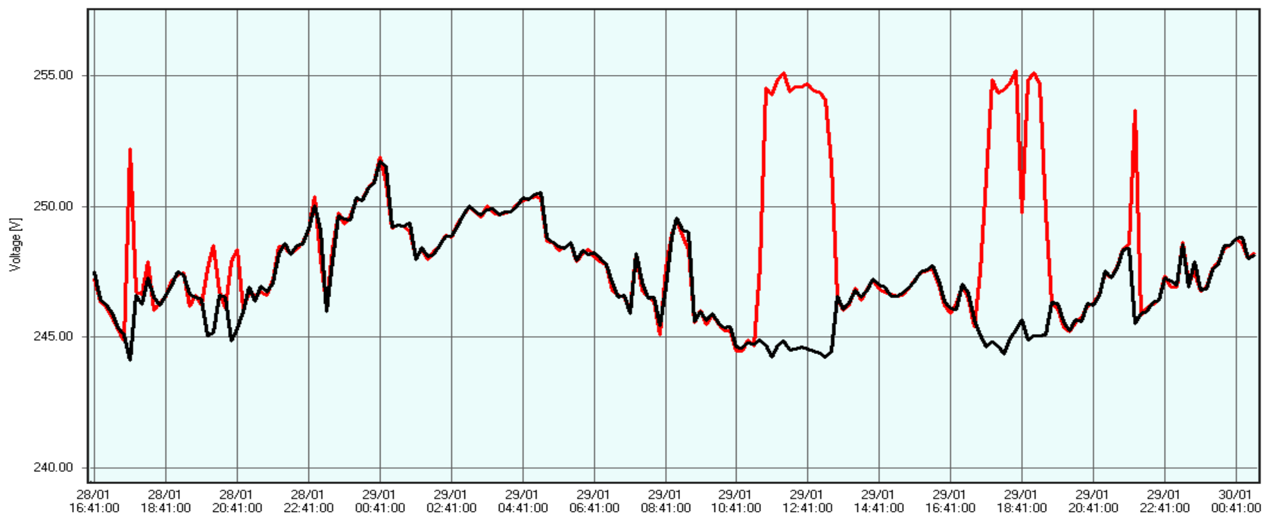


Chart 3 – Edge Green Lane, Increasing MOV to Input Voltage Level (WP2)

For this period, the MOV was increased over time to the input voltage level and the chart demonstrates the operation of the unit with varying input voltage. The step changes in output voltage occur when the input voltage changes sufficiently to require a change of optimisation setting. The mid-point and far-point voltages were maintained within statutory limits at all times.

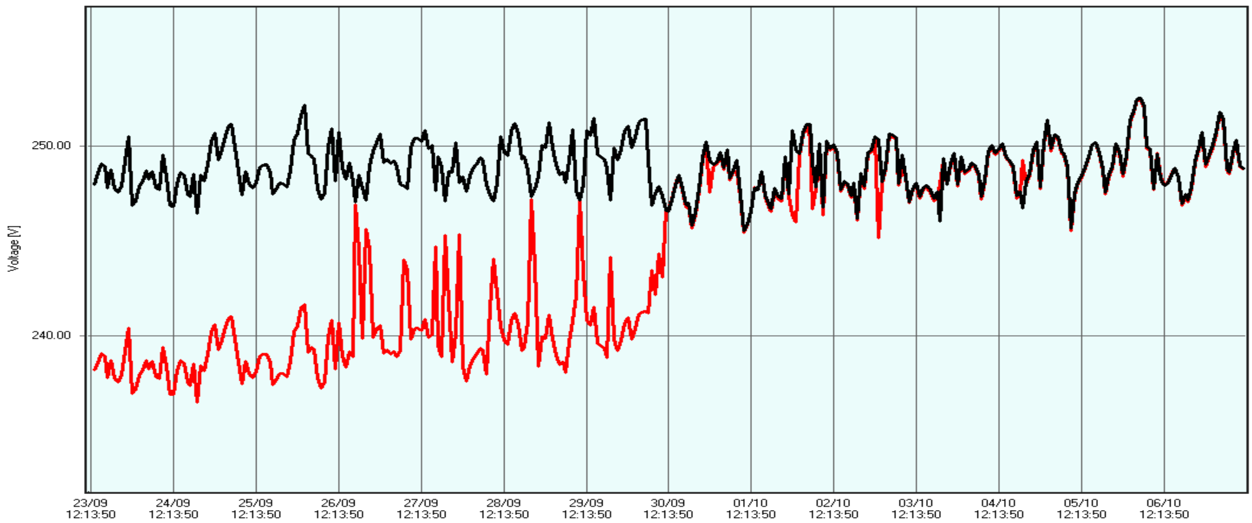


Chart 4 – Edge Green Lane, Daily Profile of Import and Export Variation (WP2)

This chart illustrates the variation in voltage and import / export (the **orange** line is the zero kW level) through the in-line LV voltage regulator over a 42 hour period. The voltage varies naturally during the day with imported electricity and increases marginally when there is export from the PV (as expected). The lower voltage in the feeder means the PV generation is not constrained due to a high feeder voltage and creates a net export from approximately 11.00 to 17.00 hours with a peak value of 45 kW. The maximum demand on the feeder is 21 kW which negates the need for any change in optimisation setting during the 42 hour period.

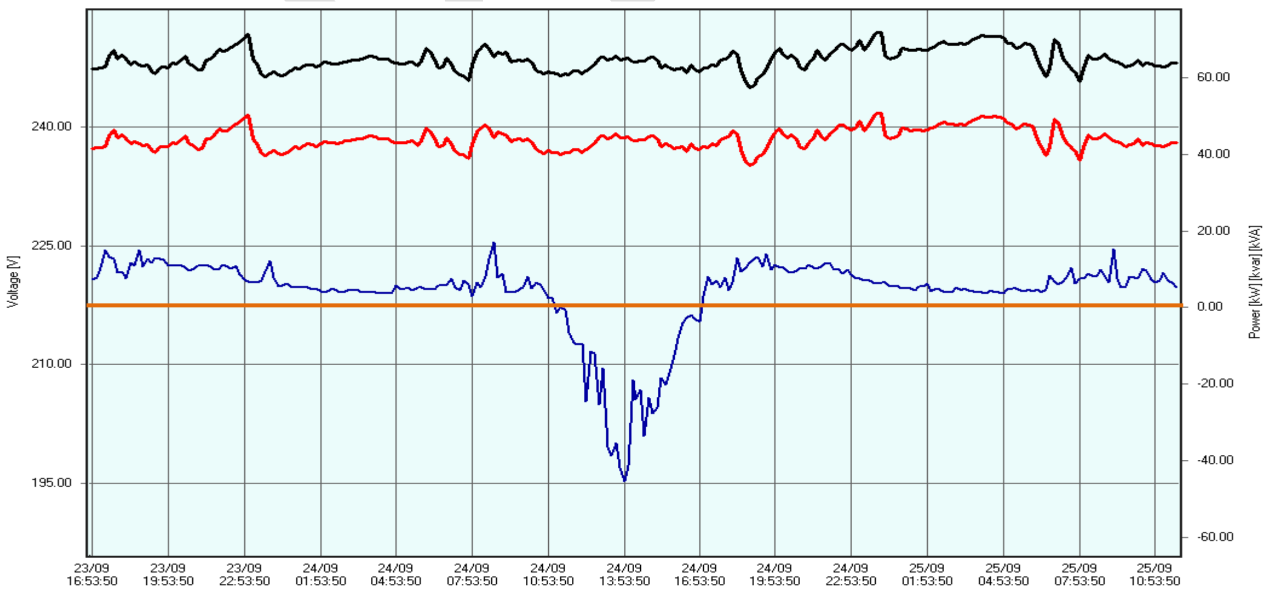


Chart 5 – Greenside Lane, Demonstration of Buck Mode (WP1)

For this period, the MOV was set to 230V and the chart demonstrates the MOV was maintained with a varying input voltage; the output voltage level is higher than 230V due to the optimisation setting range of this unit. The step reductions in output voltage occur when the input voltage increases to the point where there is a change of optimisation setting (buck mode).

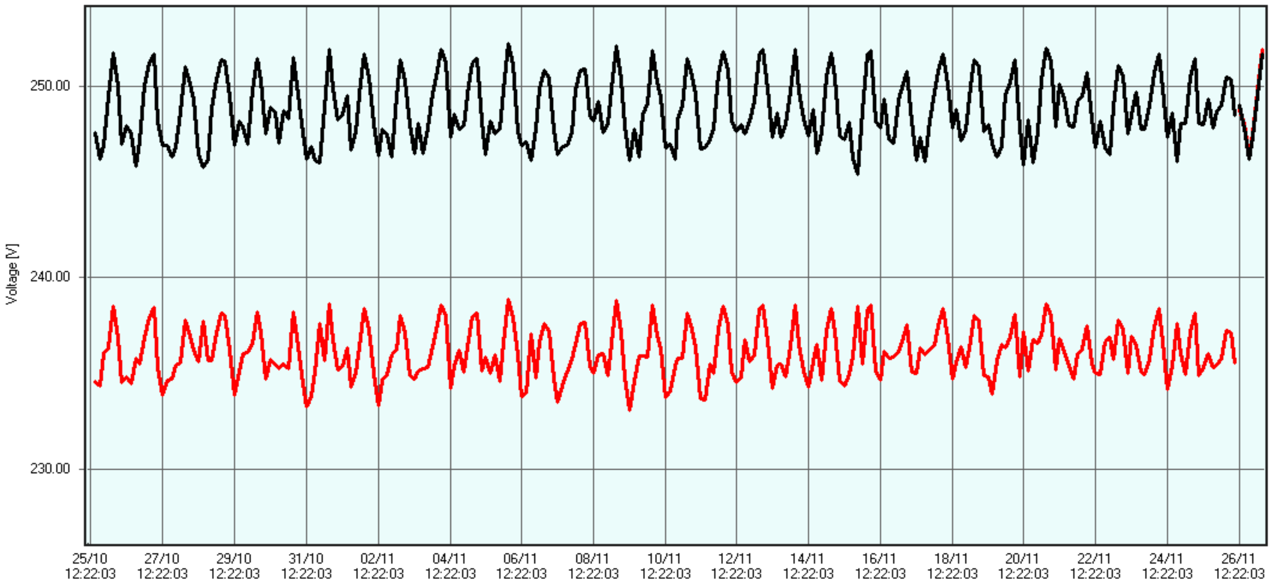


Chart 6 – Greenside Lane, Demonstration of Boost and Buck Mode (WP1)
For this period, the MOV was set to 243V and the chart demonstrates the MOV was maintained with a varying input voltage. The step increases in output voltage occur when the input voltage reduces to the point where there is a change of optimisation setting (boost mode) and vice versa (buck mode).

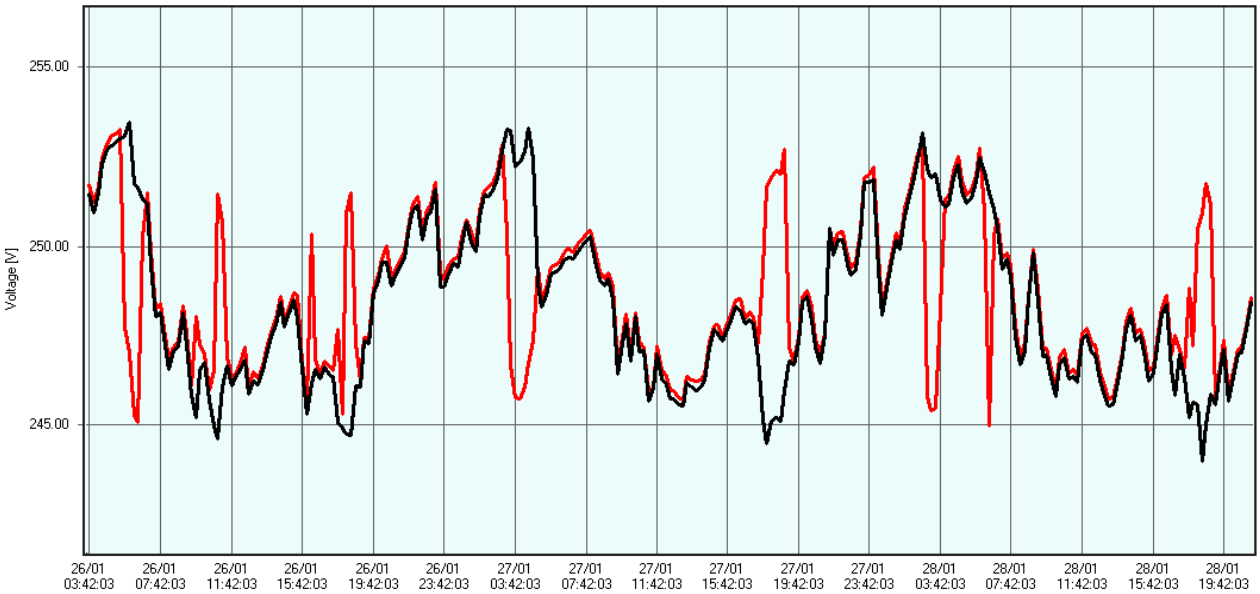


Chart 7 – Greenside Lane, Increasing MOV to Input Voltage Level (WP2)
For this period, the MOV was increased over time to the input voltage level and the chart demonstrates the operation of the unit with varying input voltage. The step changes in output voltage occur when the input voltage changes sufficiently to require a change of optimisation setting.

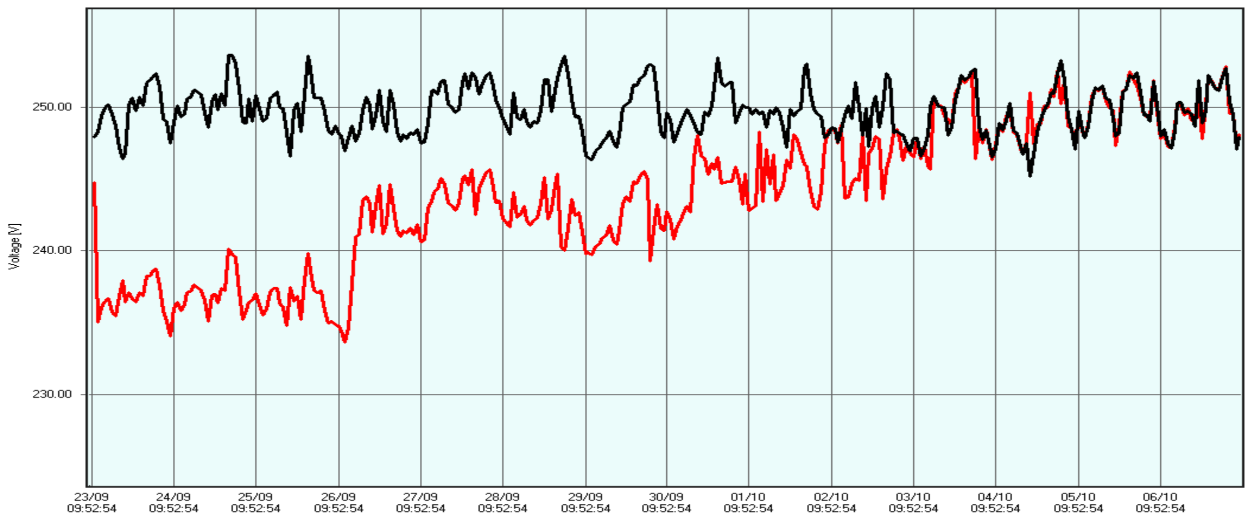
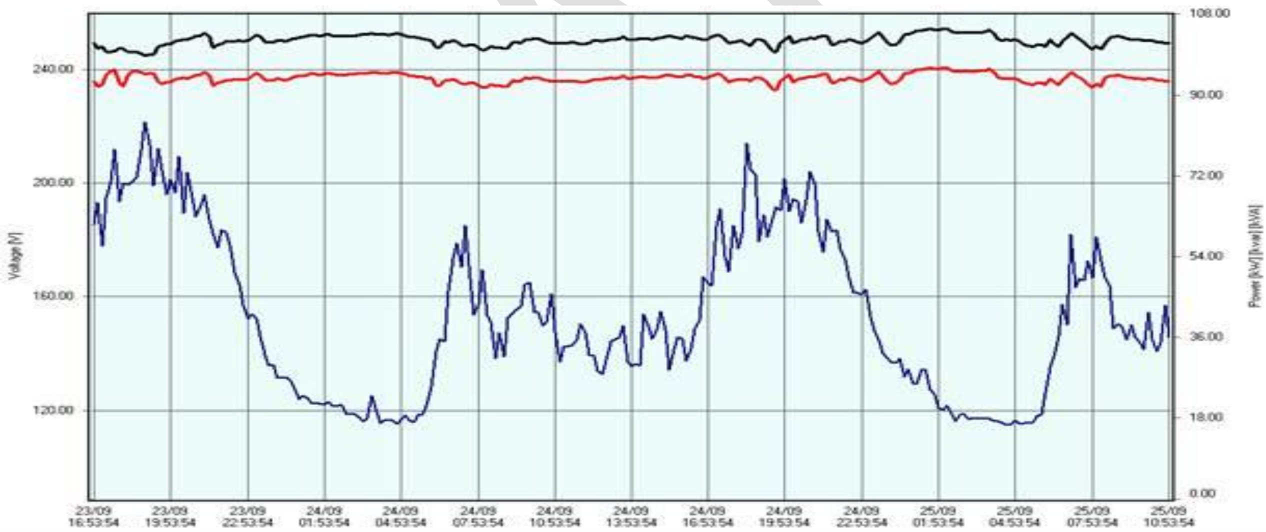


Chart 8 – Greenside Lane, Daily Profile of Import Variation (WP1)

This chart illustrates the variation in voltage and import through the in-line LV voltage regulator over a 42 hour period. The voltage varies naturally during the day with imported electricity volume. The maximum demand on the feeder is 81 kW and the minimum demand was 16 kW; the low level of these values compared to the rating of the circuit minimised the need for any change in optimisation setting during the 42 hour period.



6. Conclusions

As can be seen from section 5 above, the in-line LV voltage regulator trialled has been proven to automatically and autonomously control and manage LV voltage on two domestic feeders whilst maintaining customer voltages within statutory limits, even when the maximum demand was approximately 15% of the unit rating.

All of the project objectives have been met in full;

- The buck and boost capabilities of the powerPerfector Plus have been demonstrated and the MOV maintained (see Charts 1, 2, 5, and 6);
- A model of the powerPerfector Plus has been completed by Manchester University which will allow network modelling to be undertaken in PSCAD / EMTDC simulation tools;

- The powerPerfector Plus has been proven to manage and control voltage in two LV domestic feeders (one saturated with PV installations and another with only one PV installation, see Charts 3 and 7); and
- The unit was tested at various MOV settings, including with mid-point and far-point voltages monitored for one feeder (see Charts 4 and 8).

This project has proved the automatic and autonomous control and management of LV voltage using in-line LV voltage regulators (powerPerfector Plus) in two lightly loaded domestic networks. It has proved that these in-line LV voltage regulators have a role to play in the provision of LV voltage control and management level in either LV feeders or on the LV side of 11kV/LV transformers.

7. Recommendations

Based on this trial, it has been found that in-line LV voltage regulators can be used to provide automatic and autonomous LV voltage control and management with a greater range of variation than available with a standard secondary transformer to address the natural LV voltage variation within a feeder and LV voltage variation due to (non-peak) micro-generation export and (peak) demand. The ability to set operational parameters remotely and the lack of any constraint in the number of changes in the optimisation settings together with the speed of operation make this a viable technology for application to secondary transformers and LV feeders.

In addition, the following recommendations are made based on the experience of this project;

- **In-line voltage regulators can be used to provide automatic and autonomous LV voltage control and management**.
- The in-line LV voltage optimisers selected had different **optimisation range settings** and the range on the Greenside Lane unit did not operate often. It is recommended that voltage logging is used to determine the most appropriate optimisation setting range.
- The selected LV feeders had very low **maximum demands** compared to the unit ratings. It is recommended that higher loaded feeders are selected.
- Power quality data could not be analysed as appropriate **baseline data** had not been collected. It is recommended that a baseline is created to allow power quality benefits to be analysed.
- The **remote operation of and data retrieval from** the in-line LV voltage regulator was not required for this project. The AVC has been developed since these units were installed and it is recommended that the web-based monitoring and reporting service now available is used (including critical parameters) to reduce the number of site visits.
- Consideration should be given to the interaction of manual voltage control on secondary transformers with automatic and autonomous in-line LV voltage regulators. It is recommended that the **tap setting on the secondary transformer** is adjusted to provide the in-line LV voltage regulators the maximum operational voltage range.

8. Further Trials

Further trials are required to determine the benefits of employing in-line LV voltage regulators to other areas of the LV network and three possible trials are detailed in this section.

8.1 Voltage Management and System Loss Reduction on a Heavily Loaded Transformers or Feeders

- Investigate the effect of automatic and autonomous voltage control and management on peak demand, power factor, energy reduction, system losses (LV and HV networks and upstream to generation) and any upstream effects to quantify the carbon reduction possible.
- Install in-line LV voltage regulators and other measures at capacity constrained transformers or LV feeders supplying domestic loads, non-domestic loads, and mixed domestic / non-domestic loads to determine the effect and any benefits.
- Monitor power quality measures at;
  - (i) the input to the transformer;
  - (ii) the output from the transformer / input to the in-line LV voltage regulator;
  - (iii) the output from the in-line LV voltage regulator; and;
  - (iv) some point in the customers' network during a control period with no in-line LV voltage regulator or measures in circuit (to determine base situation) and then with them in circuit at various settings.

8.2 Voltage Management, System Loss Reduction, and Export Capacity Increase on a Heavily Loaded Micro-Generation (probably PV) Domestic Transformer or Feeder

- Investigate the effect of varying / managing line voltage on the level of micro-generation (ostensibly PV) on a transformer / feeder where there is a very high capacity of micro-generation compared to the capacity of the transformer / feeder and determine how automatic and autonomous LV voltage control and management can be used to increase export at lightly loaded periods and reduce demand at heavily loaded periods.
- Install in-line LV voltage regulators and other measures at transformers or on LV feeders that have a high capacity of micro-generation compared to the capacity of the transformer / feeder to determine the effect and any benefits.
- Monitor power quality measures at;
  - (i) the input to the transformer;
  - (ii) the output from the transformer / input to the in-line LV voltage regulator or other measure;
  - (iii) the output from the in-line LV voltage regulator or other measure;
  - (iv) at micro-generation locations at the mid-point and far point of the feeder during a control period with no in-line LV voltage regulator or measures in circuit (to determine base situation) and with them installed at various settings.

8.3 Wide Area Voltage and Demand Management

- Investigate the interaction and effect of automatic and autonomous LV voltage control and management at different voltage levels to manage network imports and exports whilst delivering savings in conjunction with other measures (energy efficiency, flexible capacity, micro-generation, storage, etc.); this may include the application of soft Normally Open Points and fast switching mesh technology to increase capacity and interconnectivity.
- Install in-line LV voltage regulators and other measures at capacity constrained transformers or LV feeders supplying either domestic loads, non-domestic loads, or mixed domestic / non-domestic loads and at transformers / LV feeders that have a high capacity of micro-generation compared to the capacity of the transformer / feeder to determine the effect and any benefits.
- Consider the wider network application of various measures to determine how they interact and the extent to which the benefits are additive, e.g. voltage control and management at

33 kV versus LV. There is the possibility to use the Strathclyde test network in conjunction with DNOs as this is an isolated and discrete network.

- Monitor power quality measures on;
  (i) the input to the transformer;
  (ii) output from the transformer / input to the in-line LV voltage regulator or other measure;
  (iii) the output from the in-line LV voltage regulator or measure;
  (iv) for heavily loaded transformers / feeders, at some point in the customers' network during a control period with no in-line LV voltage regulator in circuit (to determine base situation) and with the in-line LV voltage regulator installed at each setting; and
  (v) at micro-generation locations at the mid-point and far point of the feeder during a control period with no in-line LV voltage regulator in circuit (to determine base situation) and with the in-line LV voltage regulator installed at each setting.

9. Further Information

Please feel free to contact either of the authors for further information.

David Middleton and Martin Stevens
powerPerfector
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