electricity north west

Bringing energy to your door

Low Carbon Networks Fund Project

Voltage Management on Low Voltage Busbars

Close Down Report

December 2013

Contents

1. Executive summary

1.1 Aims

This project deployed a range of voltage management technologies and techniques across 15 distribution substations within Electricity North West Limited, hereinafter referred to as Electricity North West. These technologies were assessed in terms of their ability to effectively regulate line voltage in real time. In addition to voltage management, the ability of compensating devices to correct for poor power factor was also assessed. The project sought to develop understanding of the potential for these alternative techniques to address issues of voltage regulation of low voltage networks in response to increases in low carbon loads and penetration of generation and inform the development of Electricity North West operating practices.

1.2 Methodology

This project explored the potential for alternative, lower cost technical solutions to the management of voltages on low voltage networks in the face of increased network loads and distributed generation.

The project deployed a range of existing technologies on the Low Voltage (LV) network of Electricity North West. This included:

- Distribution Transformers with On Load Tapchanger
- powerPerfector Plus (voltage optimiser)
- Active Harmonic Filters
- LV Capacitors

These devices were monitored in real time utilising techniques developed under the "LV Network Solutions" LCNF First Tier project.

In addition to the field trials the University of Manchester have produced detailed models of both these, and other devices not deployed in the field, in order to assess their ability to successfully manage the voltages on today's networks and on those of the future.

1.3 Outcomes

The project has successfully deployed a range of voltage management technologies / techniques across a number of sites on the Electricity North West LV network.

The technologies were purchased with basic specifications which were developed during the build, installation and commissioning phases.

These technologies were installed in parallel with existing equipment to ensure a speedy changeover in the unlikely event of a failure and a new set of operational procedures were introduced.

The monitoring equipment developed and installed under our LV Network Solutions First Tier project was used to support the trials and to assess the effectiveness of the equipment to manage voltages. Various trials were performed with the support of both the technology suppliers and the University to investigate the full operational range of all the devices and to record the associated network effects.

In conjunction with the deployment phase of the project the University of Manchester developed sophisticated, validated network models to allow simulations to be performed. These simulations allowed the project to explore a number of scenarios not possible during the trials including the effects of future load patterns.

Electrical models of all the devices deployed were developed by the University and the monitoring data was used to verify that the models were correct. Importantly the manufacturers of the various devices supported the University in the production of these models. In addition, the University also used standard models of other voltage control devices not being deployed as part of this project (eg battery energy storage).

With these models the University carried out a series of simulations to assess the effectiveness of the techniques. These simulations included present and future demand and generation combinations.

1.4 Key Learning

This project has successfully shown that through the use of techniques such as distribution transformers with on load tapchangers and LV capacitors, voltages can be effectively managed on the LV systems to support the connection of increased low carbon technology.

The project has shown that more than one technology may be required to manage the voltages on LV feeders associated with a distribution substation. Feeders which contain more generation than demand may require a different control approach than those that are without generation. The issue becomes more complicated when one substation contains some feeders with significant generation and others with significant new non-diverse low carbon loads such as electric vehicles and heat pumps. In these cases a capacitor could be installed to control the individual demand biased feeders whilst a transformer with an on load tap changer manages the rest of the substation which is generation biased. The project has demonstrated that a coordinated approach to voltage control on the LV network may provide a more effective means of voltage management than the use of locally controlled devices but that both approaches offer benefits.

The successful conclusions of this project have led Electricity North West to take LV Voltage Control a stage further through the Low Voltage Integrated Automation (LoVIA) First Tier project. The technique will be further integrated into the Electricity North West network as part of the new Second Tier project, Smart Street.

1.5 Conclusions

Electricity North West has successfully deployed a range of voltage management technologies across 15 sites. A number of trials have been carried out to investigate the full operational range of the devices.

Through the real time monitoring and the simulations carried out by the University of Manchester the project has shown that voltage control can be effective for LV networks. Using these technologies, additional capacity can be released to accommodate new low carbon demands and generation.

2. Project background

The decarbonisation of energy production, transport and heating is expected to result in significant increases in electricity demand. As the demand on the network increases, the likelihood of line voltage falling below acceptable thresholds becomes increasingly more likely. In addition, the expected increase in penetration of domestic forms of generation such as PV and micro-CHP are likely to give rise to line voltage exceeding acceptable thresholds during periods of low demand. In order to avoid the potentially high cost associated with traditional forms of reinforcing existing networks to cope, consideration of new alternative solutions is required. This problem is expected to materialise initially at the low voltage network level thus reducing power quality and this project intends to focus at this level.

The project will concentrate on developing innovative and economic alternatives to traditional network reinforcement which typically accompanies voltage problems on LV networks. The forecast load and generation growth is anticipated to place significant stresses on the existing LV network infrastructure. Thermal problems are expected to represent a challenge at the transformation point of the LV busbars, and other LCNF initiatives are ongoing investigating how this issue can be addressed. However, it is the expected fluctuation in line voltages which will need to be addressed if appropriate voltage quality is to be maintained and reinforcement avoided. It is currently unclear how the future demand will affect the voltage and this project will be informed by another of Electricity North West's LCNF T1 project – Low Voltage Future Networks. However, the dynamic nature of future loads will require increased ability to control voltage at points other than just the 11kV busbars.

3. Project scope

This project will seek to deploy a range of voltage management technologies/ techniques across 15 distribution substations which will be assessed in terms of their ability to effectively regulate line voltage in real time in a safe and economical manner. In addition to voltage management, the ability of compensating devices to correct for poor power factor will also be assessed.

4. Success criteria

Success criteria are:

- Establish learning on a range of alternative techniques for management of voltages on low voltage networks
- Deployment of new technology on the network for improved voltage regulation and measurement of the effect on voltage profiles in response to changes in demand
- Production of standard designs / applications for installation of alternative voltage management techniques
- Measurement of voltage profiles and their behaviour in relation to changes in load over the load cycle and comparison with reference networks.
- Improved efficiency (ie reduction in networks losses and optimised real power distributions) on low voltage networks via improved power factor.
- Improved power quality through a reduction in voltage perturbations.

5. Details of work carried out

This project installed different voltage regulation and voltage management techniques on the LV network of Electricity North West. In parallel with the installation of the equipment the University of Manchester conducted modelling work on all the technologies installed as well as some not installed to assess their effectiveness at managing voltage.

The different types of equipment were assessed both from a practical and economic point of view. This produced a list of equipment it was considered feasible to install as part of this project whilst others would be modelled.

The devices installed by Electricity North West can be categorised into the following areas:

- Voltage Regulation
  Two distribution transformers with on-load tapchangers
  Two voltage optimisers (powerPerfector Plus)
- Reactive Compensation
  Eight LV capacitors
- Voltage Quality
  Two active harmonic filters

The University modelled all of the above devices and also modelled energy storage as a means of voltage management. This report presents extracts from reports produced by the University, ABB and powerPerfector. For more detail refer to the full reports in Appendices 1 – 12.

To further discuss the project in terms of what was done and the results obtained it can be divided into two work streams:

I. Electricity North West Deployment

II. The University of Manchester Modelling

5.1 Electricity North West Deployment

In the project registration document it was stated that five distribution transformers with on load tap changers and ten reactive compensation or other voltage management devices would be deployed across 15 substations.

When research was carried into which products were to be installed and the location of installation it became clear that more learning would be obtained from combining different techniques at the same substation. It also became clear that installing more than two transformers with on load tapchangers would not increase the learning and the funds could be used to install active harmonic filters thus obtaining additional learning outcomes.

From another of Electricity North West's First Tier projects "LV Network Solutions" it became apparent that PV generation can have an effect on the harmonic profile of the network. Therefore installing filters allowed the assessment of their effectiveness in improving the voltage waveform delivered to the customer.

5.1.1 Site Selection

Once the number of devices to be deployed was decided the next step was to decide where on the network they would be installed.

Electricity North West has a Distributed Generation (DG) database which records the details, including location, of all reported generation installed on the network. An analysis of the DG database was carried out to identify the locations of clusters of PV generation. These were the areas to be targeted with this new technology.

The business had made a decision to install this equipment either in parallel with existing equipment or via an isolation point so that the equipment could be easily removed from the network in the event of a fault or if the equipment did not function as expected. Site surveys were then conducted to assess space and access requirements and those with enough space and reasonable access were selected.

When considering where to install the equipment it was decided to put one of the voltage optimisers on a site with no generation and with the flexibility to reconfigure the network via open points to add or remove demand. The voltage optimisers (powerPerfector Plus) are marketed as a device to reduce voltage thereby delivering reduced energy to a customer and reducing energy bills. These have been predominantly marketed to large single industrial customers. So it seemed appropriate to test their functionality in a predominantly demand network as well as a predominantly generation network.

5.1.2 Distribution Transformers with On Load TapChangers

The tap changers for these devices were purchased from Maschinenfabrik Reinhausen (MR) in Germany who had recently developed a prototype solution to explore market opportunities. MR has long history in tapchanger manufacture and many utility companies use both their OilTap and VacuTap designs at 33kV and 132kV. The tapchanger used was based on the MR standard OilTap design with modifications to suit the dimensions and ratings of a distribution transformer. The tapchanger has 9 taps in steps of 2%.

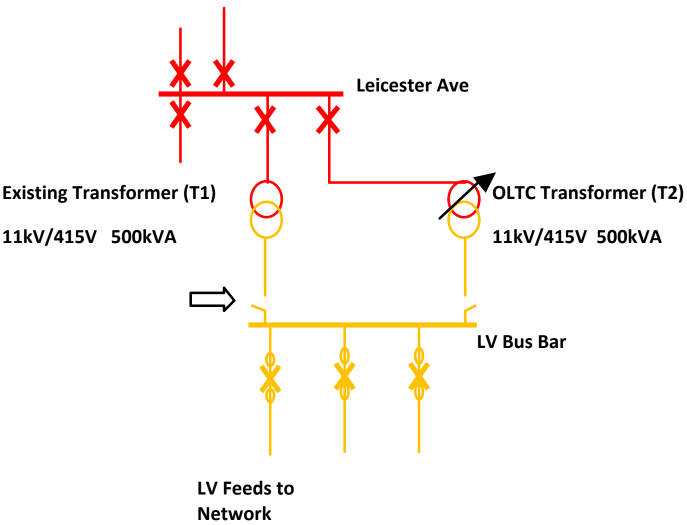
MR has now developed a new range of tapchangers specifically designed for distribution transformers and using vacuum technology called the GridCon iTap which would be used in future installations.

The transformer design was based on the standard Electricity North West Specification ES322 – Ground Mounted Distribution Transformers and was procured from our nominated supplier, Efacec, under existing contractual arrangements.

Two transformers were purchased and were installed at Landgate and Leicester Avenue distribution substations.

▲ *Figure 1 – Distribution Transformer with on load tapchanger*

As these were trial units with unknown reliability the new transformers were installed in parallel with the existing transformers. An extension piece for the LV board was specified and purchased to give another set of LV links to isolate the second transformer. The existing transformer was left on open standby and the new transformer feeding the load as per the schematic below.



▲ *Figure 2 – Schematic for Connection of Distribution Transformers with On Load Tapchangers*

Operational procedures (see Appendix 13) were written and implemented informing staff why the equipment had been installed and what to do in the event of an issue with the transformer or tapchanger.

Fundamentals, as the UK representative of MR, carried out the design and build of the tap change control panel which included the TapCon 230 relay. The drawings for the tap change panel can be found in Appendix 14. As part of this service Fundamentals also provided some guidance on the settings to be applied to the relay. This was the first time either Electricity North West or Fundamentals had devised settings for distribution transformers and there was an element of trial and error to find appropriate settings. On the day of commissioning the LV busbar voltage was measured when supplied by the existing transformer and this was used to set the relay on the new transformer. The relay was set to supply approximately 253V single phase to the LV busbars. This is a standard voltage that Electricity North West uses at distribution substations. The settings files for the relays are in Appendices 15 and 16.

5.1.3 Voltage Optimiser (powerPerfector Plus)

For this project the powerPerfector Plus voltage optimisation unit was chosen to trial at two locations. Initially it was planned to have this unit optimising the voltages on the LV busbars but this proved difficult to achieve in the timescales and would have involved significant work at site. Therefore it was decided to install these devices to control the voltage on one LV feeder. At one site the feeder with the most PV generation was chosen and at the other site it was the feeder with no generation. This would give an indication of how the unit controlled for generation and demand.

▲ *Figure 3 – powerPerfector Plus*

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 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 Plus.

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

In automatic mode the technology operates as follows;

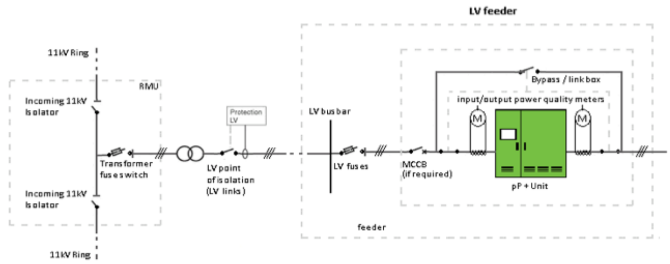
- the user sets the MOV at a level between 374V and 392V;
- the AVC constantly samples the output voltage level to ensure the AVC is at the appropriate optimisation setting to maintain the output voltage at or above the MOV;
- if a change in optimisation setting is required, the AVC will only be triggered 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.

Two different units were purchased for this project. One unit had the range +4%, 0%, -4%, -8% and -12% and the other unit range is +2.7%, 0%,

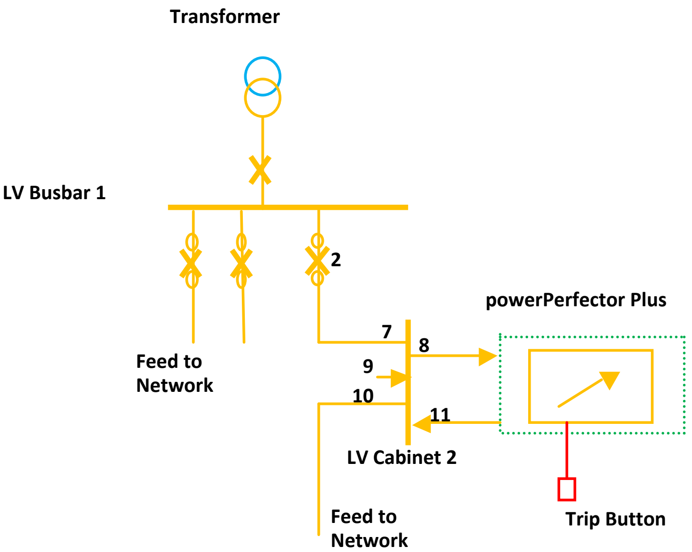
-2.7%, -5.4% and -8.1%. Both units were rated at 320kVA, 500A.

As with the Distribution Transformer with OLTC these units were installed with a bypass arrangement for supply security reasons as per the diagram below.



▲ *Figure 4 – Bypass Arrangement for powerPerfector Plus*

This bypass was created using a second LV board. The schematic below shows the connection arrangement using this second LV board.



▲ *Figure 5 – Schematic for Connection of powerPerfector Plus*

- LV Busbar 1
  Way 2 – Outgoing Feeder (630A Fuseway)
- LV Cabinet 2
  Way 7 – Incoming Feed (800A Disconnector)
  Way 8 – Outgoing Feed to powerPerfector Plus Unit (630A Link)
  Way 9 – LV Bus Section Disconnector (800A Disconnector) – Normally open
  Way 10 – Outgoing Feed to LV Network (630A Link)
  Way 11 – Incoming Feed from powerPerfector Plus Unit (630A Link)

Before any isolation of the powerPerfector Plus is carried out it is important to ensure the optimisation is at 0%, ie input voltage is the same as the output voltage. In order to reduce the training required a trip button was fitted within the second LV board. This trip button "zeroed" the powerPerfector Plus and allowed the operators to carry out isolation using standard procedures.

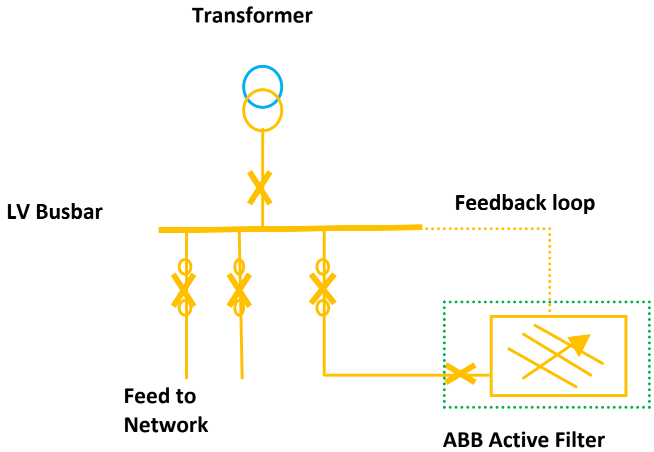
Once these units were installed a number of trials were conducted. The unit was set at different voltages used information from the monitoring equipment was used to assess the performance. These results will be discussed later in the report.

5.1.4 Active Harmonic Filter

The active harmonic filters chosen for this project were manufactured by ABB. The catalogue in Appendix 17 contains the manufacturer's information for the PQFS filter used in the trial. It was decided to install one unit in an outdoor location and one in an indoor location. The sites chosen for this equipment were heavily saturated with PV generation. PV generation can cause issues with power quality, specifically harmonics and the trial was to investigate if the installation of a filter could improve this.

▲ *Figure 6 – Active Filter*

The filter was connected to the LV cable of an outgoing feeder. A cutout was placed in series with the filter to provide isolation – see schematic below.



▲ *Figure 7 – Schematic for the connection of an active filter*

The filter measures the harmonic content in the LV network. It then injects the relevant currents (up to a maximum of 100A) in anti-phase to filter out the harmonics. As with the other technologies tests were conducted to assess how well the filter works.

5.1.5 LV Capacitors

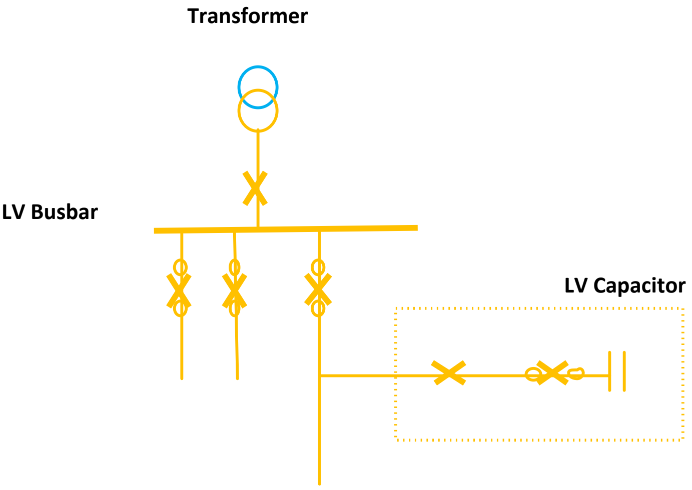
In addition to installing technologies at the distribution substation to the project looked at whether technologies could be installed closer to the customer to improve voltage profiles along feeders.

Studies carried out by both the University of Manchester and S&C Electric (see Appendix 18) showed that the installation of capacitors would have the effect of raising the voltage of the entire feeder. The studies showed that the optimum place to locate the capacitor is approximately half way along its electrical length.

These capacitors would help the voltage only on the one feeder and given that they will raise volts it seemed logical to install them on feeders with lots of demand and very little or no generation.

The capacitors were purchased from ABB using the Electricity North West specification in Appendix 19. Electricity North West worked in conjunction with ABB to design an enclosure suitable to be located on the street to contain the capacitors. The capacitors are breeched onto the main cable using a suitably rated service cable via a Moulded Case Circuit Breaker (MCCB) as per the diagram below. This MCCB provides a disconnection point and the opening of this will start a discharge cycle. As the MCCB is not considered a point of isolation some fuses were installed in series which the operators will remove as required.

▲ *Figure 8 – LV Capacitor*



▲ *Figure 9 – Schematic for the Connection of a LV Capacitor*

Although the project registration document suggested that these would be installed at sites separate to the other technologies subsequent studies suggested that greater learning would be gained by installing them in conjunction with other technologies.

Operating procedures were developed for all the technologies (see Appendix 13). The procedures gave the engineers a method to return the system to how it was before the new equipment was installed. This was in case of a fault in the equipment which could affect customer's supplies. Now that confidence has been gained in installation and operation of the equipment the bypass arrangements would not be used in future installations.

5.2 University of Manchester Modelling

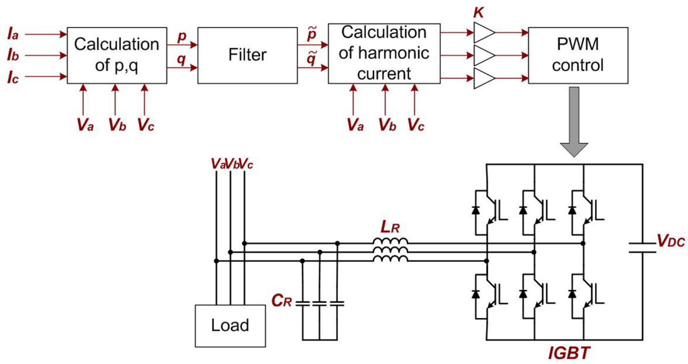
In parallel with the practical installation and measurement work, the University of Manchester have conducted modelling and analysis work.

To begin this work the University created detailed mathematical models for all the technologies being deployed. The on load tap changer and capacitor are standard pieces of equipment which are being used in a new way, therefore there was little consultation required with the manufacturer to develop these models.

For the powerPerfector Plus and Active filter a series of workshops were held with the manufacturers to allow the University to fully understand how the equipment functioned and how to construct a representative model.

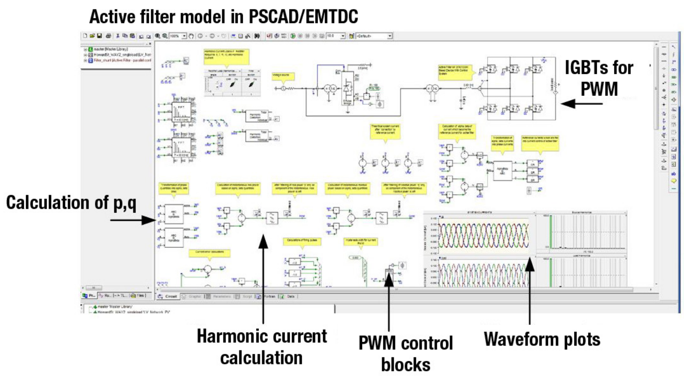
5.2.1 Modelling of active harmonic filter

To simulate the behaviour of an active filter, a model was developed in PSCAD/EMTDC . The control algorithm of the model for harmonic compensation is shown in figure 10. Va, Vb and Vc are the voltage at the connection bus, Ia, Ib, and Ic are the three phase ac currents at the harmonic load. The phase voltages and currents are first measured and converted into real and reactive components, and then the instantaneous components are filtered out. The harmonic current is calculated and then used by a Pulse Width Modulation (PWM) inverter to force the compensation current into the network.



▲ *Figure 10: Control algorithm of active filter model*

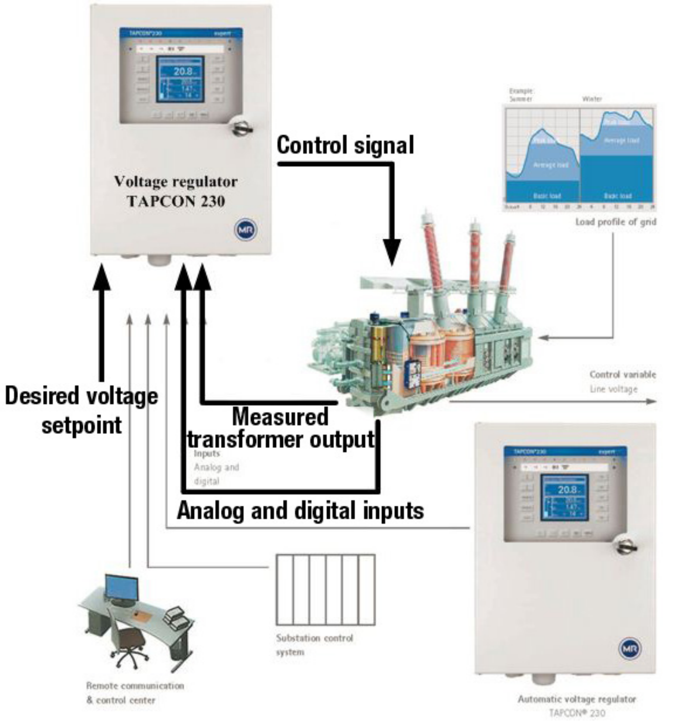
The load in the model is also acting as a harmonic source, where the active filter is connected in parallel with it. The main circuit is a three phase voltage source PWM inverter using six Insulated Gate Bipolar Transducers (IGBTs). The PWM inverter has a dc capacitor. An LC filter (LR, CR) is used to suppress switching ripples generated by the active filter. The active filter schematic in figure 10 is modelled in PSCAD/EMTDC software as shown in figure 11. When the active filter model was connected to the Electricity North West network model, the harmonics were produced by the PV connected to the network; therefore the load was no longer required.



▲ *Figure 11: Active filter modelling in PSCAD*

5.2.2 Modelling of distribution transformer with On Load Tapchanger

The voltage control relay installed for the site trial was the MR TAPCON 230 pro. The manufacturer's brochure for this product is in Appendix 20. As shown in figure 12, the device compares the measured transformer output voltage with a defined desired voltage set point. The difference between the two voltages is the control deviation, if it is greater than specified bandwidth, the device will emit a switching pulse after a defined delay time. The switching pulse triggers a tap change which corrects the output voltage of the transformer. The device parameters can be optimally adjusted to the line voltage behaviour to achieve a balanced control response with a small number of tap-change operations of the on load tapchanger.



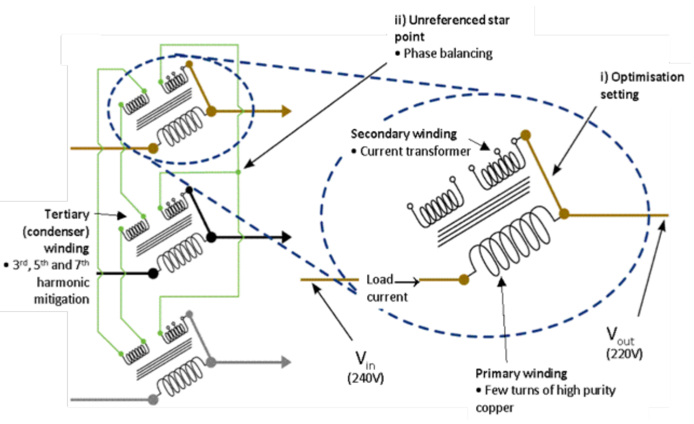
▲ *Figure 12: Overview of TAPCON voltage regulator*

Using the actual settings of a tap changer with nine tap positions, an equivalent model of a transformer with on load tapchanger was developed in PSCAD. The transformer model parameters such as leakage reactance are set according to the actual equipment datasheets.

The distribution transformer with on load tapchanger will alter the tap settings automatically as the load profile and voltage changes. In the simulation model the loads are considered to be fixed for each simulation cycle, therefore it is not possible to implement the automatic tap changing function of the on load tapchanger. The tap setting was adjusted manually for the different scenarios and the project recommendations are based on the effectiveness for several different load conditions.

5.2.3 Modelling of powerPerfector Plus unit

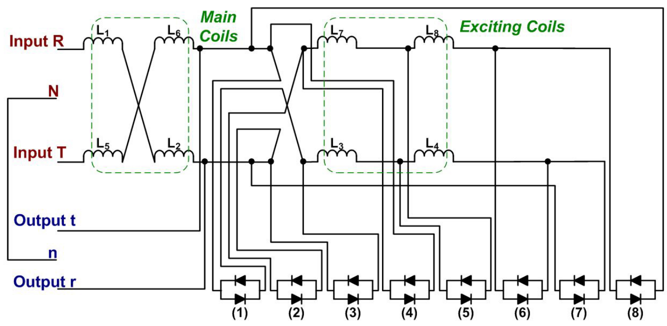
The winding schematic of the powerPerfector Plus is shown in figure13.



▲ *Figure 13: powerPerfector Plus winding configuration*

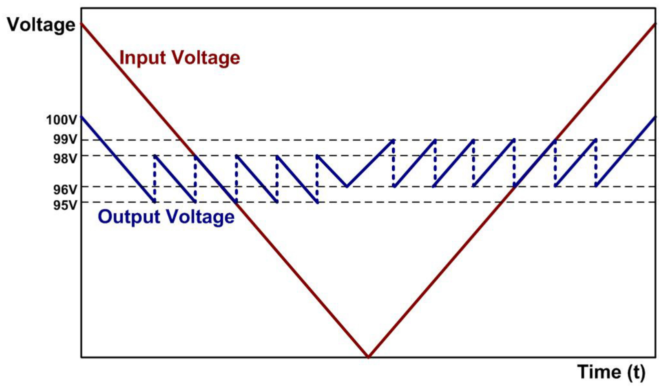
The primary winding is connected in series with the incoming power supply and carries the load current on each phase. The interaction between the primary and secondary winding on each phase acts to reduce the voltage by a fixed percentage. For example if input is 240V, output will be around 220V, assuming an -8% optimisation setting. The connection between each phase has a current flowing that is proportional to the difference between the three phase voltages. This arrangement produces an unreferenced star point on the secondary as shown in figure 13. By configuring the powerperfector Plus in such way, it could compensate the imbalanced phase voltages without additional electronic or mechanical components.

The windings are connected as a closed delta configuration. The purpose of the closed loop is to provide a path to circulate and dissipate harmonic currents on the input, thus attenuating and preventing them from circulating into the downstream load (output). This configuration has the same effect on harmonic currents that are generated downstream of the powerperfector Plus unit, preventing harmonic currents on site from circulating into the upstream load.



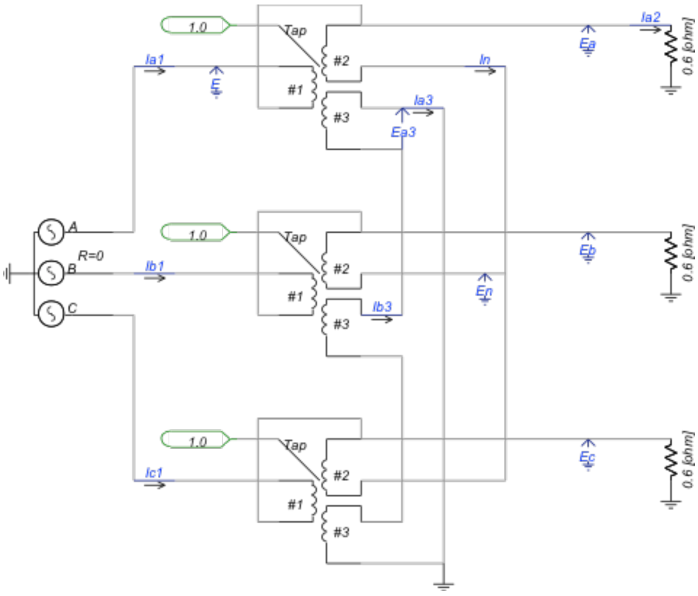
▲ *Figure 14: Two winding schematic of a powerPerfector Plus unit operation*

The schematic of the powerPerfector Plus operation is as shown in figure 14 where L1, L2, L5 and L6 are the main coils, R and T are the input terminals, L3, L4, L7 and L8 are the exciting coil, r and t are the output terminals, zero phase N and n are connected to one another. Thyristors (1)-(8) are connected between coils respectively. The thyristors are switched ON/OFF by the voltage value detected in the voltage sensor. Figure 15 illustrates the input and output voltage of a typical powerPerfector Plus unit.

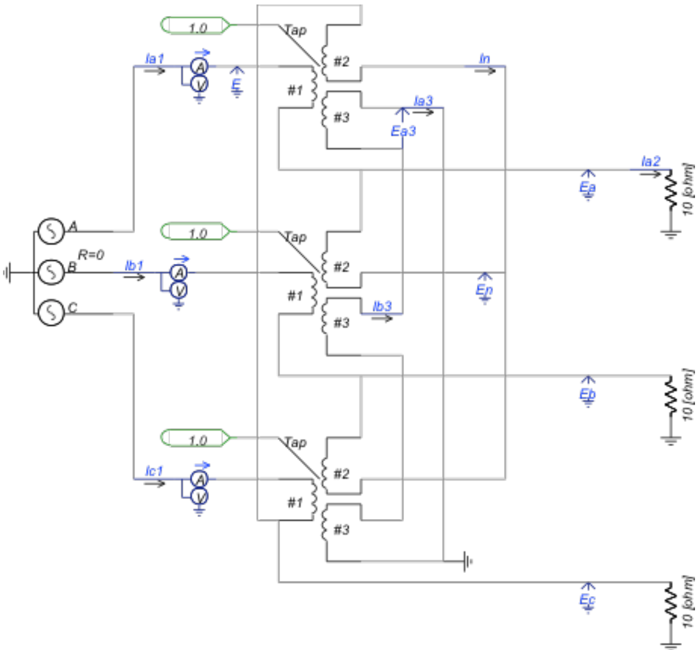


▲ *Figure 15: Input vs. output of powerPerfector Plus unit*

Based on the powerPerfector Plus winding configurations, two equivalent PSCAD models were developed as the unit uses a different winding configuration for step down (shown in figure 16) and boost (shown in figure 17). The boost winding configuration was developed based on the patent document from powerPerfector Plus.



▲ *Figure 16: Equivalent PSCAD model of powerPerfector Plus for voltage step down*



▲ *Figure 17: Equivalent PSCAD model of powerPerfector Plus boost function*

The voltage tap is achieved by the thyristor based Automatic Voltage Controller (AVC) connected in parallel to the optimiser, which will react with a time delay of between 4 and 10 seconds before it responds to any change in the incoming voltage to avoid hunting. Switching will occur in 0.001 seconds. The model parameters such as leakage reactance are configured according to the datasheets received from the manufacturer.

5.2.4 Network Model Construction

In addition to constructing models of the equipment the University also developed models of the networks where the equipment was installed using Electricity North West Geographical Information System (GIS) files as a basis to construct these network models.

The network and device models were combined to allow validation and analysis of load and generation scenarios.

Measurement data from the trials conducted were provided to the University to allow validation of the models. The models were validated for all modes of operation of the devices. In addition to models for the equipment being trialled by Electricity North West the University also developed models for one other technique not under trial, battery storage.

The models were then used to run simulations to assess the effectiveness of the different voltage management techniques with different demand and generation penetrations representing both today's and future networks. This produced some guidance on the usefulness of the techniques.

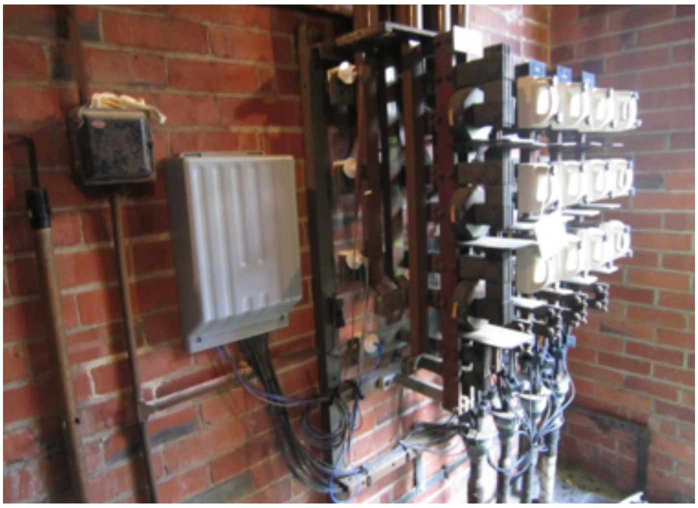
These models will be available on request from the University.

6. Project outcomes

This section presents the monitoring data from the trial and the results from the modelling work conducted by the University of Manchester. The data presented here is only an extract from the complete data set. To review the complete data see the reports in Appendices 1-12.

The monitoring data was retrieved from a number of sources:

1. Substation monitoring deployed as part of Electricity North West's First Tier project "LV Network Solutions".



▲ *Figure 18 – Substation Monitoring*

2. Mid and end point LV feeder monitoring developed and deployed as part of Electricity North West's First Tier project "LV Network Solutions."

▲ *Figure 19 – Mid / End Point Monitoring*

3. Power Quality recorders fitted on the active filters by ABB.
4. Power Quality recorders fitted on the powerPerfector Plus units by powerPerfector Plus.

The monitoring data deployed as part of the LV Network Solutions project were supplied by Gridkey and Nortech. All the units were set up to record the voltage, current, real power, reactive power and phase angle on each phase of each LV way at 1 minute intervals. The data from these units was used to assess the performance of the various assets. The data was supplied to the University who used it to validate their network and asset models.

6.1 ABB Active Filter – Monitored Results

The ABB active filter was installed in two locations with high concentrations of PV.

At each substation a full harmonic survey was carried out before and after the filter was installed. Data from one site is detailed in the tables below – table 1 lists the harmonic currents prior to installation and table 2 after installation.

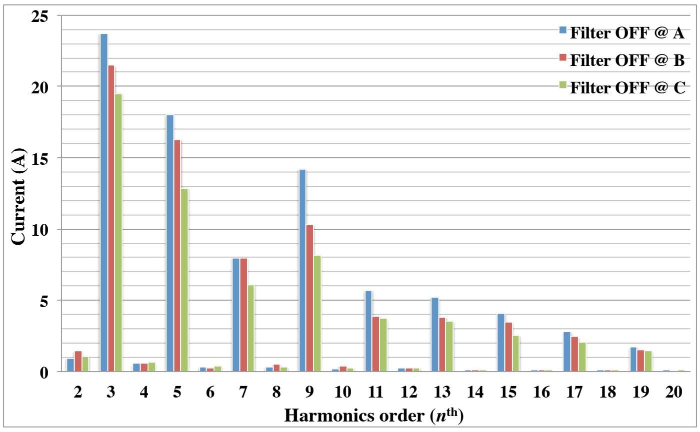
▼ Table 1 – Harmonic current measured prior to installation of the filter

Harmonic Number	Limit	Phase A	Phase B	Phase C	Status
2	28.90	0.59	0.51	0.65	PASSED
3	48.10	23.48	20.23	19.90	PASSED
4	9.00	0.33	0.23	0.36	PASSED
5	28.90	13.73	13.76	9.80	PASSED
6	3.00	0.17	0.14	0.18	PASSED
7	41.20	5.28	5.89	4.23	PASSED
8	7.20	0.21	0.21	0.21	PASSED
9	9.60	11.88	8.48	7.27	FAILED
10	5.80	0.14	0.11	0.17	PASSED
11	39.40	3.56	2.45	2.64	PASSED
12	1.20	0.17	0.13	0.17	PASSED
13	27.80	2.71	1.96	2.60	PASSED
14	2.10	0.11	0.09	0.11	PASSED
15	1.40	3.50	2.81	2.27	FAILED
16	1.80	0.10	0.10	0.12	PASSED
17	13.60	2.64	2.41	1.79	PASSED
18	0.80	0.08	0.07	0.09	PASSED
19	9.10	1.37	1.33	1.52	PASSED
20	1.40	0.08	0.07	0.09	PASSED
21	0.07	0.86	0.44	0.65	FAILED
22	1.30	0.07	0.06	0.07	PASSED
23	7.50	0.57	0.90	0.85	PASSED
24	0.60	0.05	0.05	0.05	PASSED
25	4.00	0.70	0.63	0.79	PASSED
26	1.10	0.05	0.05	0.05	PASSED
27	0.05	0.47	0.33	0.46	PASSED
28	1.00	0.04	0.05	0.04	PASSED
29	3.10	0.44	0.62	0.55	PASSED
30	0.50	0.04	0.04	0.03	PASSED
31	2.80	0.23	0.23	0.22	PASSED
32	0.90	0.04	0.04	0.03	PASSED
33	0.40	0.21	0.16	0.19	PASSED
34	0.80	0.04	0.04	0.02	PASSED
35	2.30	0.19	0.18	0.17	PASSED
36	0.40	0.04	0.04	0.02	PASSED
37	2.10	0.15	0.13	0.12	PASSED
38	0.80	0.04	0.04	0.02	PASSED
39	0.40	0.10	0.11	0.10	PASSED
40	0.70	0.04	0.04	0.04	PASSED
41	1.80	0.14	0.12	0.12	PASSED
42	0.30	0.04	0.04	0.02	PASSED
43	1.60	0.10	0.10	0.10	PASSED
44	0.70	0.04	0.04	0.02	PASSED
45	0.30	0.06	0.06	0.05	PASSED
46	0.60	0.04	0.04	0.02	PASSED
47	1.40	0.08	0.08	0.06	PASSED
48	0.30	0.04	0.04	0.02	PASSED
49	1.30	0.07	0.08	0.07	PASSED
50	0.06	0.00	0.00	0.00	PASSED

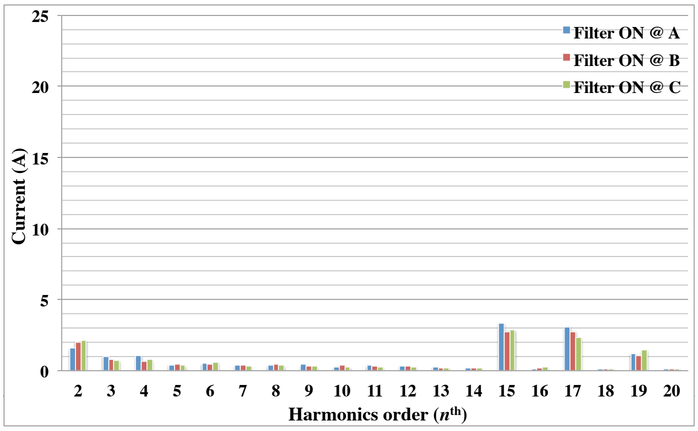
▼ Table 2 – Harmonic current measured following commissioning of the filter

Harmonic Number	Limit	Phase A	Phase B	Phase C	Status
2	28.90	1.30	1.34	1.19	PASSED
3	48.10	4.57	5.04	4.26	PASSED
4	9.00	0.67	0.48	0.53	PASSED
5	28.90	4.33	3.93	3.57	PASSED
6	3.00	0.35	0.33	0.33	PASSED
7	41.20	3.58	4.12	2.59	PASSED
8	7.20	0.37	0.29	0.41	PASSED
9	9.60	4.62	3.87	2.47	PASSED
10	5.80	0.25	0.23	0.28	PASSED
11	39.40	3.21	2.71	2.63	PASSED
12	1.20	0.27	0.24	0.26	PASSED
13	27.80	2.68	2.29	2.69	PASSED
14	2.10	0.14	0.19	0.19	PASSED
15	1.40	3.45	2.49	2.21	FAILED
16	1.80	0.14	0.15	0.17	PASSED
17	13.60	3.02	2.23	2.01	PASSED
18	0.80	0.10	0.09	0.15	PASSED
19	9.10	1.46	1.27	1.40	PASSED
20	1.40	0.09	0.11	0.13	PASSED
21	0.70	0.69	0.49	0.72	FAILED
22	1.30	0.07	0.07	0.08	PASSED
23	7.50	0.93	0.99	1.17	PASSED
24	0.60	0.06	0.05	0.05	PASSED
25	4.00	0.74	0.53	0.65	PASSED
26	1.10	0.04	0.05	0.07	PASSED
27	0.50	0.45	0.34	0.33	PASSED
28	1.00	0.03	0.03	0.05	PASSED
29	3.10	0.51	0.46	0.57	PASSED
30	0.50	0.03	0.02	0.04	PASSED
31	2.80	0.27	0.24	0.23	PASSED
32	0.90	0.02	0.02	0.03	PASSED
33	0.40	0.21	0.22	0.20	PASSED
34	0.80	0.02	0.02	0.02	PASSED
35	2.30	0.22	0.17	0.19	PASSED
36	0.40	0.02	0.02	0.02	PASSED
37	2.10	0.20	0.17	0.18	PASSED
38	0.80	0.02	0.02	0.03	PASSED
39	0.40	0.15	0.12	0.13	PASSED
40	0.70	0.02	0.01	0.02	PASSED
41	1.80	0.18	0.14	0.16	PASSED
42	0.30	0.02	0.02	0.02	PASSED
43	1.60	0.13	0.13	0.17	PASSED
44	0.70	0.01	0.01	0.02	PASSED
45	0.30	0.11	0.08	0.08	PASSED
46	0.60	0.02	0.02	0.02	PASSED
47	1.40	0.08	0.09	0.10	PASSED
48	0.30	0.02	0.01	0.02	PASSED
49	1.30	0.07	0.07	0.07	PASSED
50	0.60	0.00	0.00	0.00	PASSED

Figures 20 and 21 display some of the results from the tables above in graphical form, only the data up to the 20th harmonic is shown as this is of most importance.



▲ *Figure 20: Data when filter switched off*



▲ *Figure 21: Data when filter switched on*

These graphs clearly show that the filter is able to significantly reduce harmonic currents up to 15th order. This is maximum order of harmonics that can be reduced when all the filter functionalities have been selected, ie filtering, load balancing and power factor correction. Harmonics up to the 50th order can be reduced if only filtering is selected.

This result shows that the filter is very effective in reducing the odd order of harmonic currents that been generated by PV and other household electronic devices.

6.2 ABB Active Filter – Modelled Results

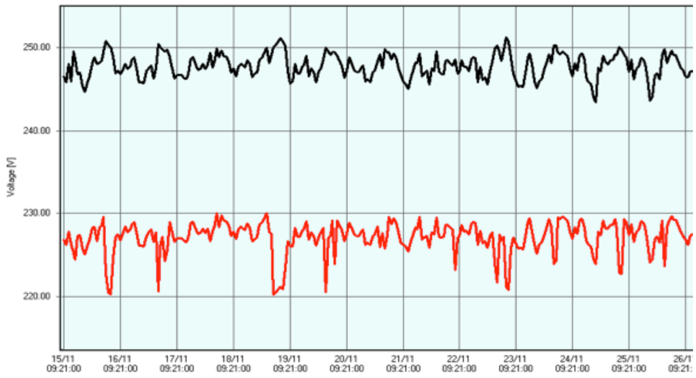
The University of Manchester did not conduct any modelling using this technology as its operation will not be affected by the addition of low carbon technologies.

6.3 powerPerfector Plus – Monitored Results

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

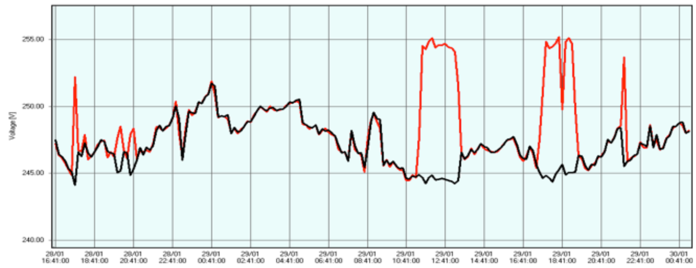
- the black trace is the input voltage to the powerPerfector Plus unit;
- the red trace is the output voltage from the powerPerfector Plus unit;
- the blue trace is the import and export power (kW).

The graph in figure 22 demonstrates the unit in buck mode with an MOV of 220V. 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).



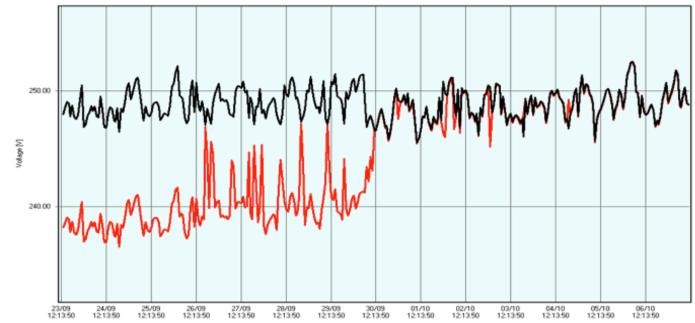
▲ *Figure 22 –Demonstration of Buck Mode*

The graph in figure 23 demonstrates the unit in boost mode with an MOV of 243V. 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).



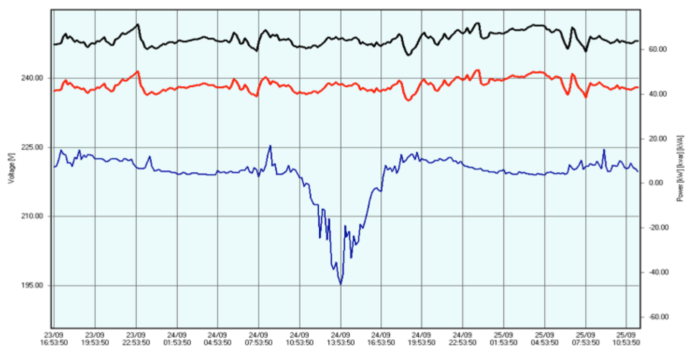
▲ *Figure 23 – Demonstration of Boost Mode*

The graph in figure 24 demonstrates the operation of the unit where the MOV was increased over time to the input voltage level. 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.



▲ *Figure 24 –Increasing MOV to Input Voltage Level*

Figure 25 illustrates the variation in voltage and import / export (the orange line is the zero kW level) through the powerPerfecftor Plus 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.



▲ *Figure 25 –Daily Profile of Import and Export Variation*

As can be seen from above, the in-line LV voltage regulator trialled has been proven to automatically and autonomously control and manage LV voltage on a domestic feeder whilst maintaining customer voltages within statutory limits.

6.4 powerPerfector Plus – Modelled Results

6.4.1 Capacity Studies

powerPerfector Plus has been studied by the University for its ability to provide additional network capacity. Figure 26 shows two aspects.

1. The additional capacity is not affected by the amount of PV connected. The capacity released is directly proportional to the number and percentage of the tap positions.
2. Connecting the powerPerfector Plus unit at the beginning of a feeder results in a larger release of capacity than connecting it near the middle of a feeder. This is because the powerPerfector Plus unit will only affect customers connected downstream.

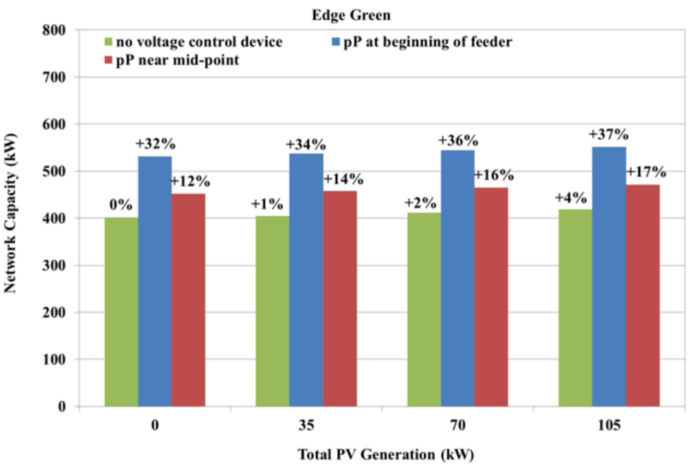
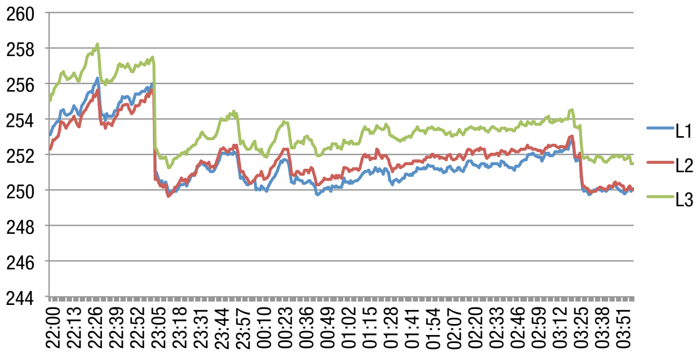


Figure 26: Network capacity with powerPerfector Plus unit

6.5 Distribution Transformer with On Load Tapchanger – Monitored Results

The substation monitoring was analysed to assess the operation of the on load tapchanger. It was noted from the relay that at both sites the tapchangers had performed approximately 80 times in a 3 month period. Figure 27 shows one such operation.

This operation occurred when the voltage increased to 258V and it was necessary for the tapchangers to tap down to bring the voltage back within setting (253V or below). Although this site has a lot of PV installed it is interesting to note that this operation occurred late at night (close to midnight) when the demand reduced. Therefore this shows that there may be a requirement for these devices today before the increased adoption of low carbon technologies.



▲ *Figure 27 – Tapchanger Operation*

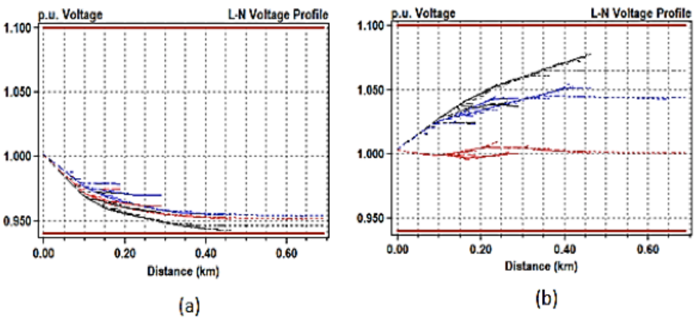
6.6 Distribution Transformer with On Load Tapchanger – Modelled Results

6.6.1 Voltage Regulation Studies

The distribution transformer with on load tapchanger was studied by the University for it effectiveness at regulating voltage.

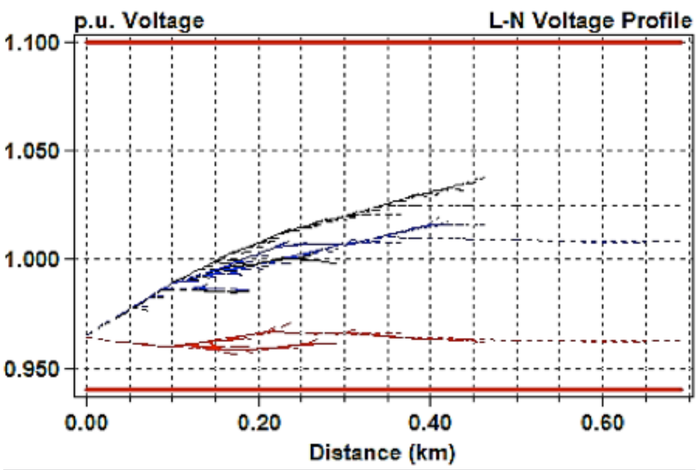
When PV generation is at maximum there will be voltage rise issues on the network and a transformer with on load tapchanger will step down the voltage at the substation to keep the feeder voltage within the statutory limits as determined by its settings.

Figure 28(a) shows the voltage profile without PV where the volt drop is due to demand only. Figure 28(b) shows the network voltage profiles with PV connected. Comparing these two network conditions, it is clear that with the PV penetration in the network will increase the voltage by as much as 10% at end of the feeder with 0% tapping.



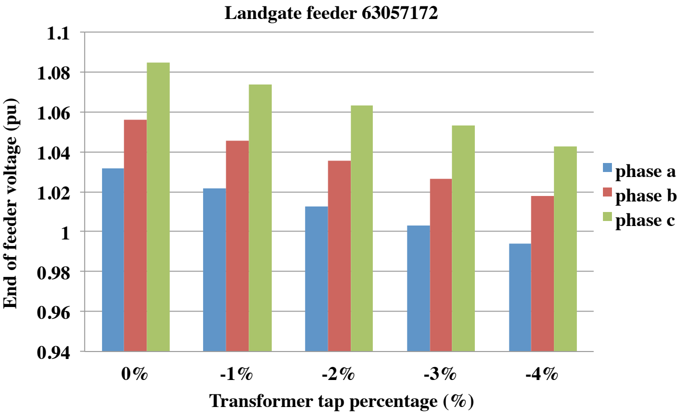
▲ *Figure 28: Feeder voltage profile (a) without PV connection (b) with PV connection*

Altering the tap position of the tapchanger from 0% to -4% could effectively control the voltage rise problem, see Figure 29.



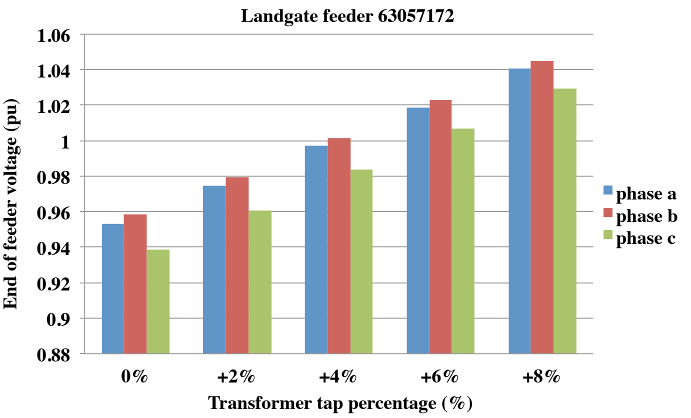
▲ *Figure 29: Feeder voltage profile with PV connected and -4% tapping*

Figure 30 gives the general trend of volt drop based on various transformer tap positions. This shows that the tapchanger can effectively control the voltage level within statutory limits to overcome the voltage rise issue throughout the feeder.



▲ *Figure 30: End of feeder voltage with various tap positions for a network feeder*

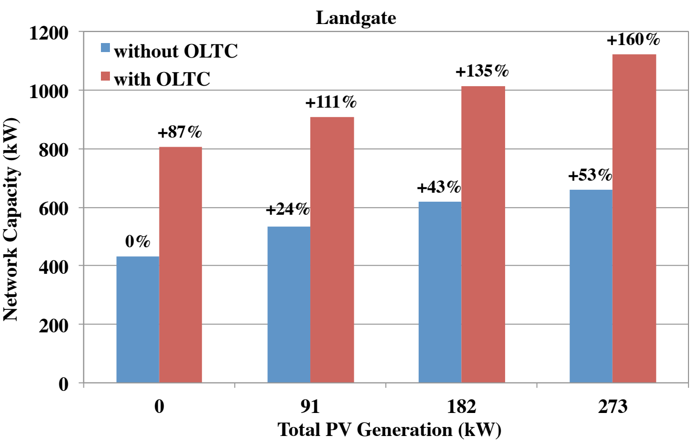
On feeders with mainly demand the tapchanger will increase the tap position to step up the feeder voltage. Figure 31 shows that the voltage level at end of the feeder for increasing tap positions in times of high demand.



▲ *Figure 31: End of feeder voltage with various tap positions for one network feeders*

6.6.2 Capacity Studies

The substation voltage can be regulated by installing a distribution transformer with on load tapchanger. The On Load Tapchanger can adjust the substation voltage so that the downstream feeder voltages can be maintained within statutory limits as the load changes and this can result in an increase in capacity. Figure 32 shows the network capacity with and without the OLTC installation for a distribution network with varying amounts of PV installed.



▲ *Figure 32: Network capacity with and without the installation of OLTC*

The graph above shows that the deployment of a transformer with an on load tapchanger can increase the network capacity by as much as 90% when the PV output is zero. The network capacity increases slightly as the total PV generation increases. The network capacity can increase by as much as 53%, even without the installation of a transformer with on load tapchanger, as the PV output increases. During periods of low demand and high generation, the voltage will rise to just below statutory limits at the substation, causing voltage rise at end of the feeder, allowing more loads to be connected. Installing a transformer with an on load tapchanger proves to be a very effective way of increasing capacity.

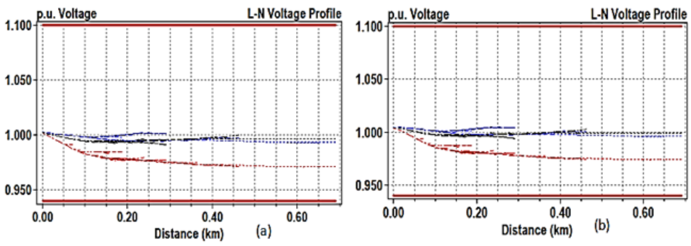
6.7 LV Capacitors – Monitored Results

There are no monitored results for this technology. This was due to the timing of the installation and issues with data handling and storage.

6.8 LV Capacitors – Modelled Results

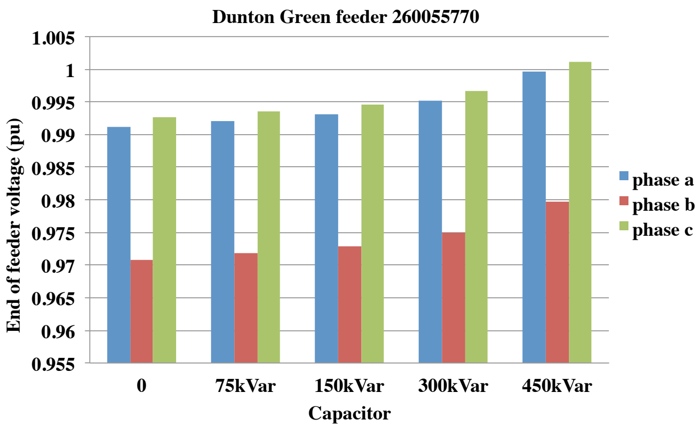
6.8.1 Voltage Regulation Studies

For the purpose of improving network voltage during periods of maximum demand, implementing capacitor banks along the feeder would produce reactive power and further boost the network voltage. However the size of the capacitor bank should always be less than the size of the transformer, to prevent reverse power flow and the creation of resonant current. In theory, the capacitor would be less beneficial when installed in a substation compared to middle of the feeder, where a higher voltage drop occurs. Figures 33 and 34 demonstrate the case when a capacitor is installed at a substation.



▲ *Figure 33: Feeder voltage profile (a) without capacitor connection (b) with a 150kVar capacitor bank at substation*

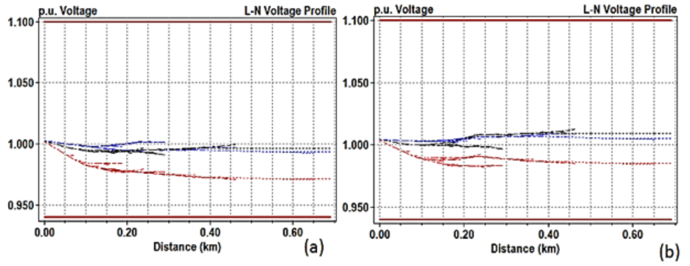
Considering a feeder with PVs connected, various sizes of the capacitor were modelled to assess the effectiveness of voltage boost.



▲ *Figure 34: End of feeder voltage with various capacitors installed at the substation*

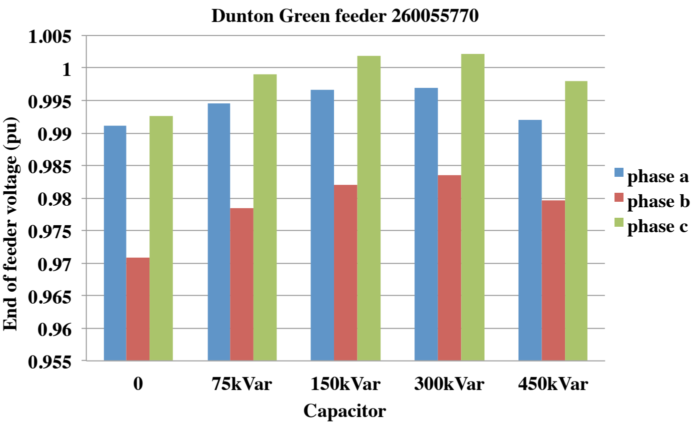
Figure 34 shows the boost in end of feeder voltage when implementing various sizes of capacitors.

In the case when the capacitors are installed at around middle point of the feeder as shown in figure 35, the voltage level at around middle point is noticeably further boosted compared to when it is connected at substation.



▲ *Figure 35: Feeder voltage profile (a) without capacitor (b) with a 150kVar capacitor bank at mid-point*

Installing capacitors at the midpoint of a feeder resulted in voltage levels as shown in figure 36. Comparing figure 36 and the previous figures when the capacitors are connected near substation, it can be noted that there is more significant voltage boost. However when the size of the capacitor bank increased to 450kVar, the voltage reduced further instead of boosting, hence the appropriate size selection is also essential.



▲ *Figure 36: End of feeder voltages with capacitors at mid-point*

To further demonstrate the difference of installing capacitor at middle point compared to when it is installed near substation. Table 3 shows the resulting volt drop for the different installations.

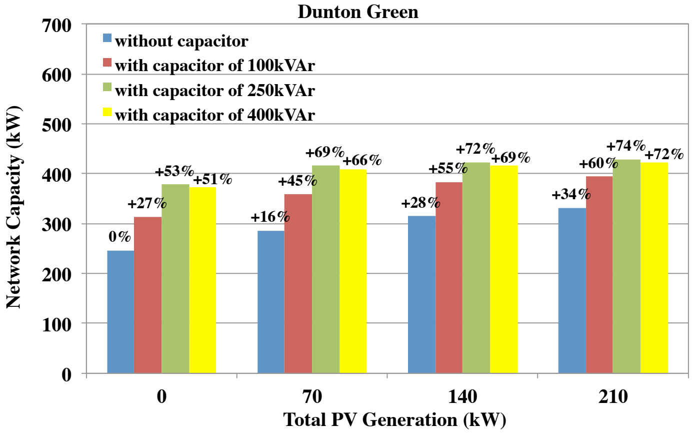
▼ *Table 3: Volt drop at the end of a feeder without PV connection*

Installation at the substation			
	Voltage drop (pu)		
	Phase a	Phase b	Phase c
No capacitor	0.04868	0.01975	0.03928
75kVar	0.0486	0.01973	0.03923
150kVar	0.04852	0.0197	0.03919
300kVar	0.04837	0.01966	0.03909
450kVar	0.04804	0.01954	0.03873
Installation at the mid-point of a feeder			
	Voltage drop (pu)		
No capacitor	0.04868	0.01975	0.03928
75kVar	0.04425	0.01994	0.0379
150kVar	0.04001	0.01762	0.03457
300kVar	0.03233	0.01479	0.02755
450kVar	0.03036	0.01466	0.02442

It is noticeably more effective to install the capacitor banks at a midpoint location where there is more significant voltage drop.

6.8.2 Capacity Studies

Since voltage can be controlled by reactive power compensation, the network model has been tested by deploying a capacitor to regulate the reactive power flow. The capacitor can be installed at the substation or on the feeder but as shown it is more effective to install the capacitor at feeder midpoint. Figure 37 illustrates the network capacity released when a capacitor of 100kVar, 250kVAr and 400kVar is installed at mid-point of a substation feeder with the highest volt drop or longest cable length.



▲ *Figure 37: Network capacities with different capacitors installed on the feeder*

When there is no PV generation, a capacitor with 100kVAr is able to increase the network capacity by as much as 27%. Note that the network capacity does not always increase with the higher rated capacitor banks. The network capacity has decreased slightly when the capacitor rating increases from 250kVAr to 400kVAr, is due to the reverse power flow caused by the large reactive power injection. As a consequence, the line voltage drop increases again, reducing the network capacity instead. However when the appropriate size of the capacitor is installed, the network capacity generally increases with higher rated capacitor banks. The study also shows the amount of capacity released is not as significant for some networks. This is because some networks are more resistive than others; therefore installation of a capacitor is not the most effective option for some networks.

6.9 Other Technologies Modelled by the University of Manchester

6.9.1 Storage – Voltage Regulation Studies

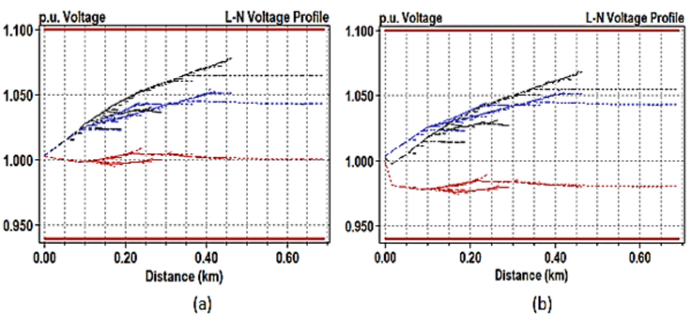
One effective method to control voltages in distribution networks is the installation of storage. The increasing amount of distributed generation has allowed energy storage to bring several benefits to the existing network. Renewable generation connected to the network such as PVs are generally considered as an intermittent source, which produce power during the daylight period and are ineffective at night.

Energy storage installed on the network could be charged by the PV during the period of low demand and release power during the peak demand period.

Storage is considered to have two operating modes, charge and discharge mode. During the charging mode, storage is treated similar to a load that consumes active power. During the discharging mode, the storage acts similar to a generator as a backup power supply. It is known that the integration of PVs into the network will cause a certain amount of voltage rise, if energy storage is connected to the network, it could use the additional amount of the power generated to charge the unit therefore eliminating the voltage rise issue.

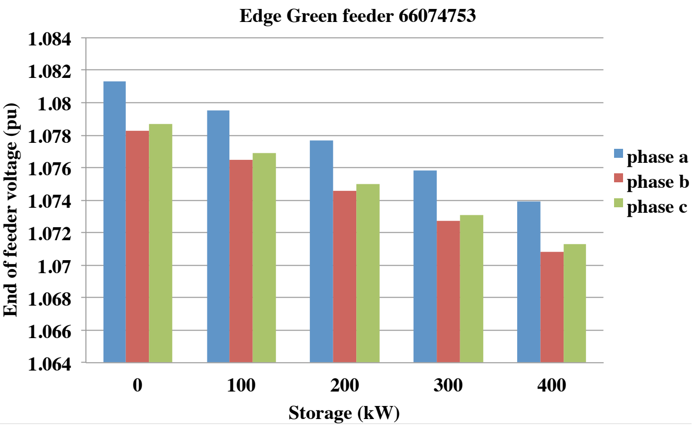
Investigations were carried out into the effect of installing energy storage at different locations on the network, during both charge and discharge operation mode. The influence of PV connection in conjunction with storage was also investigated. The maximum rating of the storage is generally selected to be less than the transformer rating to prevent instable current which could damage the units within the network.

The effect of installing storage with and without PV was investigated initially with the storage installed at the substation and the resulting voltage profile is shown in figure 38. The storage is considered to be in charge mode with the different sizes reflecting the amount or percentage of the unit being charged.



▲ *Figure 38: Feeder voltage profile (a) with PV connection and without storage (b) with PV connection and storage at the substation during charging mode*

By implementing the storage unit during charge mode in a network feeder, the maximum volt drop, as shown in figure 39 is dependant on the amount of the storage being charged. The simulations were carried out considering maximum penetration of PV.

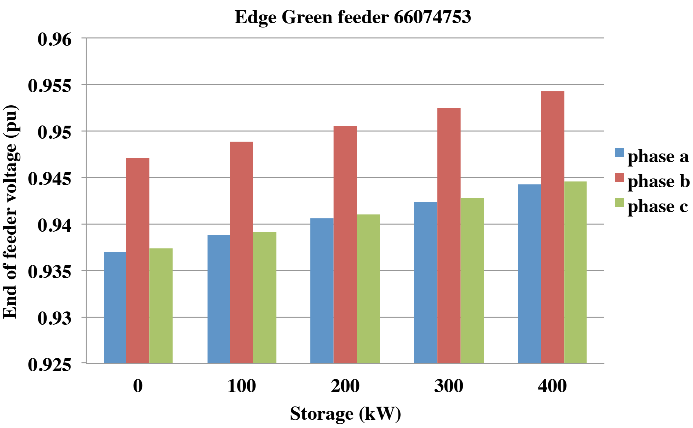


▲ *Figure 39: network voltage profiles with various capacity of storage and maximum PV at substation*

The amount of voltage drop caused by storage is approximately 0.01pu. Hence the storage will help eliminate a proportion of the voltage rise in the network, however the amount of voltage reduction is limited or may not as effective as transformer with on load tapchanger in this particular scenario. If however the storage elements are all fully charged, there would be no additional effect to the network.

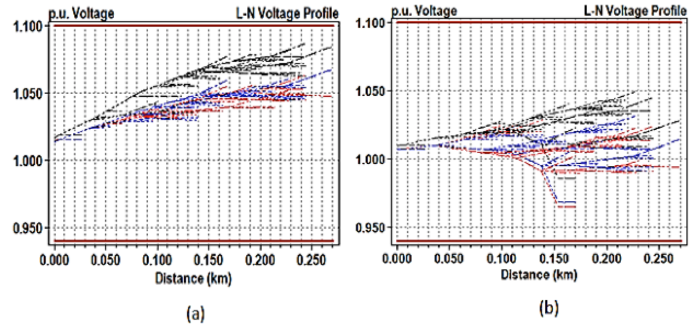
A high penetration of PV would increase the network voltage level and the storage acts as a load during charge state which helps to reduce the voltage rise effect.

Without any PV connected, the storage element would switch to discharging mode and behave like a generator. The storage unit will continue to supply power to the network until it fully discharged. Figure 40 shows the effect on voltage level for a network feeder.

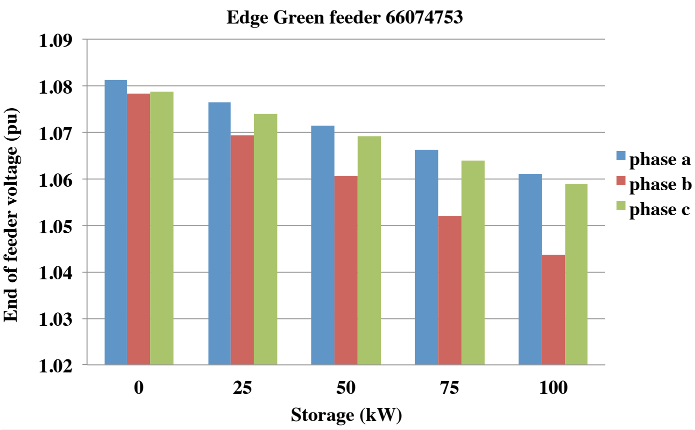


▲ *Figure 40: Network feeder voltage profiles with various storage sizes during discharge mode near substation and without PV*

The effect of installing storage with and without PV was then investigated with the storage installed at the mid-point location for a feeder. The 41(a) shows the voltage profile with PV connections which causes the voltage rise throughout the feeder. Figure 41(b) shows the voltage profile when the storage unit is connected and working in charging mode. There is more voltage drop in this scenario compared to when it was implemented near substation.



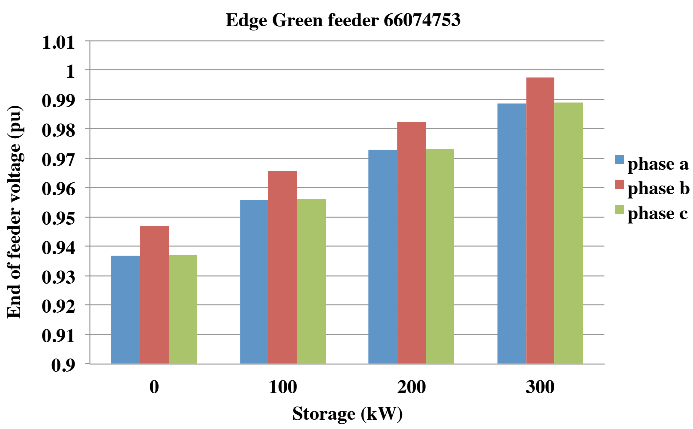
▲ *Figure 41: Feeder voltage profile (a) with PV connection (b) with PV connection and storage at mid-point location*



▲ *Figure 42: Feeder voltage levels with PV and various storage sizes during charge mode at mid-point location*

Figure 42 shows the voltage level of a network feeder when the storage is connected near mid-point location and operating during charge mode, it can be seen that the unit is able to significantly reduce the voltage level compared to when it was implemented at substation, therefore the storage offers an effective option to address the voltage rise issue caused by PV, when the storage unit is located near mid-point.

During the period of maximum load demand with no PV generation and the storage is then switched to its discharging operation mode the voltage level resulting on the feeder is shown in figure 43.

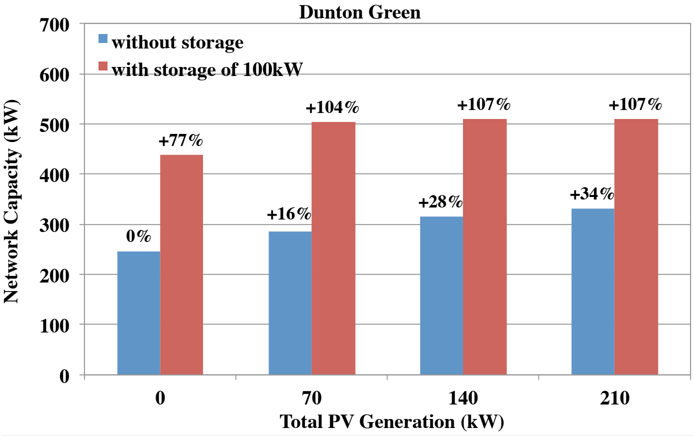


▲ *Figure 43: Feeder voltage levels with various storage sizes at mid-point location without PV generation*

Figure 43 shows the storage could provide the additional power to the network during the period of high load demand. Under fully discharged condition, it is able to boost the voltage level further compared to when it was at substation. Hence the most effective location to install storage further down the feeder.

6.9.2 Storage - Capacity Studies

The network has been set up with 100kW of storage connected at the midpoint of the longest feeder. As shown in figure 44, the deployment of a 100kW energy storage device at the midpoint of the feeder can increase the network capacity by as much as 77% when PV outputs are at zero. Compared with the capacitor, the installation of storage is more effective on improving the network capacity. However, the storage device is only able to provide the constant power within its energy capacity. Therefore, it cannot support the network voltages for a long period.



▲ *Figure 44: Network capacity with and without the installation of a storage*

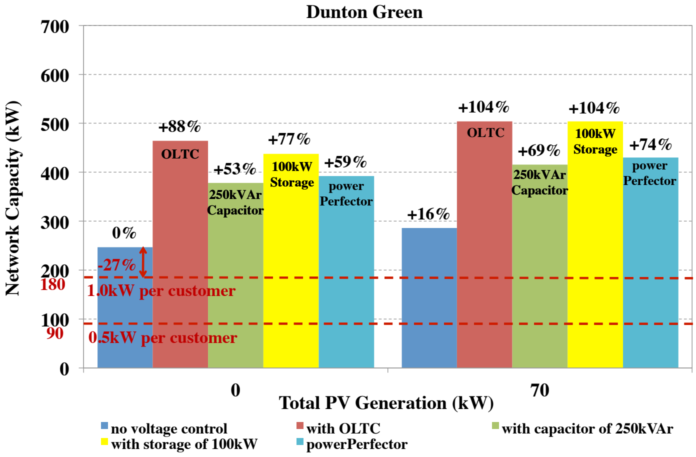
The amount of capacity increase is dependant on the location where the storage and PV is installed as well as the load on the feeder. In some cases the midpoint is not necessarily the most optimum location to install the storage and it may need to be installed nearer to the endpoint due to increased volt drop. However installing storage at the midpoint will in theory affect more customers than an installation at the endpoint, due to more wide spread voltage boost effect along the main cable line.

6.10 Comparisons between different voltage control options

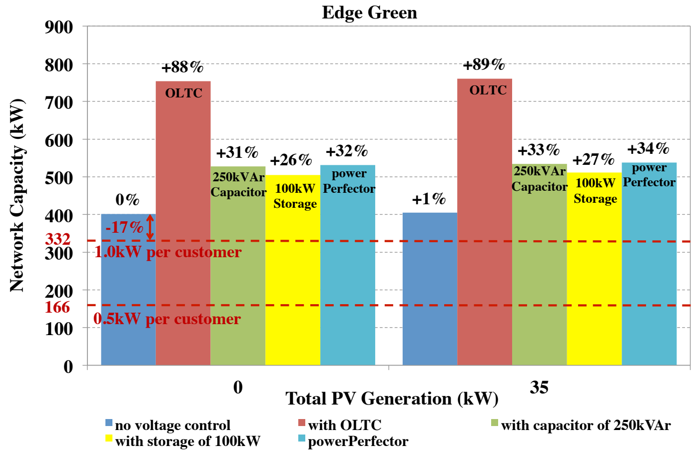
Figures 45 and 46 compare several different options of the voltage control equipment for two distribution networks.

If a maximum load demand of 1kW per customer is assumed the network capacity of Dunton Green substation can be increased by 27%. If the total demand is increased by more than 27%, the network will require an intervention, either the installation of a voltage control device or traditional reinforcement.

When PV is connected, the network capability can be increased by 16%, assuming there are no power quality issues. The comparison shows that the distribution transformer with on load tapchanger is the most effective method to increase network capacity.



▲ *Figure 45: Dunton Green network capacities with various voltage control devices*



▲ *Figure 46: Edge Green network capacities with various voltage control devices*

When comparing figure 45 and figure 46, it shows that installing capacitors and storage at Edge Green is not as effective as for Dunton Green due to the different network conditions and line impedances. Dunton Green has two very effective options in a distribution transformer with on load tapchanger and storage, and Edge Green only has the transformer with on load tapchanger as an option. Hence existing network conditions are very important when choosing the appropriate voltage control devices.

6.11 Conclusions

The distribution transformer with on load tapchanger option can be used to regulate and maintain the transformer secondary voltage within a permitted dead-band. The automatic voltage control relay will adjust the tap position used to regulate the voltage within the statutory limits. The number of tap positions and tap steps will limit the range of the voltage it can regulate.

However it is not a simple answer to say the transformer with on load tapchanger is the most effective method compared to others, as the effectiveness of voltage control is also largely dependant on the network conditions. For example when there are several feeders connected to a single substation and one of the feeders has significantly higher volt drop at end of the feeder it could be more effective to use a feeder such as storage or capacitors.

It has been shown that an increasing the number of distributed generation installed on the network will also limit the effectiveness of the transformer with on load tapchanger.

Generators such as PV panels will cause voltage rise and changes the power flow in the network. However if each generator is appropriately controlled, such as fixed power factor and operation under a voltage cap, or even controlled energy storage, then the distributed generation could be a very effective option for voltage control in LV network.

In terms of the network capacity, the transformer with on load tapchanger could offer a significant increase for a substation over other equipment. With increased load demand such as the connection of heat pumps, the transformer with on load tapchanger could still maintain the voltage level within the statutory limits.

Each powerPerfector Plus unit has 5 tap positions compared to the 9 tap positions of the on load tap changer. One tap position is for boost, one for the zero position and the other 3 for stepping down the voltage. The fundamental difference between the two units is that the powerPerfector Plus is operated based on a set minimum voltage. The powerPerfector Plus units trialled for this project have tap steps of around 4%, which may be excessive for existing distribution networks but the transformer with on load tapchanger has tap steps of 2%. A suggestion for future development for the powerPerfector Plus unit would be to review the tap step and reduce the percentage change to around 2%.

The main focus for network operators is to maintain the network reliability, but future networks will also need to take into consideration the effect on power quality on the network.

The increasing implementation of PV and household electronic equipment will increase the harmonics level in the network and harmonic issues can cause several problems such as ageing effect of the transformer and cables. In addition, an increasing proportion of customer devices use power electronics, which can be more sensitive to supply voltage and quality.

The project has trialled two active filter units, in order to assess its ability to address the power quality issues in the LV network. From the results obtained during the trial, the filter units could reduce the harmonic current in each phase, which would allow more new types of loads and PVs to be connected in the network.

The project has trialled several capacitor banks, the units are all installed around midpoint of the feeder to offset the load reactive power reducing the amount that needs to be supplied from the substation resulting in a lower volt drop.

Voltage control using capacitor banks can be less effective in the LV network compared to HV network, as the feeders are more resistive. For more resistive feeders, the study shows that it reduces the voltage boost. The size of the capacitor which can be installed is limited depending on network conditions.

It is predicted that the number of electric cars could be significant in future networks. The charge cycle for each car would last several hours, and customers are more likely to charge them in the evening, causing the voltage drop during peak time to be even more significant. Therefore, the network may need to be further optimised and energy storage support could be an option, utilising the charging stations as well as energy storage installed along the feeders.

While there is no significant driver to introduce voltage control equipment on every feeder at present, this need will increase proportional to the uptake of distributed generation and loads such as electric vehicles and these techniques have been proven to be of use.

7. Performance compared to aims

As detailed earlier in the report the success criteria for this project were:

- Establish learning on a range of alternative techniques for management of voltages on low voltage networks
- Deployment of new technology on the network for improved voltage regulation and measurement of the effect on voltage profiles in response to changes in demand
- Production of standard designs / applications for installation of alternative voltage management techniques
- Measurement of voltage profiles and their behaviour in relation to changes in load over the load cycle and comparison with reference networks.
- Improved efficiency (ie reduction in networks losses and optimised real power distributions) on low voltage networks via improved power factor.
- Improved power quality through a reduction in voltage perturbations.

The following sections discuss each criterion in turn detailing any successes or failures.

7.1 Establish learning on a range of alternative techniques for management of voltages on low voltage networks

The project has fully delivered on this criterion. The monitoring data and the simulations conducted by the University have proven the effectiveness of all the devices in the project.

It is important to note that the network construction is an important factor in deciding which of these devices is the most appropriate.

One other key learning point is that a combination of different devices may be required to solve certain issues particularly where a substation contains both demand and generation dominant feeders.

7.2 Deployment of new technology on the network for improved voltage regulation and measurement of the effect on voltage profiles in response to changes in demand

The project has successfully deployed 14 devices on the LV network. The registration document stated that we would deploy 15 devices but due to time and resource constraints this was not possible. A significant amount of learning was gained from the 14 devices installed and it was felt that the project would still fulfil its objectives without the 15th device.

The project has successfully recorded voltage profiles on 6 devices and proven through measurement their effectiveness at managing voltage. Due to timings on the project and issues encountered with data handling / storage there is no measurement data for the capacitors. The University proved that the models created were correct and reflected the practical applications, therefore the simulation data from the University can be used to assess how effective the capacitor can be.

The timings on the project were affected by the lead times on the devices. It was not anticipated how long it would take to procure and receive the equipment.

7.3 Production of standard designs / applications for installation of alternative voltage management techniques

As stated earlier in the report, an analysis of the Electricity North West DG database was carried out to identify the locations of clusters of PV generation. These were the areas to be targeted with the new devices. Also considered were the space and access requirements. This resulted in five distribution substations and associated networks.

For the voltage optimisers it was decided to install one on a site with no generation and the flexibility to reconfigure the network to add or remove demand to further assess its effectiveness. This gave us the sixth substation and associated networks.

As it was decided to combine some techniques S&C and the University used the networks of these six sites to assess for the installation of capacitors. The size and approximate location were decided directly from this study work.

Although this was a trial “Business As Usual” techniques were employed wherever possible particularly for the approval, procurement, site design and installation of the devices.

New procedures were produced to inform staff of the operation of the devices and how to remove them from the system in the event of a problem.

From the University capacity report it is intended to review Electricity North West's LV network design policy to include these devices in the solution portfolio. This will be conducted after further trials, under other projects, have been completed.

7.4 Measurement of voltage profiles and their behaviour in relation to changes in load over the load cycle and comparison with reference networks.

As stated previously there is only measurement data for 6 of the devices but these were measured over a period of up to 12 months. The detail in the reports from the University and powerPerfector clearly demonstrate the behaviour of the devices in response to changes in load over a period of time.

7.5 Improved efficiency (ie reduction in networks losses and optimised real power distributions) on low voltage networks via improved power factor.

Although not proven in practice the studies from the University demonstrate the effectiveness of the capacitors in improving network losses and power factor.

7.6 Improved power quality through a reduction in voltage perturbations.

The deployment of the active filter and the associated reports from ABB demonstrate the effectiveness of the filter on harmonics.

The monitoring on the other devices do not show any adverse effect on the LV network by the deployment of the new technology.

8. Required modifications

An extension to the project was required due to the issue with lead times. As there was a delay in the installation of some of the technologies and the associated monitoring the data could not be supplied to the University. This in turn had a knock-on effect with the validation of the models and subsequent scenario simulations.

The number of devices deployed and number of independent sites used differed from the project registration. As stated earlier in the report the combination of devices added to the learning and allowed demonstration of feeder control in conjunction with substation control.

9. Variance in costs and benefits

This section provides details on relevant variances in the costs and benefits for the project.

9.1 Cost variance

Two factors have resulted in a variance from forecast to actual costs on the voltage management project.

Firstly, the anticipated completion date for the project was originally stated as October 2012 representing an 18 month total duration. Owing to a combination of equipment delivery and site installation delays, it became necessary to extend the project by a further 12 months to allow sufficient time for the trials to complete and the associated trial data to be collected and analysed; the project thus completing in October 2013. An amended project registration document was submitted to Ofgem accordingly. However, the additional 12 months of project activity incurred a number of costs in respect of project management and additional academic support. These are quantified further below.

The second more material factor was the decision to increase the number of trial sites where reactive compensation devices would be installed. Originally, the project anticipated that low voltage capacitors would be installed at a maximum two locations assumed at the time to be a low voltage street mounted pillars housing a capacitor connected to a low voltage feeder via a simple switch. However, results obtained during the early stages of the project via academic and consultants reports into the potential benefits from use of low voltage reactive compensation technologies, suggested significant potential for them to help support voltage regulation of these networks. As such it was considered appropriate to increase the number of trial sites from two to eight in order to allow for a range of networks, demand types and capacitor sizes to be investigated. The connection and operation of these devices is detailed in section 5.1.5 with further details provided in sections 6 and 7.

Table 4 below provides a breakdown of the additional costs that were incurred on the project. In total an additional £217,110 of costs was incurred versus the estimated cost submitted during initial project registration.

▼ *Table 4 – Cost variance: project items requiring additional costs*

	Item	Additional Cost	Forecast	Actual
[1]	Programme and project management costs	£8,800	£73,500	£82,300
[2]	Project technical support	£80,448	0	£80,448
[3]	Further academic support costs and consultancy	£30,000	£173,860	£203,860
[4]	Additional LV capacitors sites, plant items and monitoring	£72,200	£179,068	£251,268
[5]	Materials and installation	£25,662	£63,571	£89,233
	Total costs variance	**£217,110**	**£490,000**	**£707,109**

Notes on cost variances:

1) 11.9% variance: Additional programme and project management costs were incurred on this project owing to the increase in the project duration by 12 months.
2) 100%variance: Internal technical support was not originally forecast. This was an oversight which has been corrected in future projects. The technical support involved approval of equipment, installation procedures and providing technical expertise to academia.
3) 17.2% variance: As a result of the decision to increase the number of LV capacitor installations, together with a number of delays in the start of the site installation works, it was necessary to extend the contract duration for the academic support on this project. In addition, a small piece of additional consultancy work was undertaken by S&C Electric to support the design stage for the capacitor elements.
4) 40% variance: The increase in the number of LV capacitor installations incurred additional plant, ancillary equipment and monitoring costs. The largest of these was the cost for the additional six LV capacitors and their associated controllers.
5) 40% variance: The actual costs for materials and installation across all the various trial technology sites were higher than forecast owing to the increase in the number of LV capacitor installations together with inclusion of a supply stand-by configuration associated with the OLTC trial sites. Specifically these included excavation, supervision, reinstatement of the public highway, contract labour/plant and installation resource and operational engineers.

9.2 Benefits variance

In the main the benefits obtained upon completion of the project were in line with the benefits expected. However, the benefits associated with the use of low voltage capacitors to address issues of voltage regulation where greater than originally anticipated. This prompted the increase in the number of trial sites as noted previously. The use of low voltage connected capacitors are also included in the scope of works of further LCNF projects namely the Tier 2 funded project Smart Street.

10. Lessons learnt

This project has successfully demonstrated that new application of existing technologies such as distribution transformers with on load tapchangers and capacitors can effectively regulate voltage to yield a material increases in network capacity. This capacity increase can allow the connection of more low carbon technologies thus providing a viable alternative to traditional network reinforcement.

The project has investigated through trial application the potential for new technology to help with the anticipated future challenges presented by the connection of low carbon loads. However, it is recognised that the use of this technology will also require further consideration of the control methodologies that are required to ensure that these devices operate appropriate under all conditions.

Electricity North West has decided to take this learning and apply it to two new projects. The First Tier project Low Voltage Integrated Automation (LoVIA) aims to combine the learning from this project and the First Tier LV Network Solutions project by using the voltages measured at the mid and end points of feeders to drive the tap change control scheme.

A further extension to this project is Electricity North West's 2013 Second Tier project, Smart Street. This project will combine the learning gained in this project on voltage regulation and control with new network configurations and a central control system. This will result in a wider deployment of the techniques investigated and a control system to manage it centrally.

This project has highlighted a number of challenges associated with the transition of learning outcomes into business as usual activities. This is a challenge which is common across all innovation led projects. The use of new technology such as low voltage capacitor installations represents a significant departure from the traditional methods and Electricity North West recognises that successful transfer to BAU will require internal briefing and dissemination. To facilitate this, the Future Networks Team of Electricity North undertakes regular project briefings will key personnel across the business.

Using the learning from this project and the new First and Second Tier projects Electricity North West plan to carry out a detailed review of the LV planning codes of practice. This should result in more comprehensive guidance with a wider portfolio of solutions to cater for different network conditions.

As part of the project Electricity North West have produced:

1. Operational Procedures for all devices.
2. Settings for the tap change control relay.
3. A draft specification for the LV capacitors.

Electricity North West has presented this project at three LCNF annual conferences. Further details on this project including all of the academic reports, manufacturer's reports, specifications and procedures produced will be available on the Electricity North West website.

Electricity North West and the University of Manchester are planning to host a project dissemination event to cover specifically the key academic learning and mathematical modelling work carried out in this project and our LV Network Solutions Tier 1 project.

11. Planned implementation

As stated previously Electricity North West intends to implement the learning from this project through the LoVIA and Smart Street projects.

Electricity North West plan to carry out a detailed review of the LV planning codes of practice following all these projects. This should result in more comprehensive guidance with a wider portfolio of solutions to cater for different network conditions which can be used as part of business as usual.

Electricity North West has learnt that specifications for the devices need to be more detailed in certain areas.

The tapchanger delivered for this project did not have local mechanical indication if this product is to be used more widely this feature must be included.

The enclosures for the filters will need to be modified if they are to be deployed further. The enclosures provided needed modifications due to noise issues at one site and ventilation issues at the other site. It is important to specify the environmental requirements for all of these devices so that they are fit for purpose.

As part of the wider deployment Electricity North West plan to produce improved specifications to cover the issues found and also new functionality developed on some products since the start of the project.

12. Facilitate replication

The objective of this project was to field trial commercially available technology to understand its potential to help with anticipated future challenges associated with the connection of low carbon loads. The trials were used to investigate the benefits (or otherwise) of using these technologies to assist with voltage management on the LV network. This project did not however give consideration to the associated control methodology that would be required in order to ensure appropriate operation of the devices during the loads cycles. These issues are however being explored as part of other LCNF projects.

As a direct outcome of this project Electricity North West has produced and made publicly available:

1. Detailed Operational Procedures for all devices
2. Settings for the tap change control relay (TAPCON 230)
3. A specification for the LV capacitors

These documents are referred to in the appendices and will be made available for download via the Electricity North West Future Networks website.

Electricity North West have not produced a specification for the distribution transformer with on load tapchanger as the manufacturer MR (and others) are developing new products and it may be prudent to include any new features developed. The transformer purchased is based on the standard Electricity North West design with the tapchanger being the only modification; therefore the specification should be easily modified to include the new functionality.

The planning and installation work for this project was carried out using the standard Electricity North West policies and procedures.

Following the successful completion of its Tier 1 Low voltage Network Solutions project (Summer 2014), Electricity North West plan to carry out a detailed review of its existing LV planning and design codes of practice. This should result in more comprehensive guidance with a wider portfolio of solutions to cater for different network conditions which will be made available once complete.

The reports from the University give some guidance on which devices are suitable for the different network conditions. DNOs can use this as a basis as to which technique to apply. These reports will be made available on the Electricity North West website.

For the successful operation of these devices it is important to have monitoring equipment. It is necessary to use this monitoring equipment as a guide for the setting of some of the devices.

13. Appendices

1. Evaluation of Voltage Control Options through Simulations – University of Manchester.
2. Analysis of the Site Trial Equipment Performances through Comparison – University of Manchester.
3. Solutions for Voltage Control Options at LV Busbars – University of Manchester.
4. Electricity North West Project Summary – powerPerfector.
5. Dunton Green Filter Load Balance – ABB.
6. Dunton Green Filter Run – ABB.
7. Dunton Green PFC – ABB.
8. Dunton Green Report – Before Filter Install – ABB.
9. Howard Street Filter all – ABB.
10. Howard Street Filter Load bal & PFC – ABB.
11. Howard St Filter on – ABB.
12. Howard Street Report – Before Filter Installation – ABB.
13. CP619 – Future Networks Asset Procedures – Electricity North West.
14. Drawings for Tap Change Panel – Fundamentals
15. TAPCON230 Leicester Avenue Settings – Fundamentals
16. TAPCON203 Landgate Settings – Fundamentals
17. Active Harmonic Filter Data – ABB
18. Report for Capacitor Placement – S&C Electric
19. LV Capacitor Specification – Electricity North West
20. Brochure for TapCon 230 Relay - MR