The University of Manchester

Tier 1/IFIXX:

Voltage Control Options on Low Voltage Busbars

Version: 3.0

Report title:

Analysis of the site trial equipment performances through comparison

Executive Summary

The aim of the voltage control options project is to deploy a range of voltage management methods and techniques across several distribution substations which will be assessed in terms of their ability and effectiveness to regulate line voltage in real-time in a safe and economical manner. In addition, the ability to correct poor power factor and the feeder power quality will also be assessed.

In order to assess the voltage control options on distribution network, it is important to understand and simulate existing distribution networks. This document describes the simulation of six low voltage networks including Dunton Green, Edge Green Lane, Greenside, Howard Street, Leicester Avenue and Landgate, based on their real network data such as cable length and types. The voltage profiles and geographic data of each network have been plotted.

In addition, the network site trial data are also presented and analysed in this report, the results are plotted accordingly.

The works described in this document will provide important information such as the load and line impedance of the trialled distribution networks, which is essential for assessment of the voltage control equipment effectiveness on LV network. The site trial result also gives an indication of other equipment functionalities such as power factor correction.

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1. Introduction

In order to investigate the benefits of implementing voltage control devices on existing distribution network, the simulation model of each trialled distribution network were produced. The power flow and voltage profile of each feeder was shown in this report. The feeders corresponding to the same substation has been merged into a single simulation model, therefore the model can also be used to study the network capability.

The site trial monitoring data and the voltage control device data were also presented. The site monitoring data were used to validate the simulation model, and the monitoring result for each voltage control devices are used to assess the performance of its functions. The results provide an important understanding of each equipment trialled.

The simulated distribution network includes all feeders connected to Dunton Green, Edge Green Lane, Greenside, Howard Street, Leicester Ave and Landgate substations. The parameters of the simulation model are based on the actual cable distance and cross sectional impedance. Hence the model provides an estimation of the current distribution network.

2. Simulation of six low voltage networks

2.1 Dunton Green network

Figure 1: Dunton Green s/s connections overview

There are four feeders connected to Dunton Green substation, the total number of loads connected for each feeder is shown in Table 1. The cable layout of Dunton Green network is shown in Figure 1, the power flow and voltage profile are shown in Figure 2-Figure 5 respectively.

Table 1: Dunton Green feeder load information

Substation	Feeder	No. of loads
Dunton Green s/s	Feature number 260055770	70
	Feature number 260055773	31
	Feature number 260055780	26

	Feature number 260055783	53

This voltage profile is produced in OpenDSS software package, based on the assumption that there is no PV connected, and the maximum load demand is 1.5kW with 0.95pf per customer. In Figure 2, the voltage profile of a single feeder is plotted, the linear line illustrates the trend of voltage drop (per phase). However the phase of some loads are unknown, therefore they were connected randomly. If the voltages are monitored on every nodes of the LV network, the load phases can then be approximated based on the actual voltage profile.

The actual voltage drop in the network is more complex, the voltage unbalace shown in the simulation does not always reflex the exsisting network voltage profile, difference between the actual voltage profile and the result through simulation is expected. The mid-point and end-point monitoring of each feeder could be used to validate the simulation models. Therefore, the simulation model could provide information of maximum and minimum voltage drop at end of the line, it is not possible yet to estimate the actual voltage unbalance behaviour on the LV network.

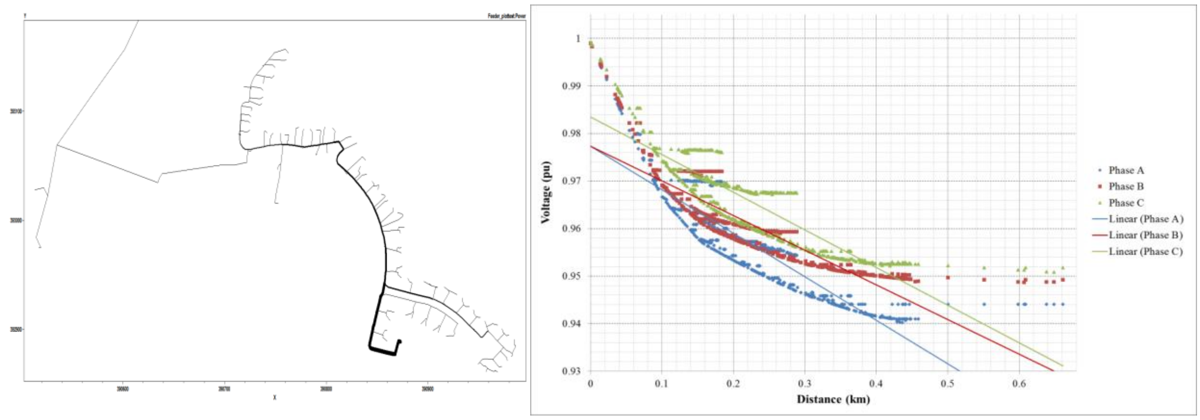


Figure 2: Power flow and voltage profile of Dunton Green feeder 260055770

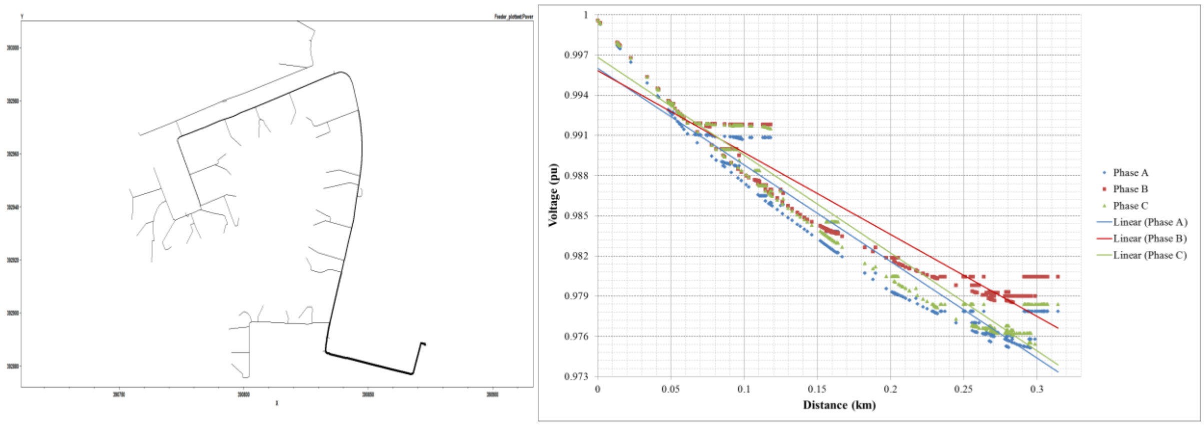


Figure 3: Power flow and voltage profile of Dunton Green feeder 260055773

The voltage drop at end of the each feeder may seems excessive, this is due to the 1.5kW per customer is considered at absolute maximum, in reality the maximum demand per house is generally considered to be less than 1kW, hence less significant voltage drop at each end of the feeder could be expected.

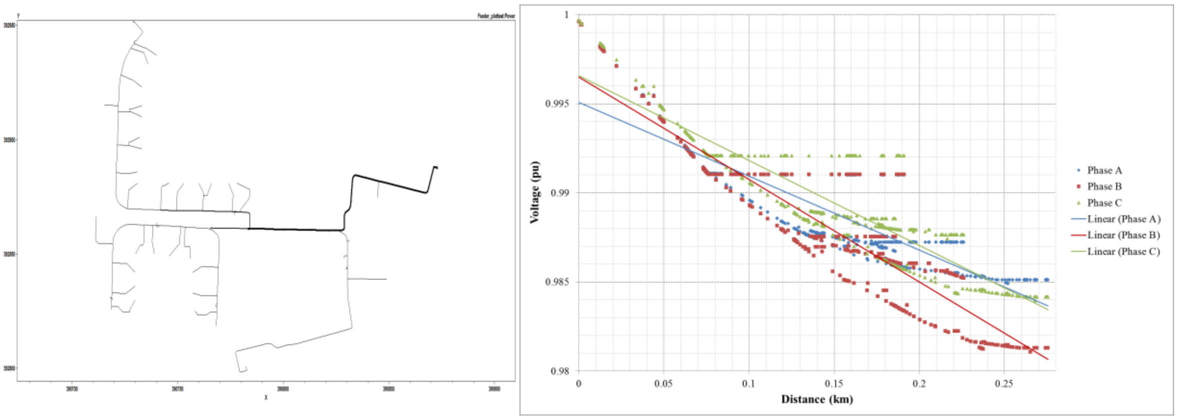


Figure 4: Power flow and voltage profile of Dunton Green feeder 260055780

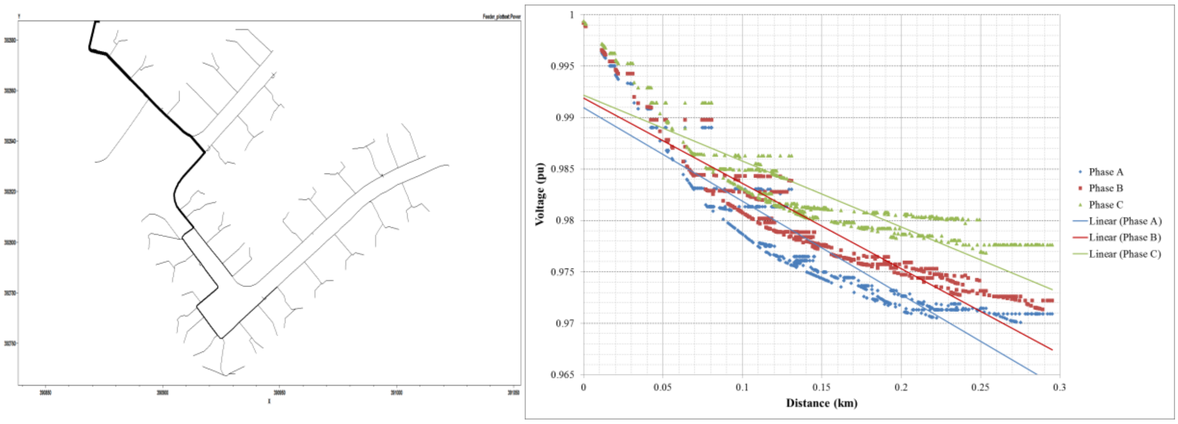


Figure 5: Power flow and voltage profile of Dunton Green feeder 260055783

2.2 **Edge Green Lane network**

Figure 6: Edge Green Lane network overview

There are total of 8 feeders connected to Edge Green lane substation. The number of loads connected for each feeder is given in Table 2, greater number of loads connected or longer cable distances are directly proportional to higher voltage drop of each feeder. The power flow and voltage profiles are shown in Figure 7-Figure 14.

Table 2: Edge Green Lane feeder load information

Substation	Feeder	No. of Loads
Edge Green Lane s/s	Feature number 66074748	38
	Feature number 66074749	23
	Feature number 66074750	17
	Feature number 66074751	49
	Feature number 66074752	29
	Feature number 66074753	156
	Feature number 66074754	16
	Feature number 66074755	4

It can be seen from Figure 7-Figure 14 that the most significant voltage drop occurs at feeder 66074753 which has highest number of loads connected, this result in very different voltage drop compare to other feeders, hence if the voltage is being controlled at substation level, this will not be as effective compare to some of other substations. The best solution could be to implement the voltage regulator or capacitors along the feeder.

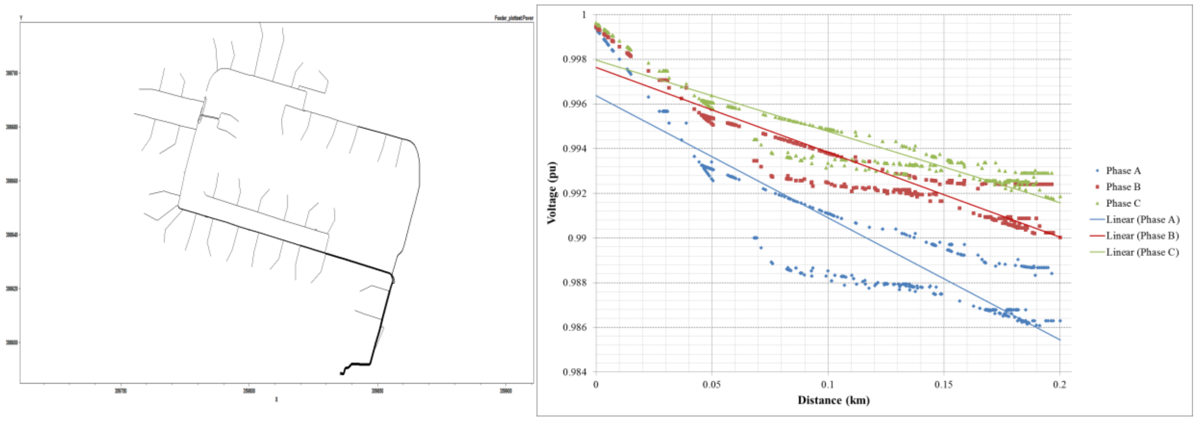


Figure 7: Power flow and voltage profile of Edge Green Lane feeder 66074748

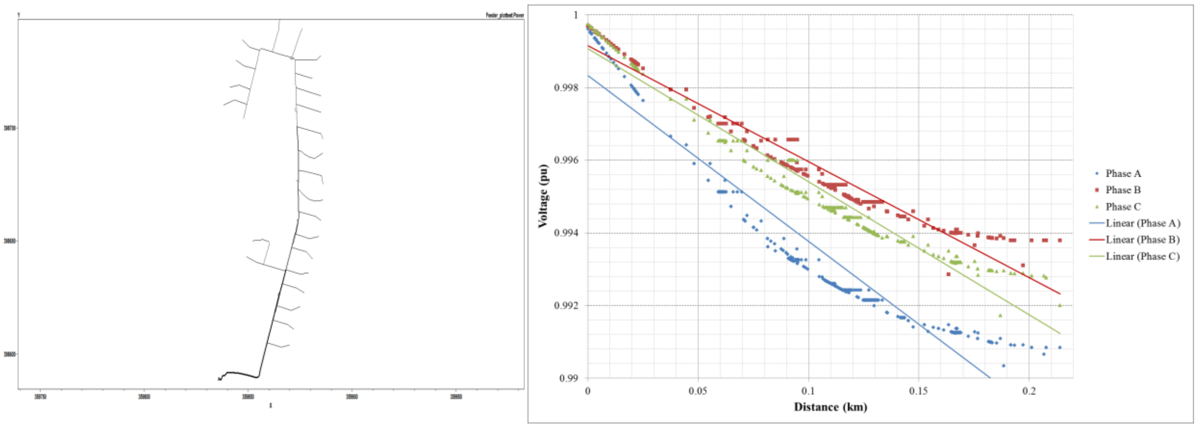


Figure 8: Power flow and voltage profile of Edge Green Lane feeder 66074749

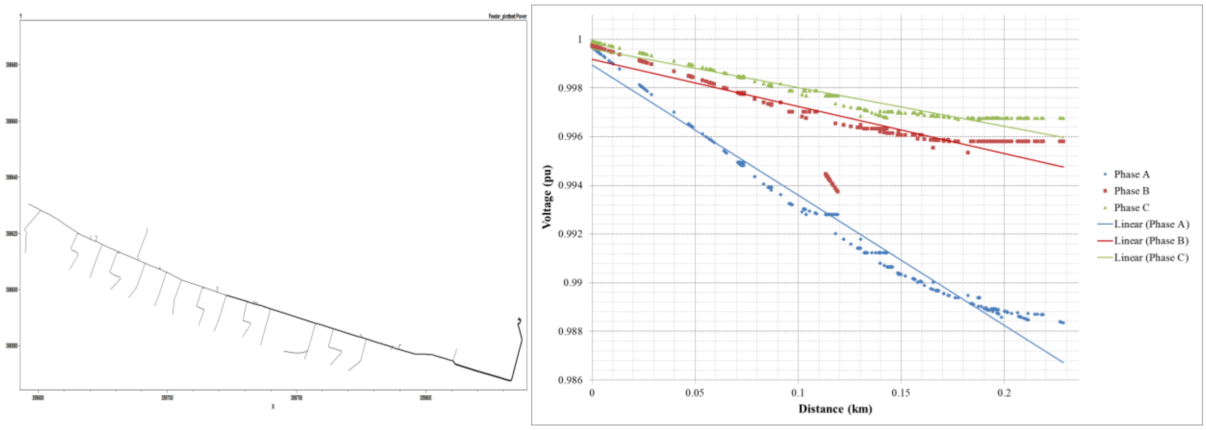


Figure 9: Power flow and voltage profile of Edge Green Lane feeder 66074750

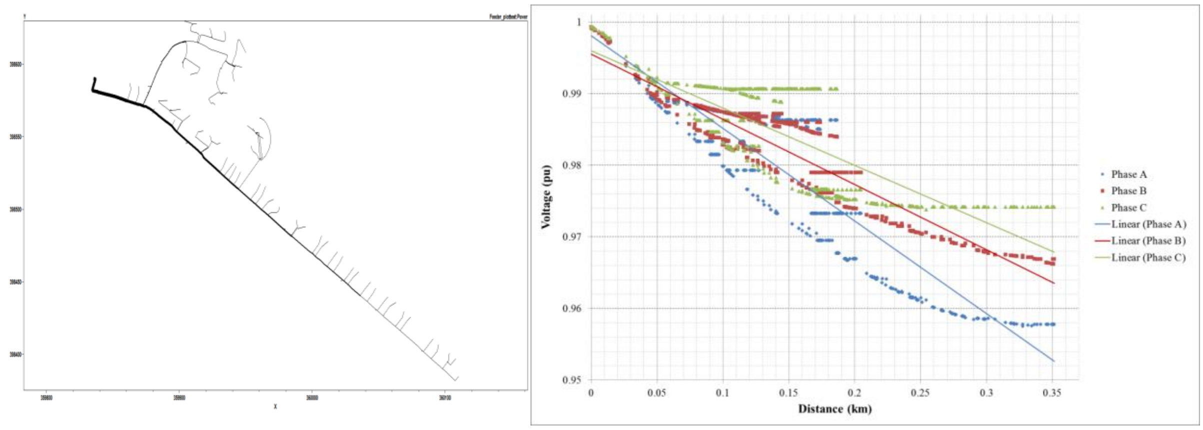


Figure 10: Power flow and voltage profile of Edge Green Lane feeder 66074751

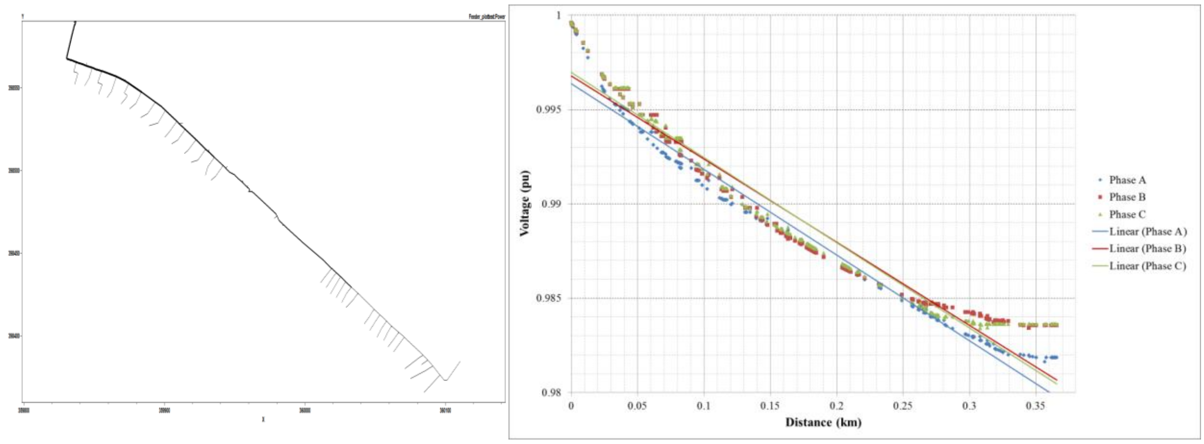


Figure 11: Power flow and voltage profile of Edge Green Lane feeder 66074752

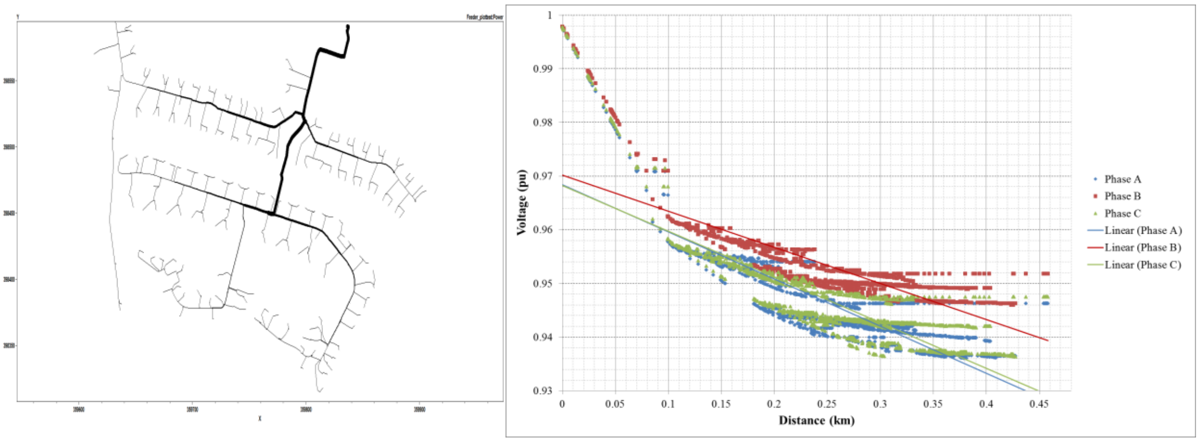


Figure 12: Power flow and voltage profile of Edge Green Lane feeder 66074753

Figure 12 clearly shows a much complex voltage profile with significant more nodes in the network, this is also illustrated in the power flow result. Compare to the feeder shown in Figure 13 whereas the cable is laid as a single line, the voltage drop against cable distance in this case is almost linear. Hence the most effective method of voltage control for this particular network is to install equipment such as capacitor or storage at downstream of the feeder (66074753).

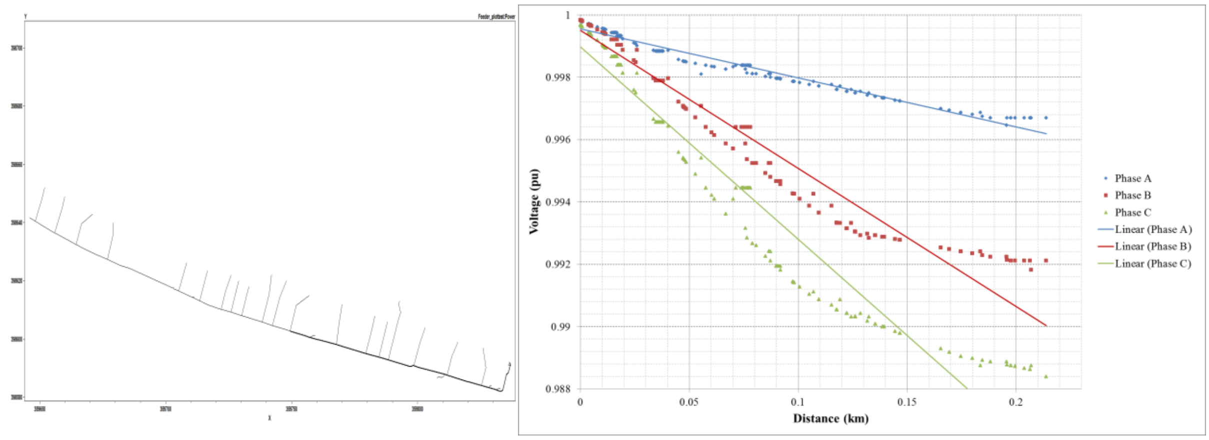


Figure 13: Power flow and voltage profile of Edge Green Lane feeder 66074754

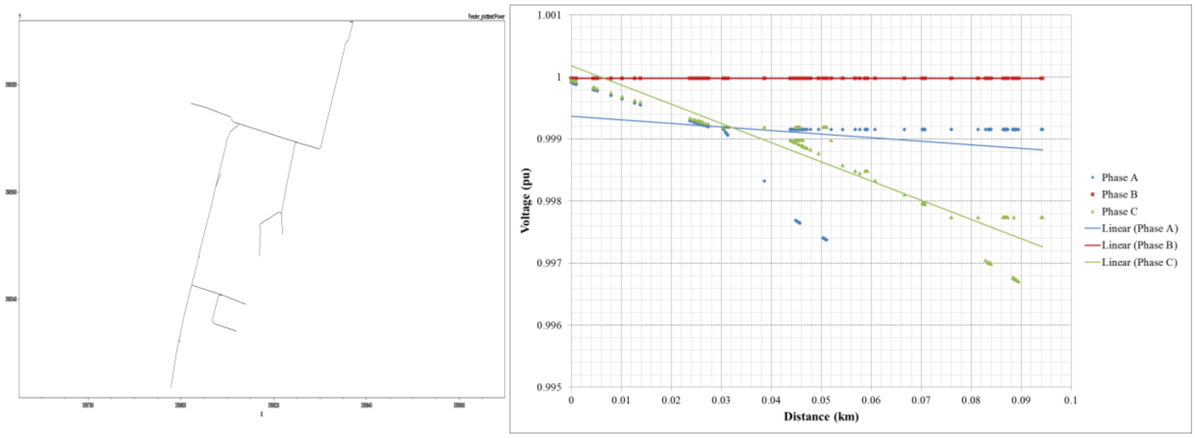


Figure 14: Power flow and voltage profile of Edge Green Lane feeder 66074755

2.3 Greenside Lane network

Figure 15: Greenside Lane network overview

There are total of 5 feeders connected to Greenside Lane substation, the number of loads connected are given in Table 3. The voltage profiles are shown in Figure 16-Figure 20.

Table 3: Greenside Lane feeder load information

Substation	Feeder	No. of loads
Greenside Lane s/s	Feature number 527400004	23
	Feature number 527400005	15
	Feature number 527400006	106
	Feature number 527400007	135
	Feature number 527400008	149

Due to feeder 527400004 and 527400005 has significantly less customers connected compares to other feeders, the voltage drop at end of the feeders are significantly less than others. This has raised a difficult issue for voltage control, if the distribution transformer with OLTC was installed at this substation, it would be effectively maintains the statutory limits for all feeders. However to install downstream voltage control equipment such as capacitors for 3 feeders that are heavy loaded could also be a very effective option.

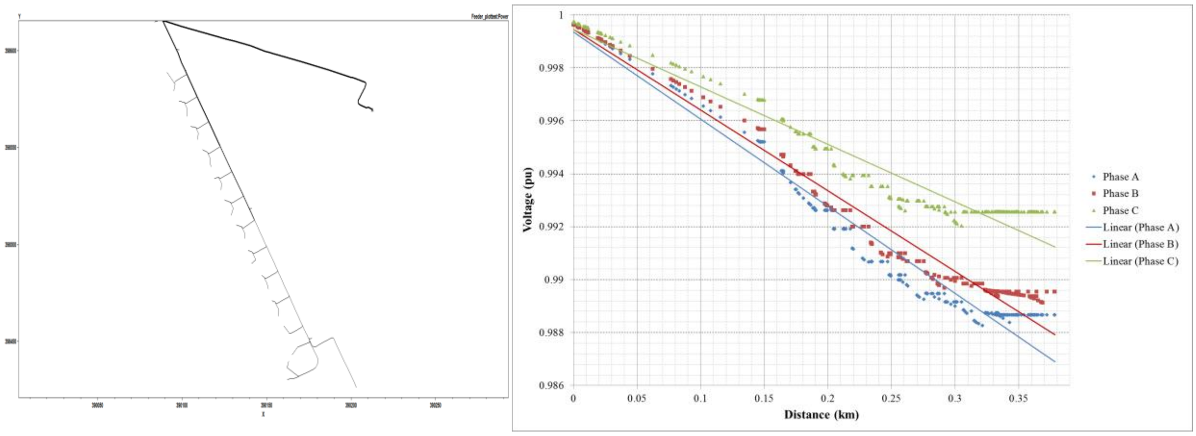


Figure 16: Power flow and voltage profile of Greenside feeder 527400004

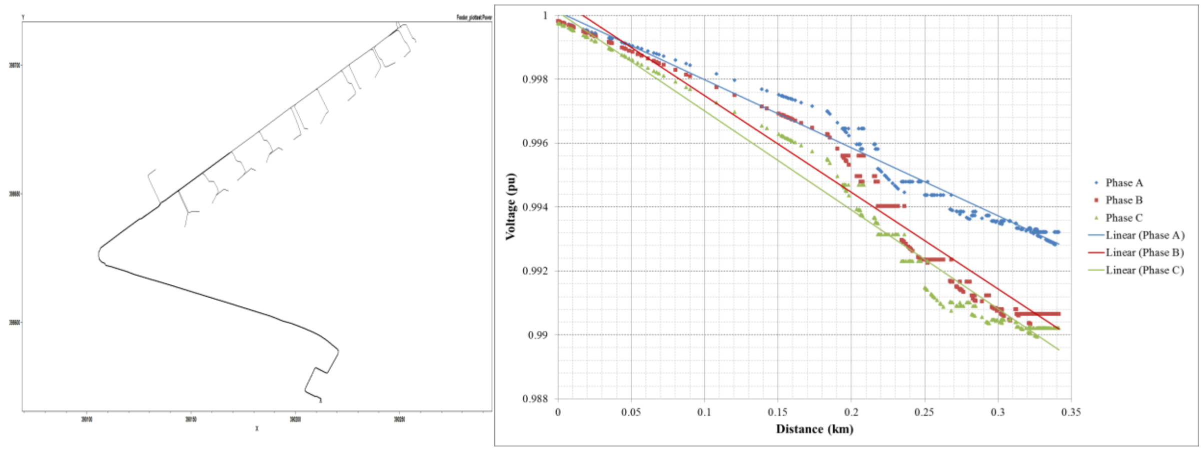


Figure 17: Power flow and voltage profile of Greenside feeder 527400005

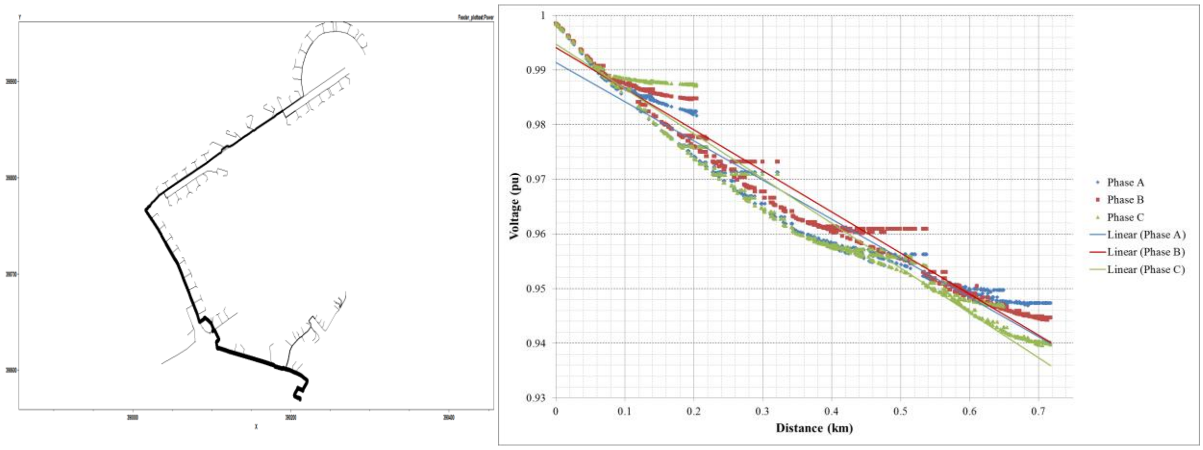


Figure 18: Power flow and voltage profile of Greenside feeder 527400006

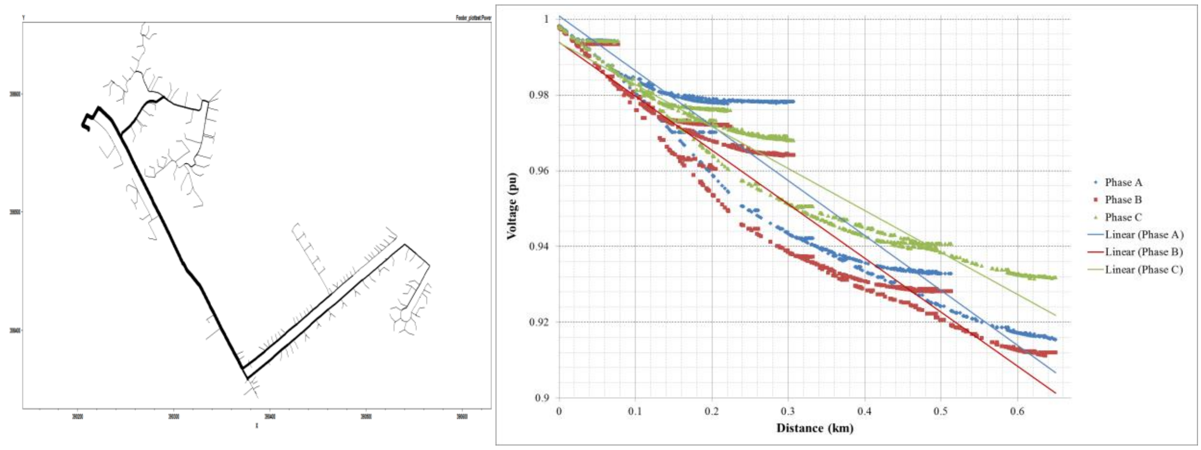


Figure 19: Power flow and voltage profile of Greenside feeder 527400007

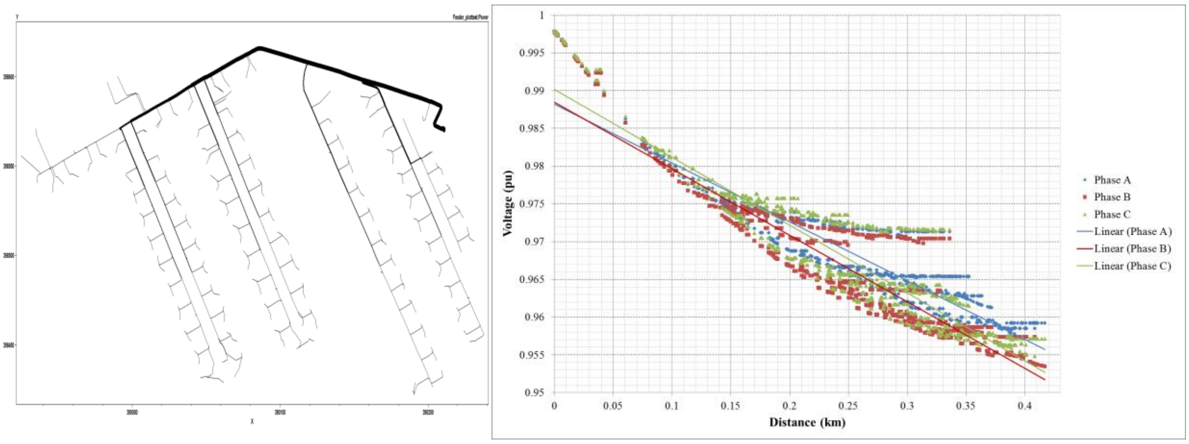


Figure 20: Power flow and voltage profile of Greenside feeder 527400008

As shown in Figure 20, the loads are connected in random phases, the phase voltage drop mainly depending on the load demands and distributed locations. When implementing voltage control equipment at feeder downstream, it would be more effective to install it at a feeder that has most number of loads connected or longest cable length between substation point and end-point location.

2.4 **Howard St network**

Figure 21: Howard Street network overview

There are total of 2 feeders connected to Howard St substation, the number of loads connected are shown in Table 4. The power flow and voltage profiles are shown in Figure 22-Figure 23.

Table 4: Howard St feeder load information

Substation	Feeder	No. of loads
Howard St s/s	Feature number 216044694	54
	Feature number 216044696	120

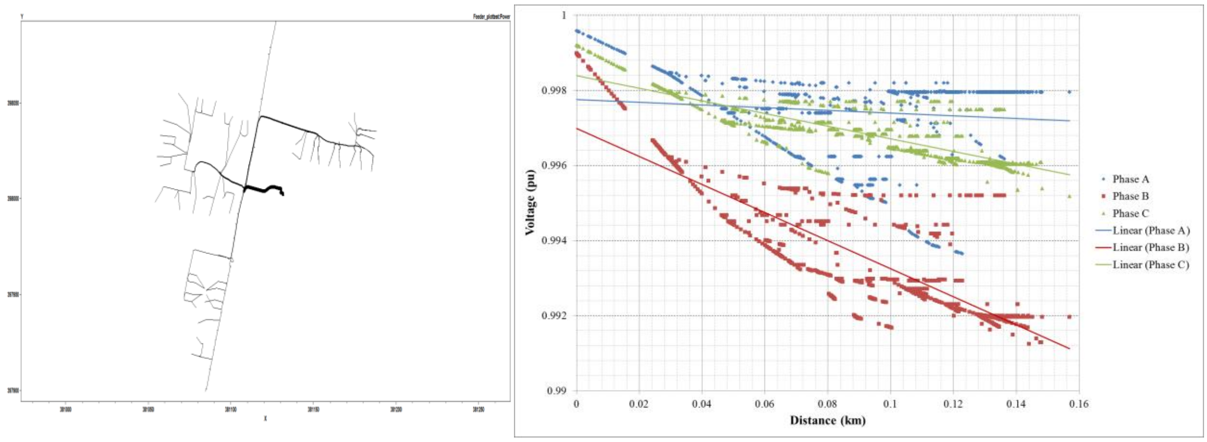


Figure 22: Power flow and voltage profile of Howard St feeder 216044694

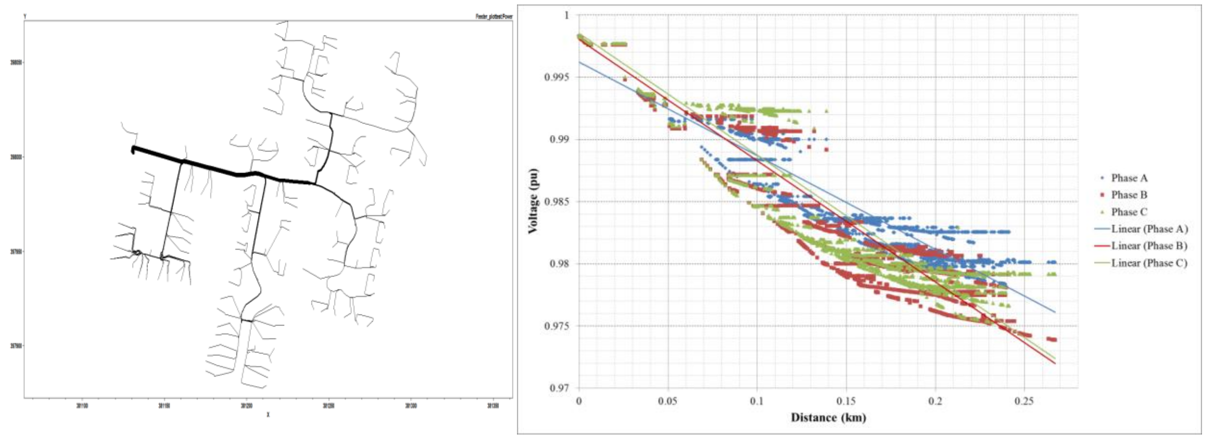


Figure 23: Power flow and voltage profile of Howard St feeder 216044696

2.5 **Leicester Ave network**

Figure 24: Leicester Avenue network overview

There are total of 6 feeders connected to Leicester substation, the number of properties connected for each feeder are given in Table 5. The power flow and voltage profiles are shown in Figure 25-Figure 30. Feeder 69051565 has around four times more loads connected compares to other feeders. The voltage control devices such as capacitor on a single feeder would be most effective method to maintain voltage within the statutory limits. Due to other feeders has relatively low number of loads connected.

Table 5: Leicester Avenue feeder load information

Substation	Feeder	No. of loads
Leicester Ave s/s	Feature number 69051549	20
	Feature number 69051565	82
	Feature number 69051573	17
	Feature number 69051590	4
	Feature number 69051618	27
	Feature number 69051980	25

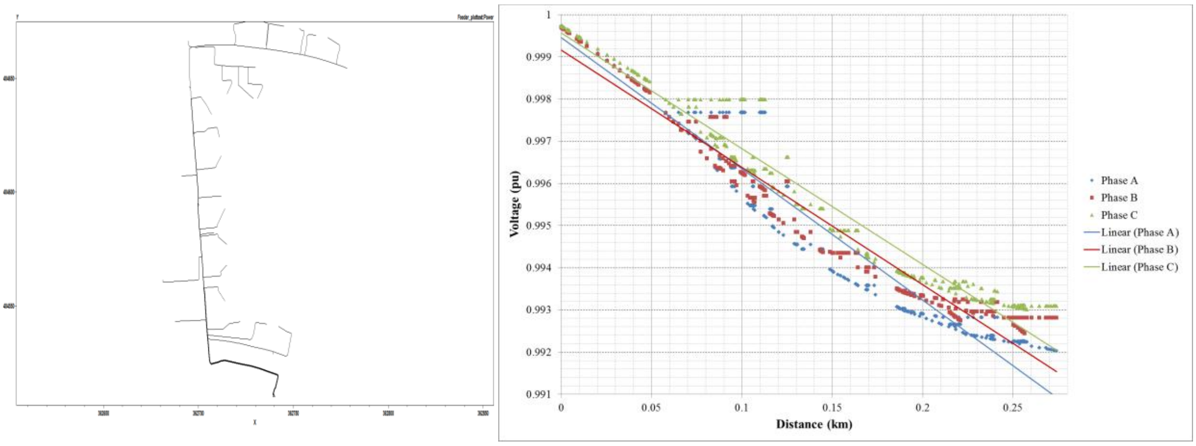


Figure 25: Power flow and voltage profile of Leicester feeder 69051549

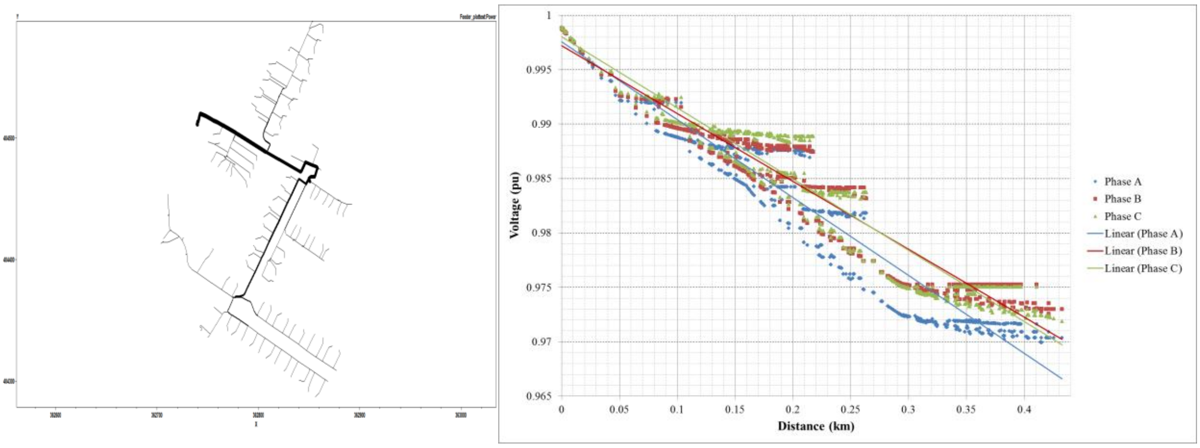


Figure 26: Power flow and voltage profile of Leicester feeder 69051565

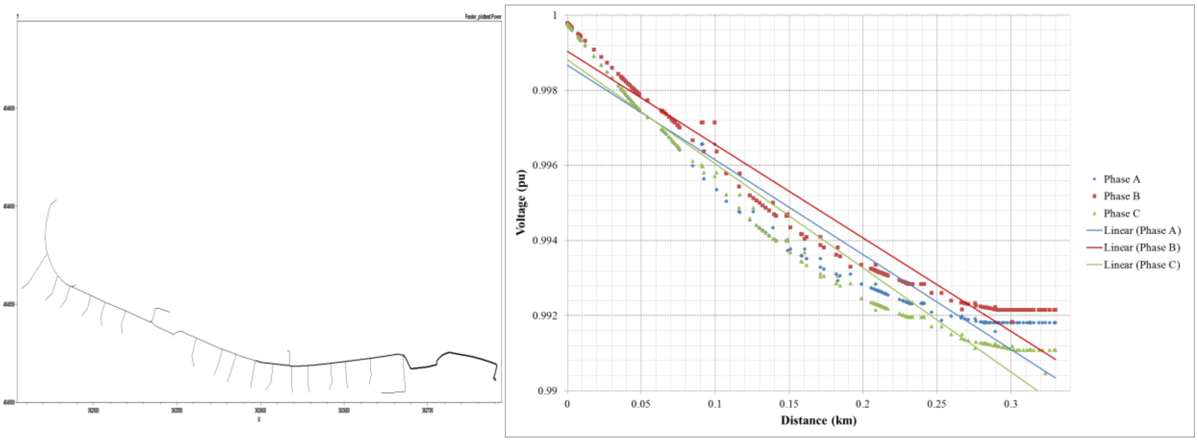


Figure 27: Power flow and voltage profile of Leicester feeder 69051573

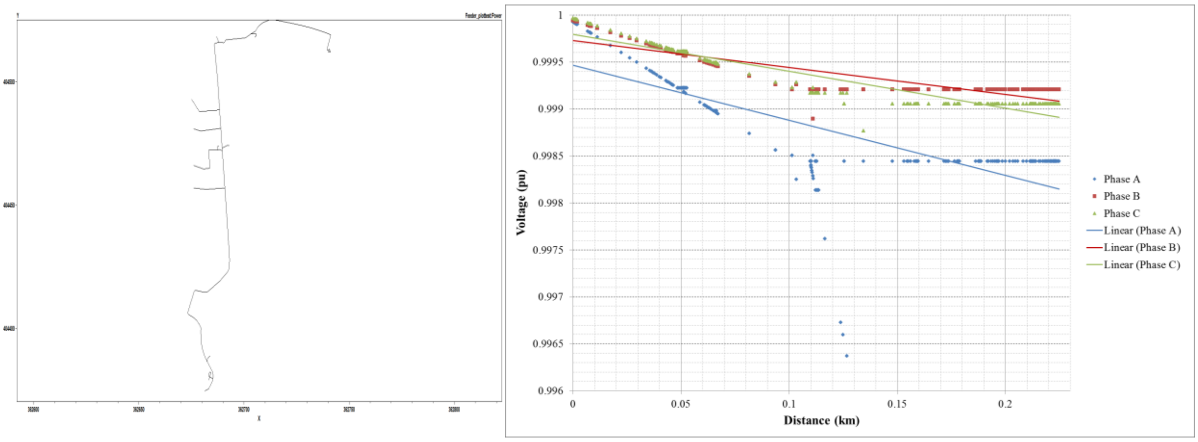


Figure 28: Power flow and voltage profile of Leicester feeder 69051590

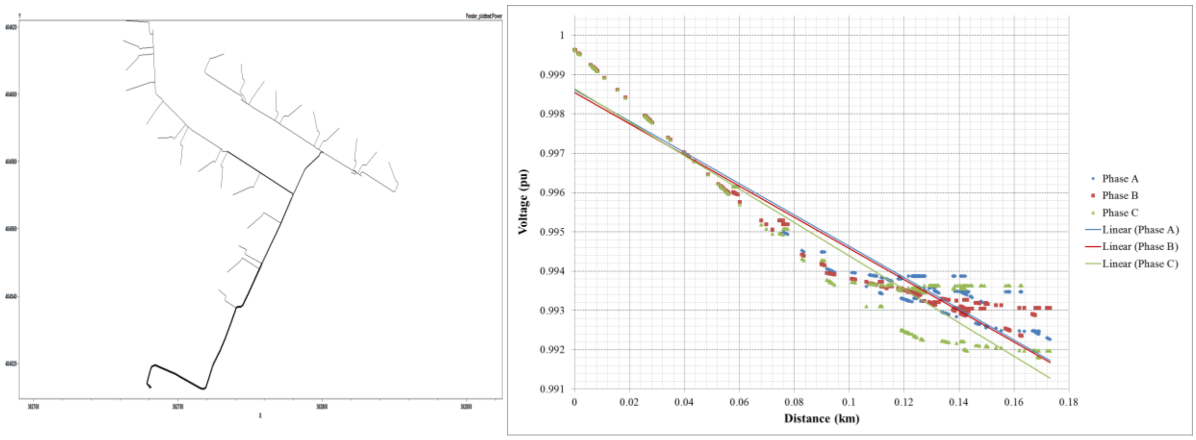


Figure 29: Power flow and voltage profile of Leicester feeder 69051618

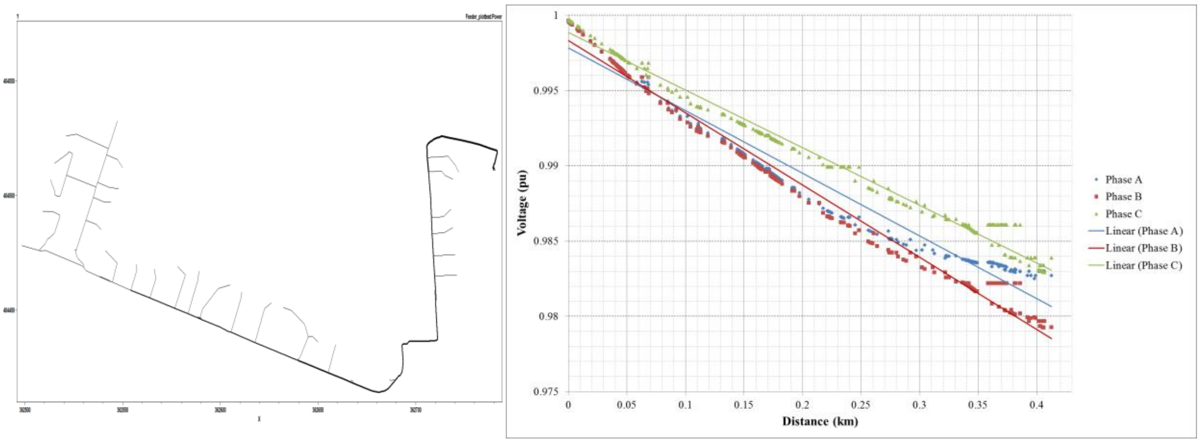


Figure 30: Power flow and voltage profile of Leicester feeder 69051980

2.6 Landgate network

Figure 31: Landgate network overview

There are total of 6 feeders connected to Landgate substation, the properties connected for each feeder is shown in Table 6. The power flow and voltage profiles are given in Figure 32-Figure 37. This feeder has many similarities with Leicester substation. Due to feeder 63057172 and feeder 63057174 has much more loads connected, results more significant voltage drop at end of the feeder.

Table 6: Landgate feeder feeder load information

Substation	Feeder	No. of loads
Landgate s/s	Feature number 63057169	49
	Feature number 63057170	21
	Feature number 63057171	30
	Feature number 63057172	100
	Feature number 63057173	68
	Feature number 63057174	83

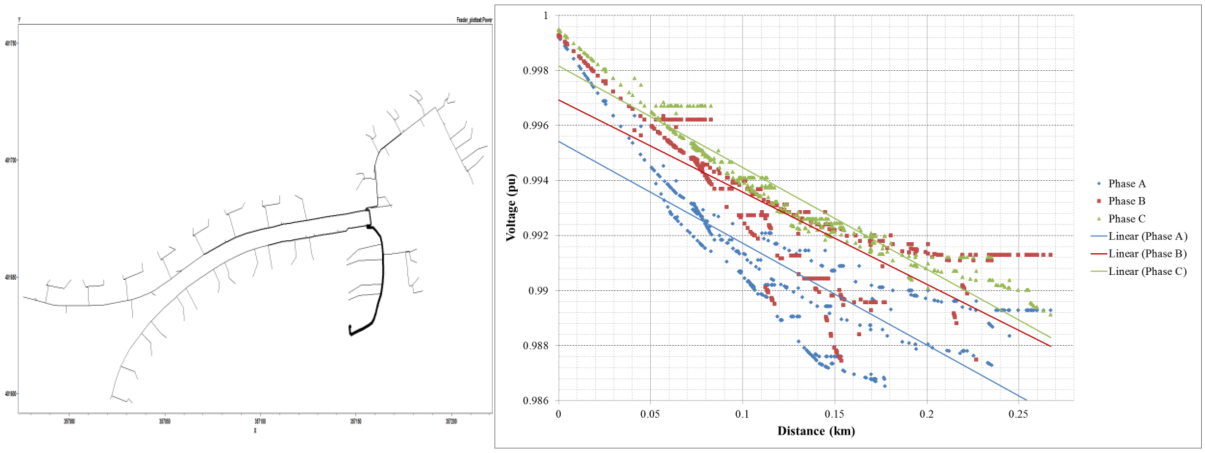


Figure 32: Power flow and voltage profile of Landgate feeder 63057169

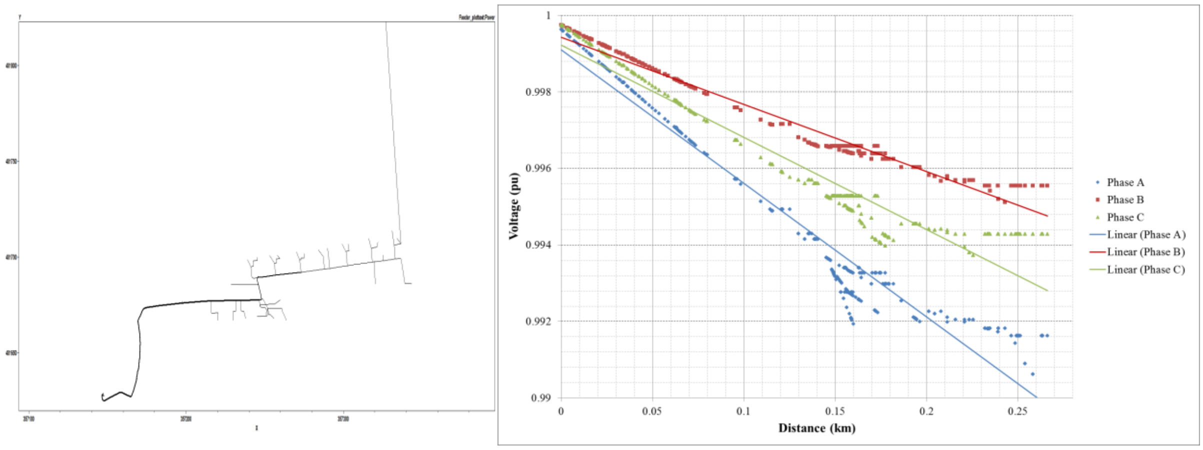


Figure 33: Power flow and voltage profile of Landgate feeder 63057170

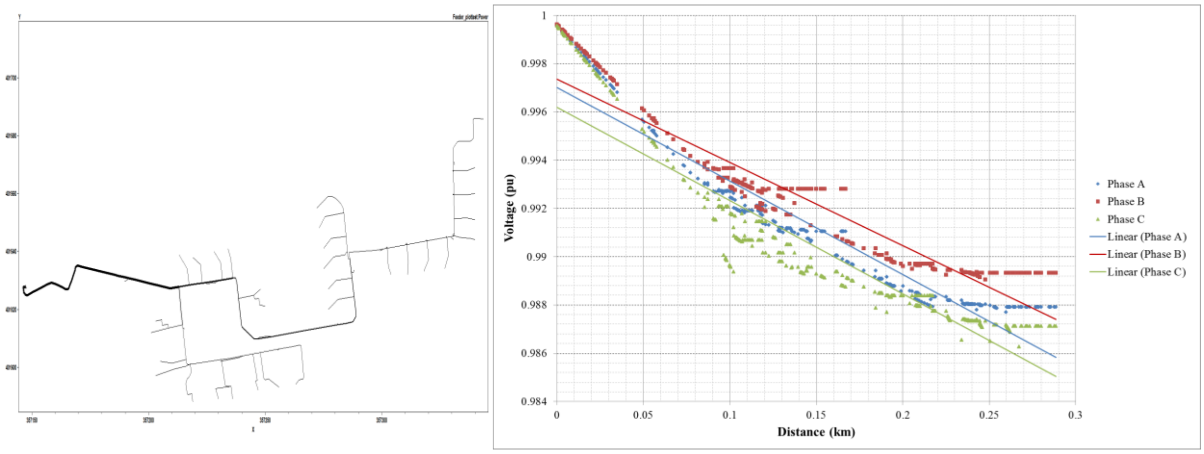


Figure 34: Power flow and voltage profile of Landgate feeder 63057171

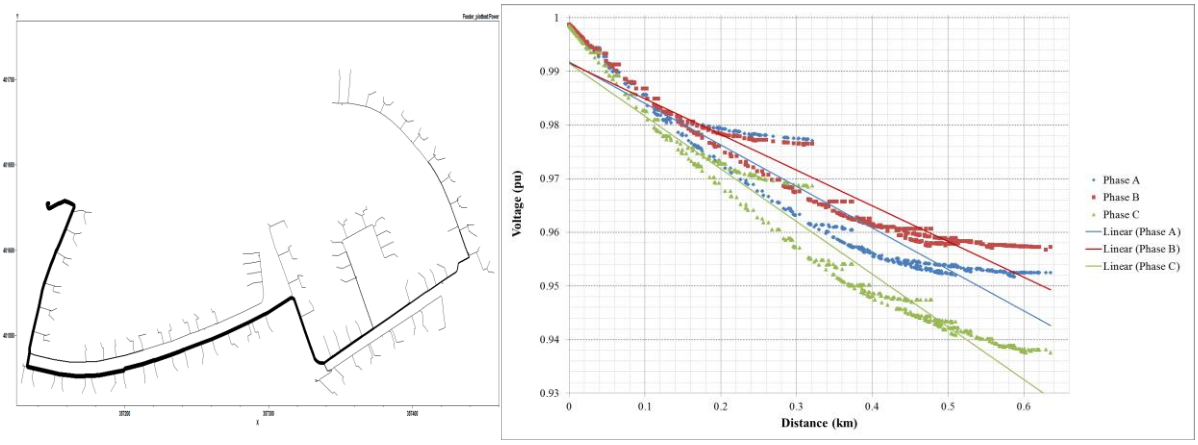


Figure 35: Power flow and voltage profile of Landgate feeder 63057172

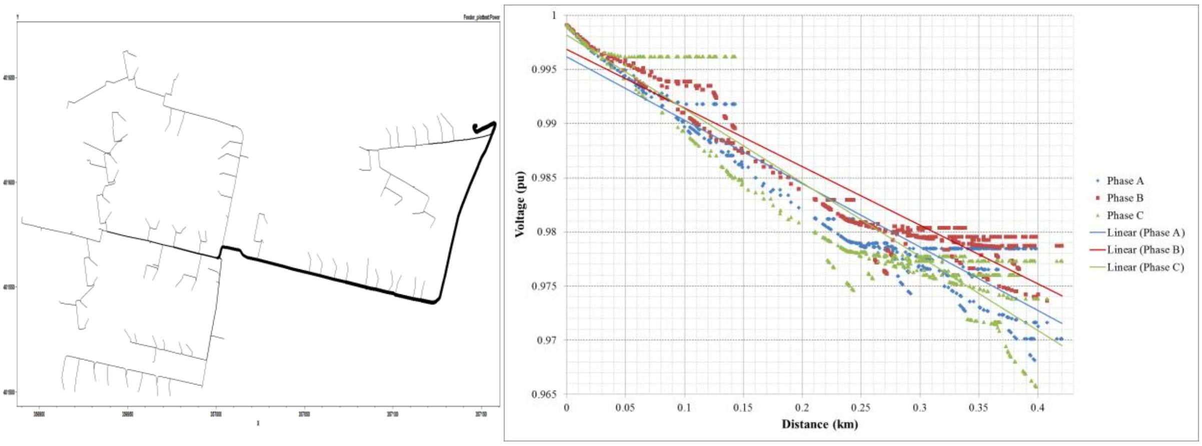


Figure 36: Power flow and voltage profile of Landgate feeder 63057173

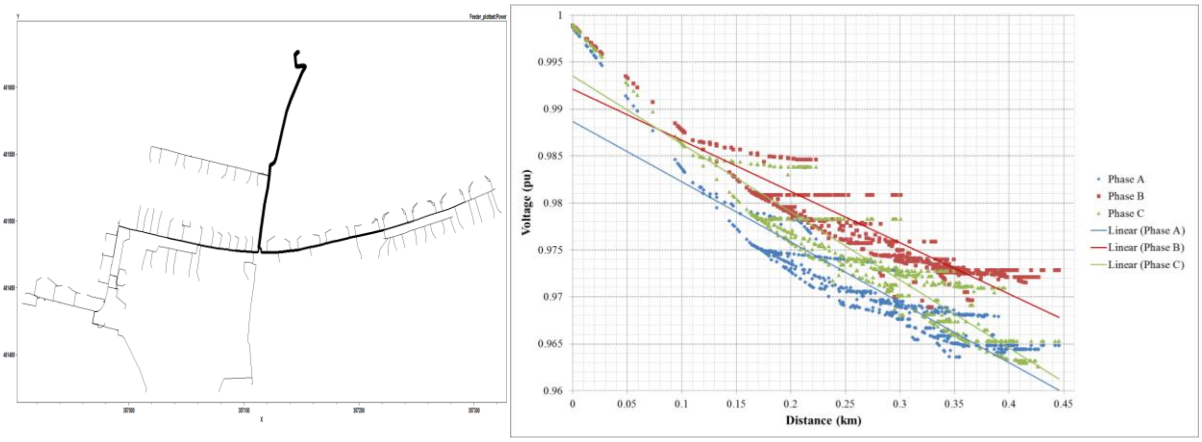


Figure 37: Power flow and voltage profile of Landgate feeder 63057174

3. Merging of substation feeders and simulation in PSCAD/EMTDC

In order to carry out substation penetration studies, all feeders corresponding to each substation are merged together into a single load flow study, the transformer settings are altered to be more close to reality. The leakage reactance for example has been changed from 1% to 4%, hence more voltage drop at substation end. The maximum load demand for each house is set at 1.5kW, this is at an absolute maximum. From Figure 38-Figure 43, it can be noted that the phase voltages between each feeder are very different especially at end of the feeder.

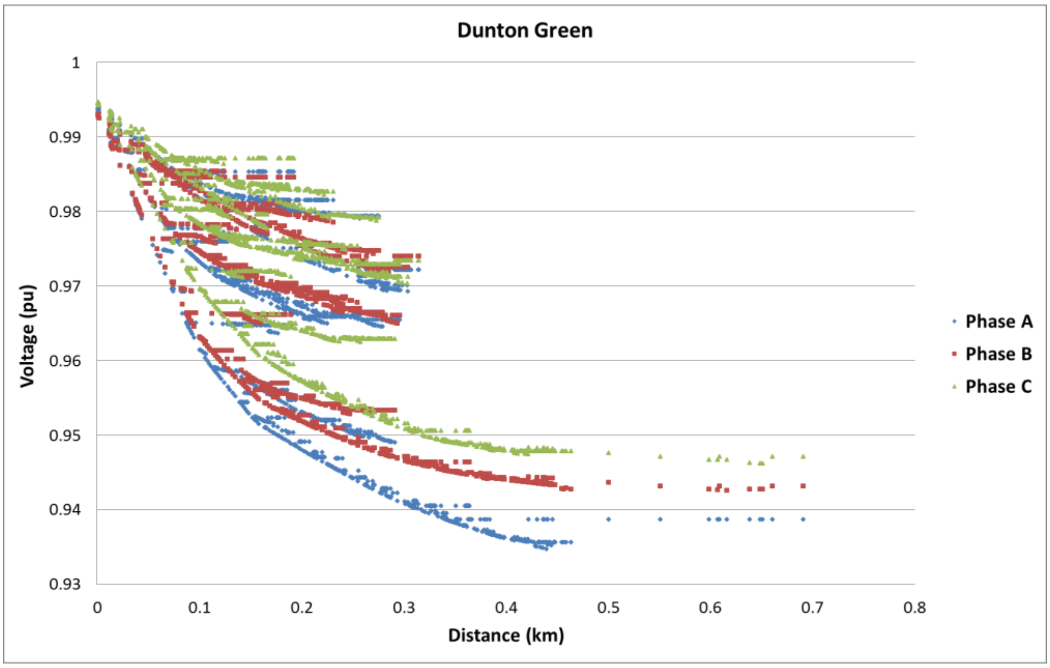


Figure 38: Dunton Green merged network

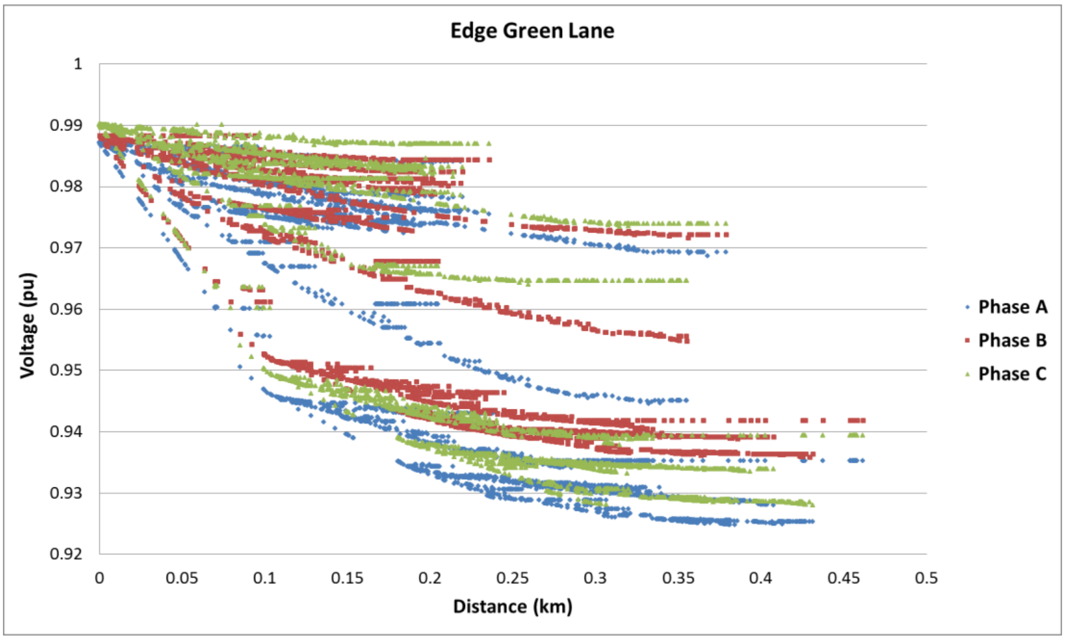


Figure 39: Edge Green Lane merged network

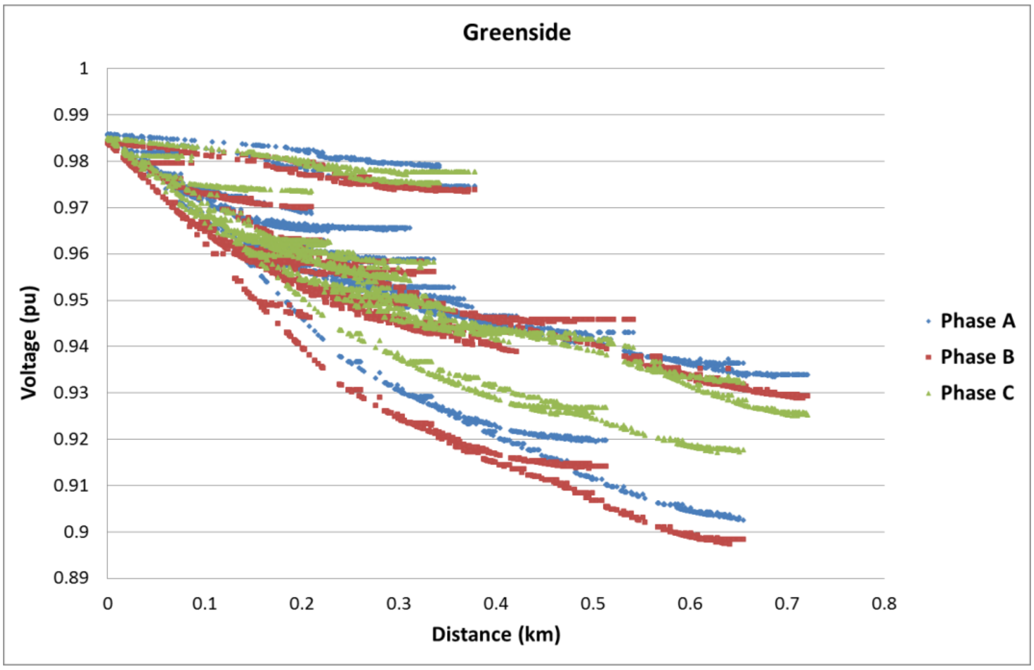


Figure 40: Greenside merged network

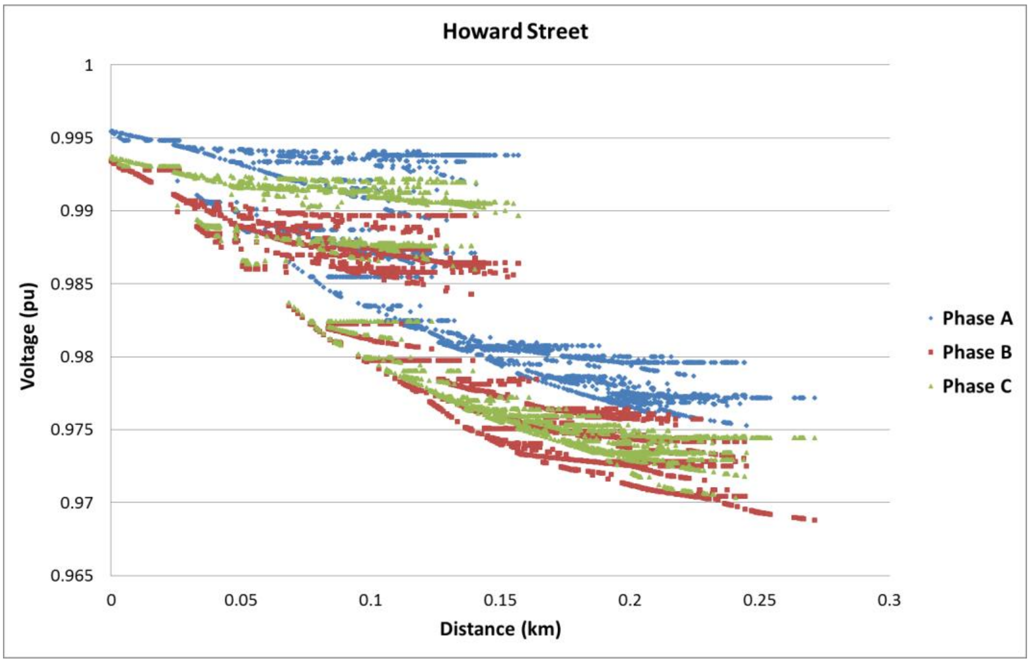


Figure 41: Howard Street merged network

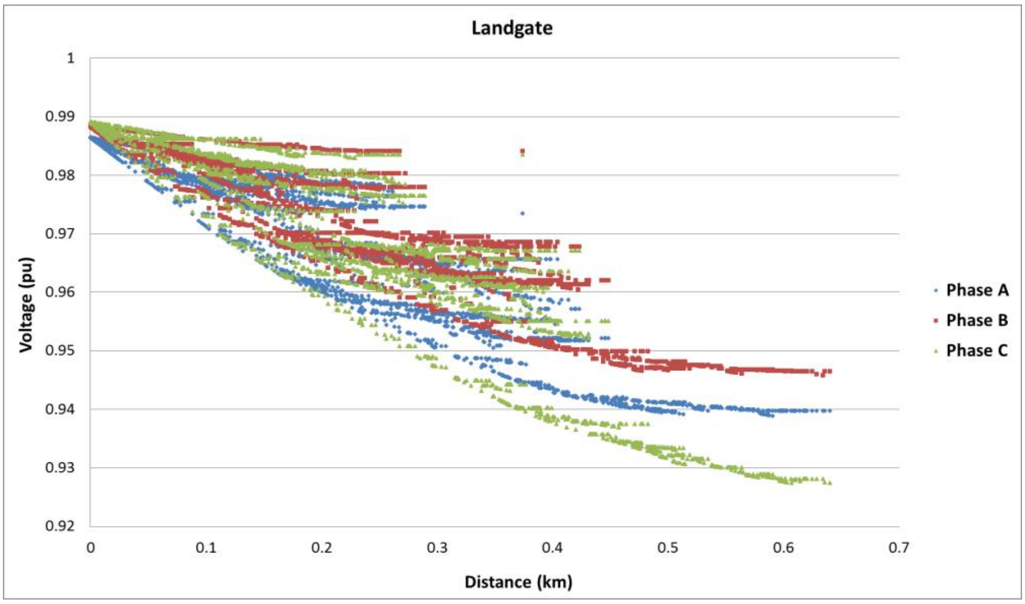


Figure 42: Landgate merged network

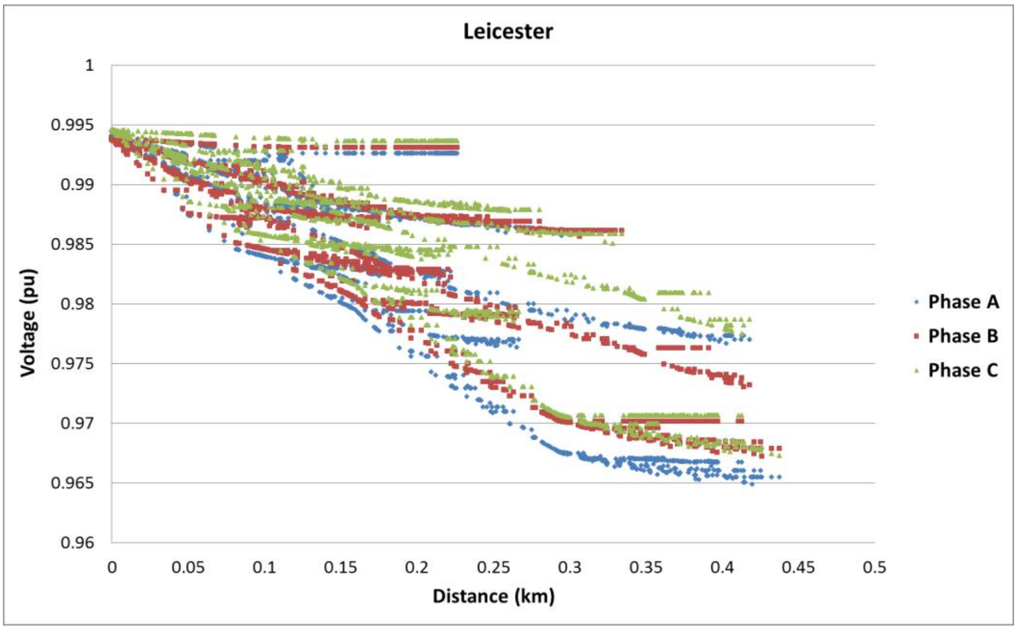
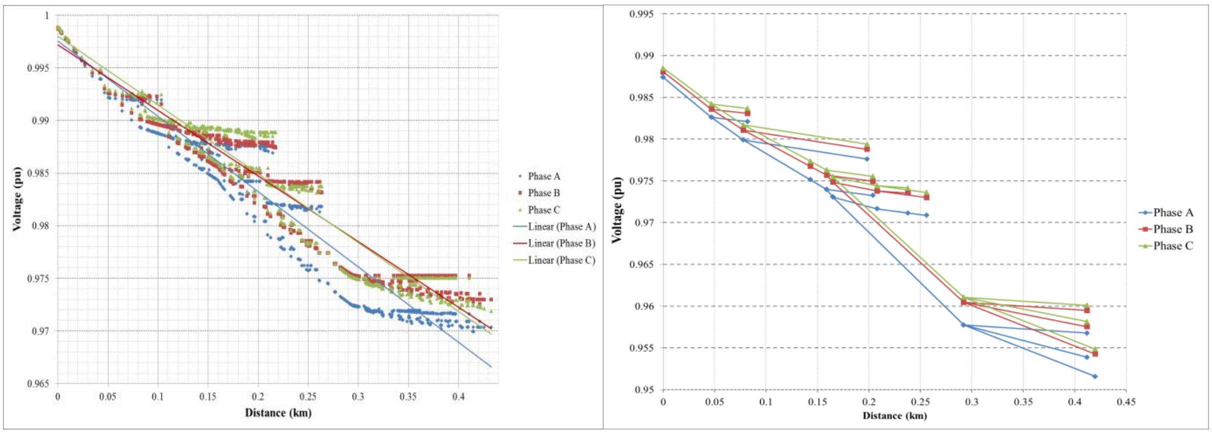


Figure 43: Leicester merged network

As some voltage control equipment require a unique simulation model with different control algorithms such as active filters and powerPerfectors, therefore to further analyse the network, a different software package was needed. PSCAD/EMTDC has the ability to carry out transient studies, and also be able to model three phase network along with single phase devices such as single phase PV generators, each with its different level of output. However the size of some network feeder is excessive to model in EMTDC, which contains thousands of nodes, hence the number of nodes in the network needs to be reduced.

After the network data has been validated, the network reduction technique can be applied to feeders that has significant amount of nodes. The reduced data can then be implemented into the EMTDC with voltage control models. The six network models produced in EMTDC are shown in the Appendix.



(a) (b)

Figure 44: Voltage profile of original (a) and reduced (b) Leicester feeder 69051565

In Figure 44, Leicester feeder 69051565 was plotted and shown as an example, the original feeder data has greater number of nodes as shown in Figure 44(a). To reduce the nodes while maintaining the voltage profile, only nodes associated with the start and end point for each cable are considered. This will give the maximum voltage drop at end of the each cable. The nodes along the line are therefore not being monitored, the reduced network feeder developed in EMTDC is shown in Figure 44(b). Due to the EMTDC uses more realistic transformer models, the voltage at substation point is hence lower due to more realistic parameters such as transformer rating and leakage reactance.

To model the household load in EMTDC, it is important to understand the behaviour of load demand throughout the year, such as different seasons will have different impact on the loads. For instance, the winter load is generally being considered as higher than other seasons due to more household will have heaters switched on. There are mainly two types of loads are being considered, one with PV connected and another without PV connection.

4. Network site trial monitoring data

4.1 Active filter site trial

The ABB active filter used for site trial has the ability to select 2nd to 50th order of harmonics for three-wire connection and up to 15th of harmonics for four-wire connection. The site trials were carried out on Dunton Green and Howard Street substations, the main trial action was aimed to assess the filter functions such as harmonics filter, load balancing and reactive compensation.

Dunton Green substation site has 4 feeders connected (feeder feature number 260055770, 260055773, 260055780 and 260055783), and Howard Street substation site has 2 feeders (feeder feature number 216044694 and 216044696). Before the site trial, the filters were both switched off for approximately a period of one week, so that the network data such as busbar voltage, active power, reactive power and THD were collected. This data provides the reference when comparing the data when the filter was switched on. The network loads are constantly changing therefore the data obtained from two different weeks are not absolute comparable, however it would provide a very good indication of the effect by implementing the equipment and when altering the various settings. Each trial action generally lasts a period of one week with different filter setting such as voltage balancing and harmonics filtering.

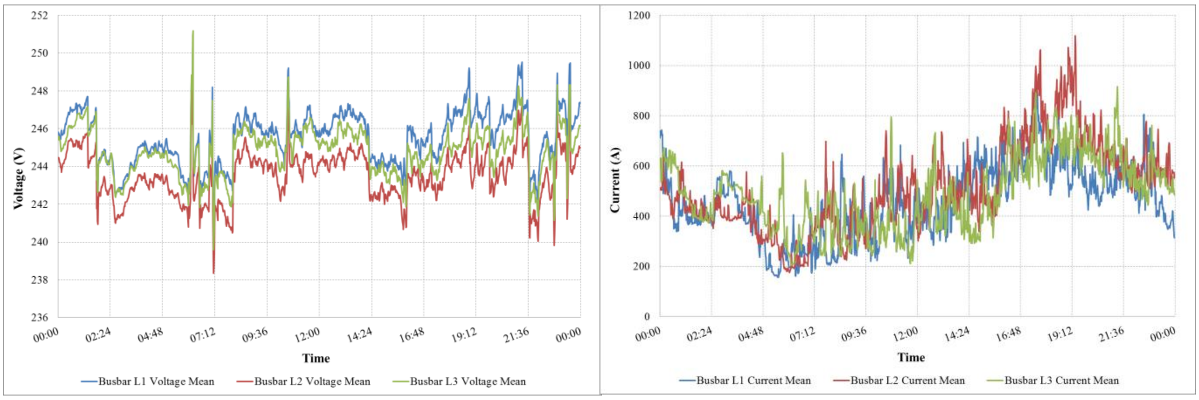


Figure 45: Howard Street busbar voltage and current on 03/01/2013

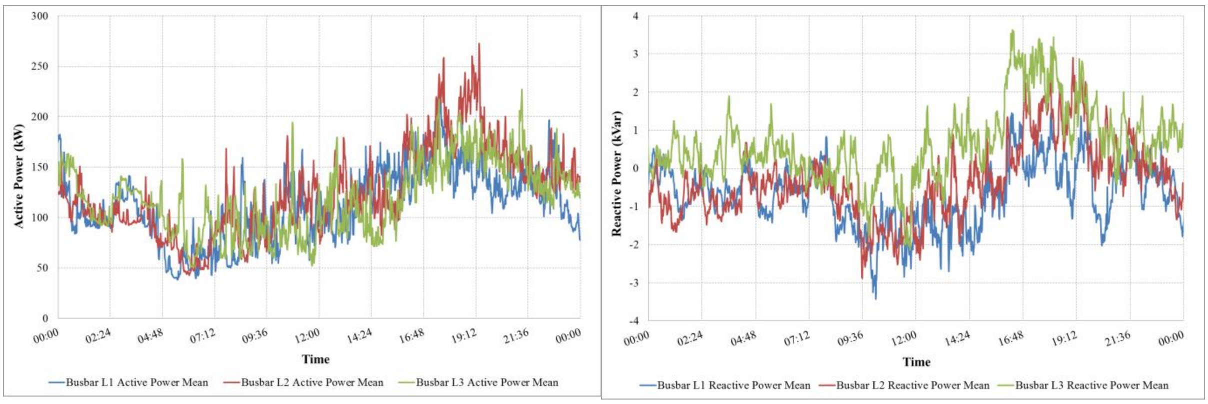


Figure 46: Howard Street busbar active and reactive power on 03/01/2013

Figure 45 and Figure 46 shows a set of data monitoring on 3rd of January 2013 within a period of 24 hours, which contains the busbar voltage, current, real and reactive power. The result illustrates a typical load demand within a day period, whereas the demand is at its peak around 19:00 in the evening and lowest in early morning around 04:00.

One of the most important functions of the active filter is its ability to filtering out the network harmonic currents. Figure 47-Figure 48 shows the harmonic currents up to 20th order measured at Dunton Green.

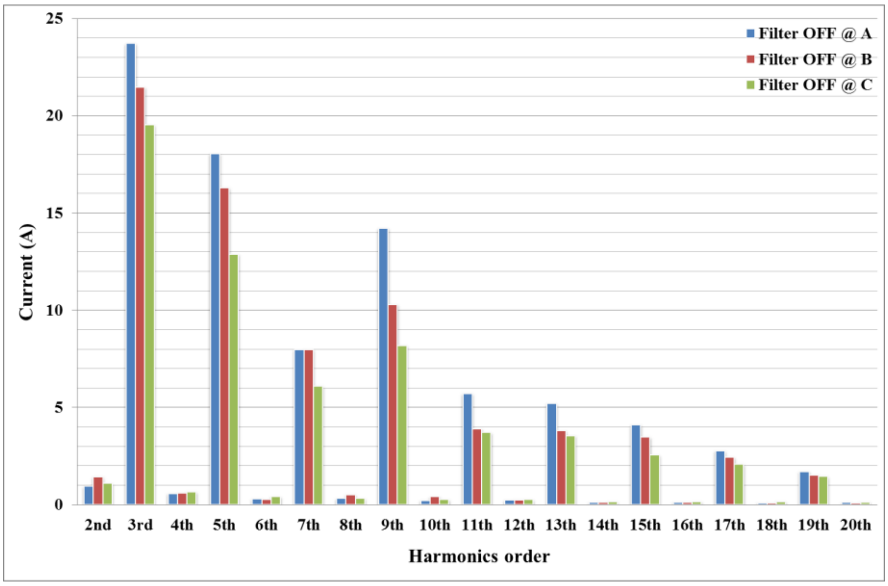


Figure 47: Data when filter switched off between 12:25 on 13/05/2013 and 12:15 on 20/05/2013 at Dunton Green substation

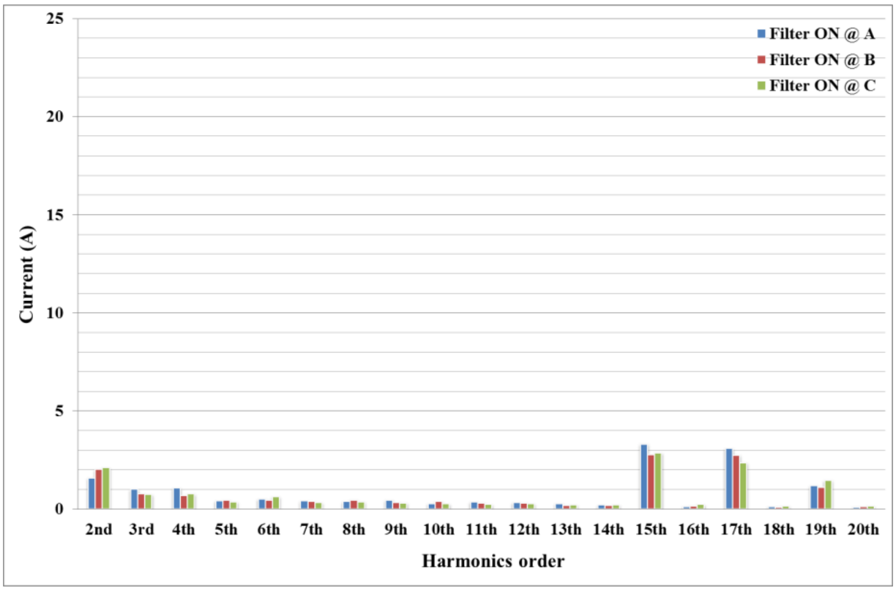


Figure 48: Data when filter switched on between 11:55 on 10/06/2013 and 13:10 on 17/06/2013 at Dunton Green substation

From Figure 47-Figure 48, it shown that the filter was able to significantly reduce the harmonics current up to 15th order where it was most significant. This is maximum order of harmonics (up to 15th) that can be reduced when all the filter functionalities has been selected such as load balancing and power factor correction.

This result shown that the filter was very effective to reduce the odd order of harmonic currents that been generated by the PV and other household electronic devices. Figure 49-Figure 50 shows similar data and in this case it was monitored at Howard street substation. The filter at Howard street station however is not as effective as the one installed at Dunton Green, whereas the 3rd and 5th order harmonic currents are still above 10A.

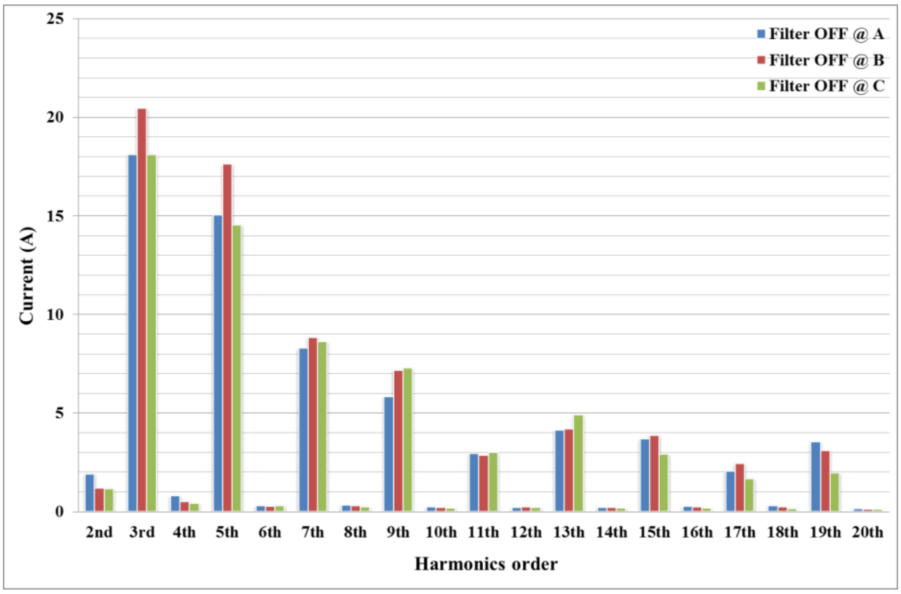


Figure 49: Data when filter switched off between 13:30 on 21/05/2013 and 14:00 on 28/05/2013 at Howard street substation

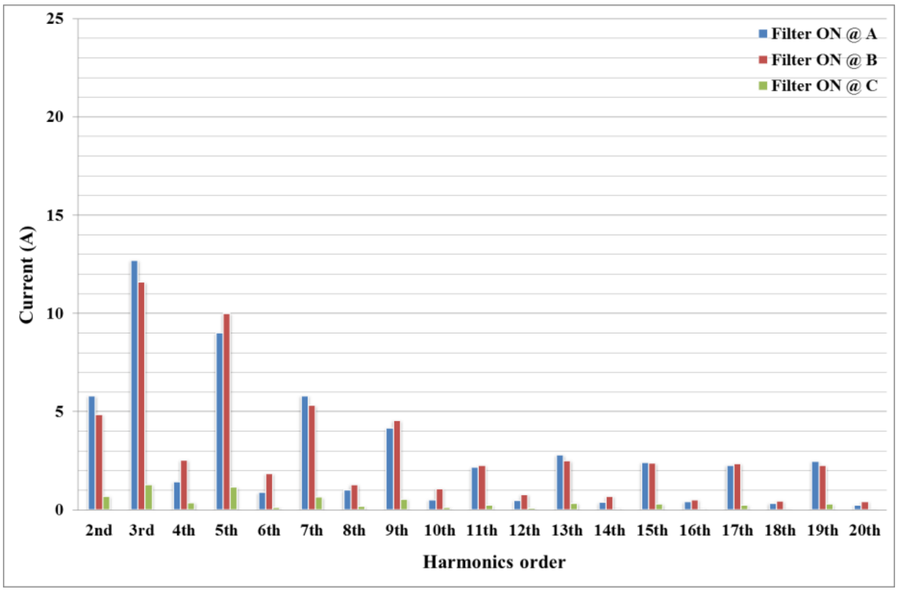


Figure 50: Data when filter switched on between 10:55 on 10/06/2013 and 13:55 on 17/06/2013 at Howard street substation

4.2 powerPerfector (pP) site trial

Greenside Lane (Droylsden) and Edge Green Lane (Golborne) substations were selected for powerPerfector unit trial. Similarly to other voltage control equipment trial, voltage, current, real and reactive powers are recorded before and after the equipment installation. In addition to this monitoring circuit, there are two PQM meters which are installed for each pP unit, which are connected to input and output of the pP unit respectively. Therefore the data were monitored both at substation and also the feeders where the pP unit was connected.

Two 350kVA powerPerfector units were installed at two selected substations and each unit has different tap percentages.

- One pP unit set to automatically increase by 4%, maintain at 0% or decrease by -4%, -8% and -12% the voltage according to the pre-set voltage reference level.
- One pP unit set to automatically increase by 2.7%, maintain at 0% or decrease by -2.7%, -5.4% and -8.1%.

A link box was also installed by Electricity North West to allow redirection of the electrical supply through an alternative route to the load, thereby allowing the unit to be taken out of circuit, hence the network can also be operated without the pP unit if needed. The pP unit could also be set in either auto or manual operation mode, both settings were accessed during the site trial.

The monitoring data at both Edge Green and Greenside Lane substation were collected and Figure 51-Figure 54 shows the voltage, current, active and reactive power measured on 3rd of January, 2013.

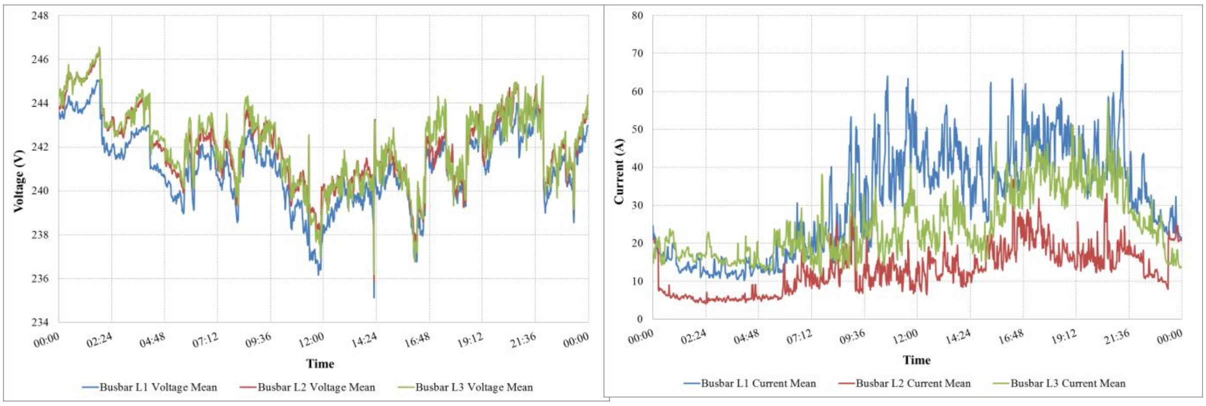


Figure 51: Edge Green Lane busbar voltage and current on 03/01/2013

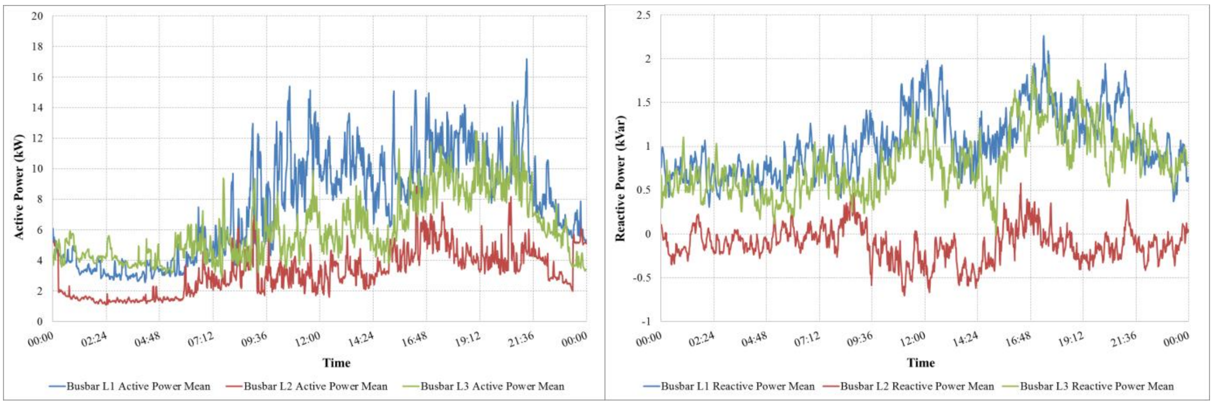


Figure 52: Edge Green Lane busbar active and reactive power on 03/01/2013

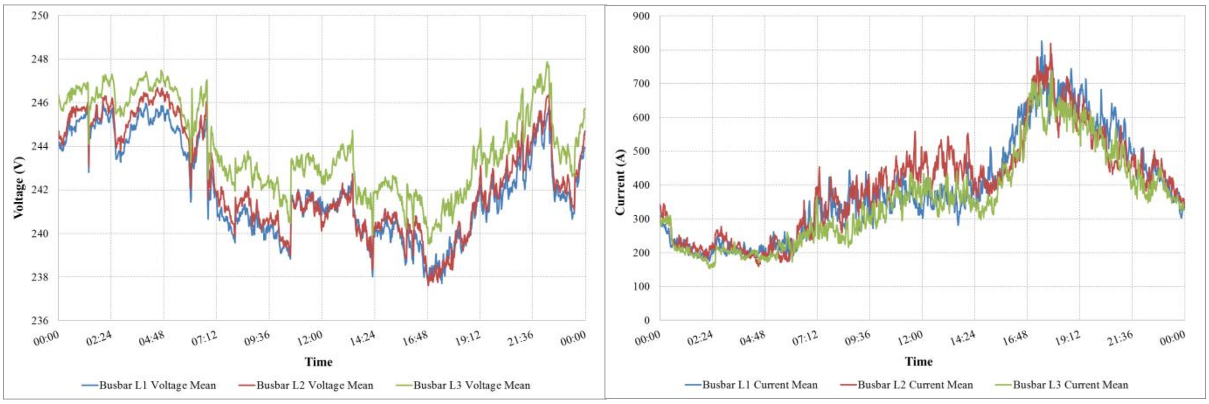


Figure 53: Greenside Lane busbar voltage and current on 03/01/2013

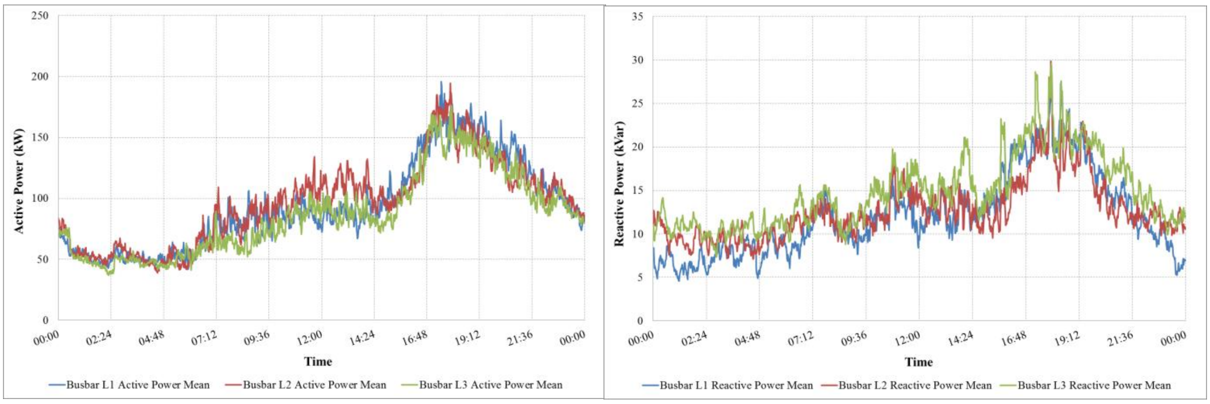


Figure 54: Greenside Lane busbar active and reactive power on 03/01/2013

Figure 55 shows the pP unit installed at Edge Green substation. According to the GIS data, Edge Green Lane network has significant PV connected and Greenside Lane has none. It can be noted from the results that the active and reactive power at Greenside has much less ripples compare to Edge Green Lane. However there is a significant difference in current and powers seen between the two sites.

Figure 55: powerPerfector unit installed at Edge Green Lane substation

In order to assess the effectiveness of powerPerfector unit to control network feeder voltage, several trial actions has been carried out.

4.2.1 powerPerfector step down tap setting

Figure 56-Figure 60 shows the pP unit was able to effectively control the feeder voltage by altering different tap positions as in the figures. When the input terminal of the pP unit was set at voltage reference that it steps down the voltage by -8% for the 4% unit, and when the input voltage reaches above 250V, the unit switches to the next available tap which is at -12%.

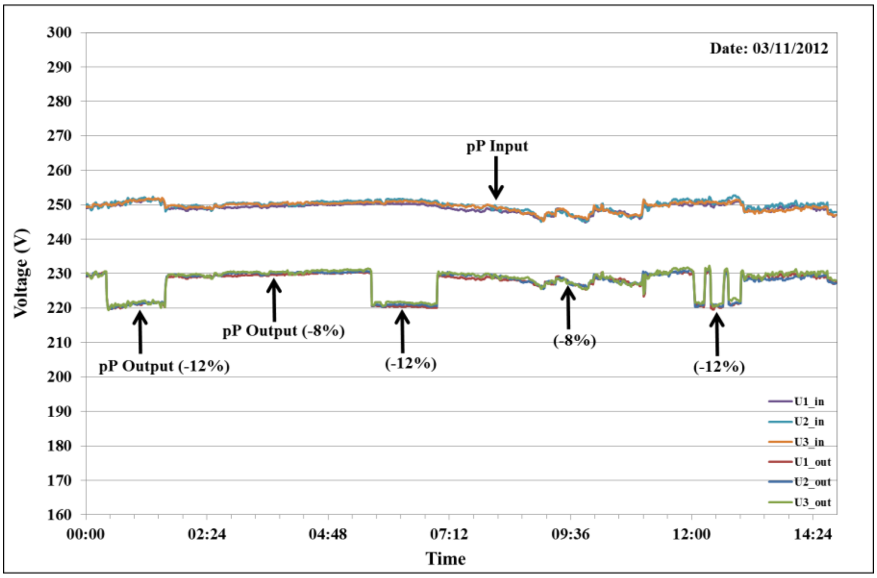


Figure 56: 4% powerPerfector unit measured on 03/11/2012

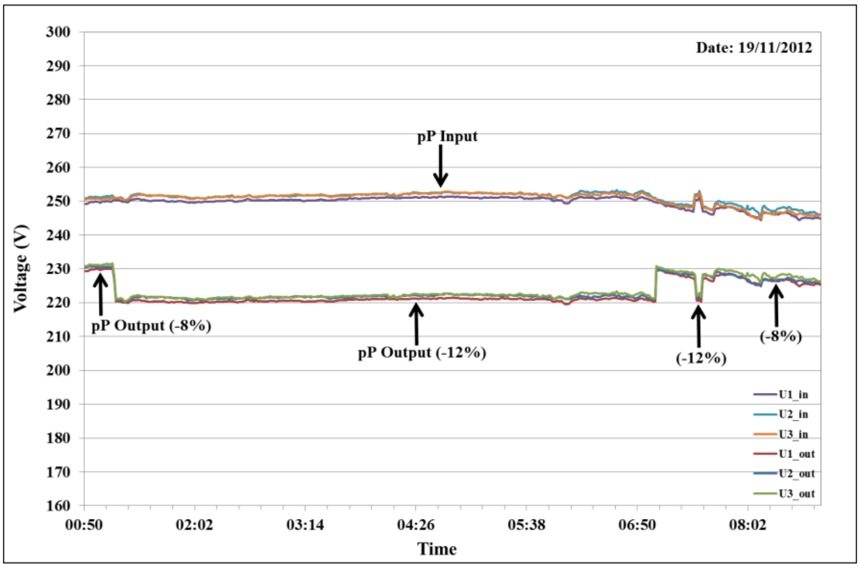


Figure 57: 4% powerPerfector unit measured on 19/11/2012

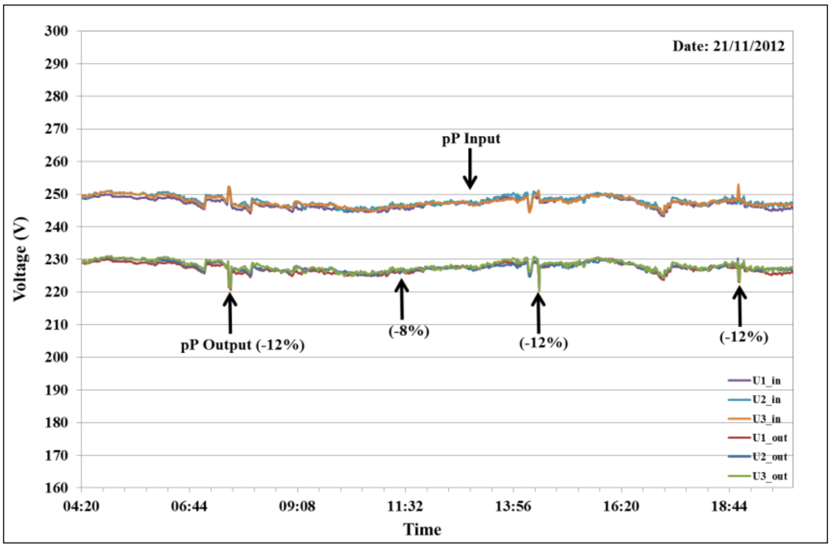


Figure 58: 4% powerPerfector unit measured on 21/11/2012

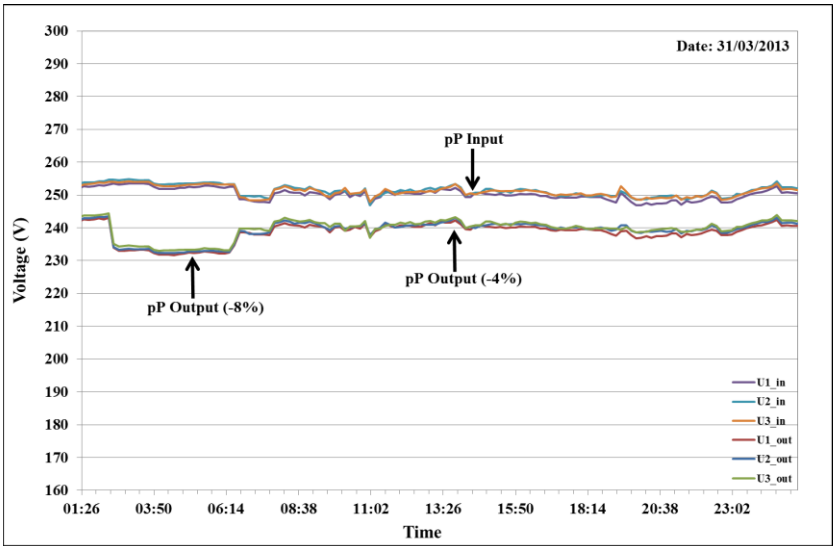


Figure 59: 4% powerPerfector unit measured on 31/03/2013

Similarly for the 2.7% unit as shown in Figure 60, in this case the powerPerfector has constantly changed the tap positions to regulate the feeder voltage. The smaller tap steps may to be more suitable for distribution networks, as the changes in voltage level are less significant between each tap positions.

It can be also noted that the -2.7% tap was occurred between around 17:20 and 19:00, this is generally considered as when the load demand is at highest of the day, hence the voltage drop even more at the substation level, forcing the pP unit tap position to switch from -5.4% to -2.7%.

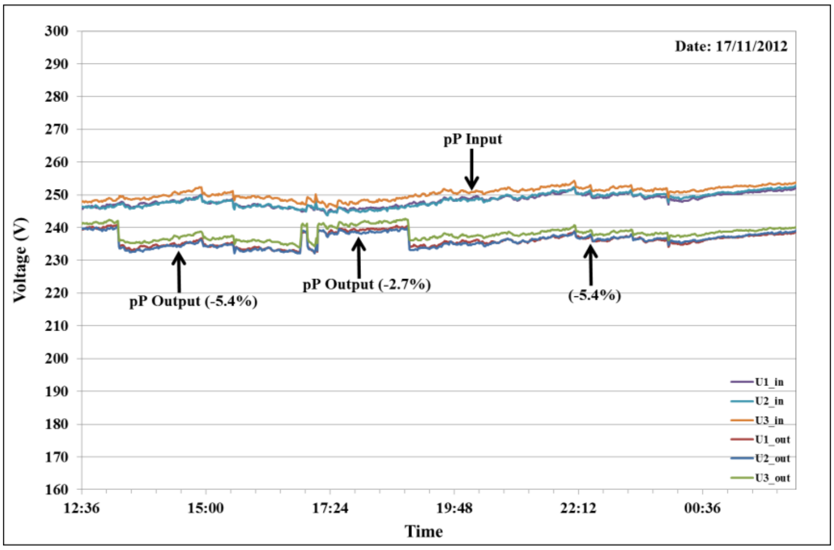


Figure 60: 2.7% powerPerfector unit measured on 17/11/2012

4.2.2 powerPerfector boost setting

By altering the reference minimum voltage setting higher, the two pP units able to boost the voltage by 4% and 2.7% respectively, as shown in Figure 61 and Figure 62. There is no significant variation in current each time the tap positions alters, however it is relatively difficult to analyse the current as the load condition is constantly changing.

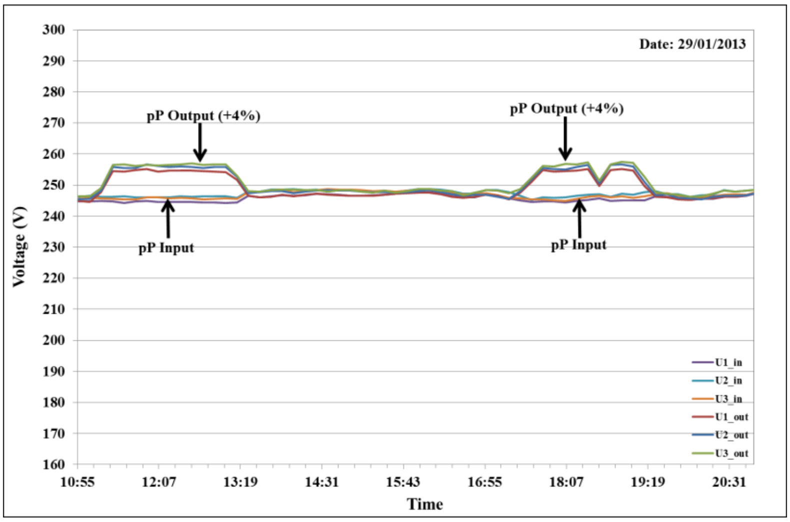


Figure 61: 4% powerPerfector unit measured on 29/01/2013

From Figure 61, the voltage level was boosted further by 4% during the period of peak load demand, at the time when the voltage level at substation is relatively lower. This particular function could provide many benefits to the LV network, which is to step down the voltage level if voltage rise occurs and boost the voltage at period of high demand. Also for heavy industrial loads or customers that are located far from the local substations, by installing pP unit would help to maintain the desired voltage level as the voltage drop tends to be more significant.

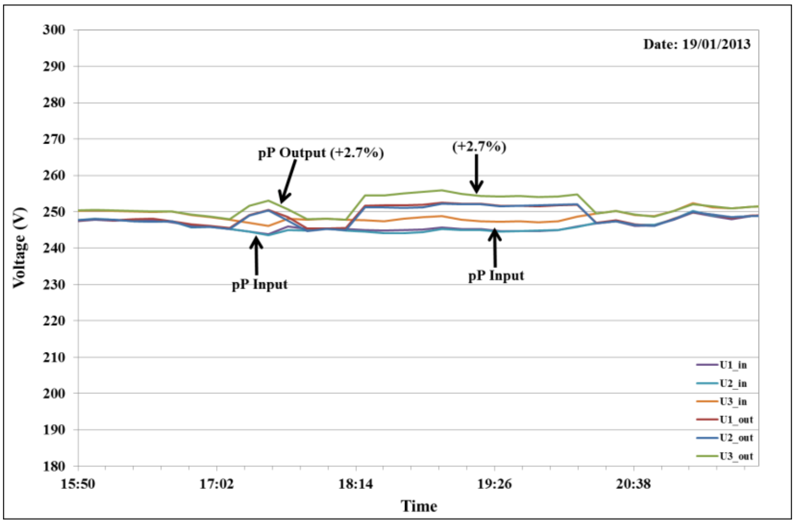


Figure 62: 2.7% powerPerfector unit measured on 19/01/2013

The secondary voltage from distribution transformer (pP unit input) is constantly set at close to 250V, therefore the output from the pP unit is able to boost the voltage to a level above the input voltage (250V).

4.2.3 powerPerfector 0% tap setting

The last trial action is to manually set pP unit to 0% tap setting, a period of two days data has been plotted and the input and output of the pP unit are maintains at the same voltage level as expected.

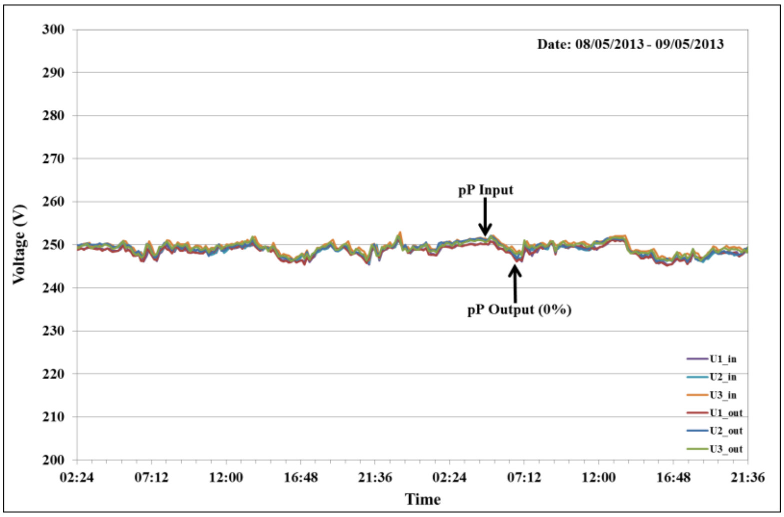


Figure 63: powerPerfector unit measured on 09/05/2013

4.3 Distribution transformer with On Load Tap Changer (OLTC) site trial

The equipment site trials are carried out at Landgate and Leicester Avenue substation, the main trial action consists of both automatic and manual OLTC setting tests. For manual setting, different tap positions were used. The voltage, current, real and reactive powers were recorded. Figure 64 shows the transformer with OLTC unit installed at trialled substations.

Figure 64: Transformer with OLTC installed for Landgate and Leicester Av substations

Figure 65-Figure 68 shows the pre installation data measured on 3rd of January 2013, the voltage monitoring data in particular is important to determine the suitable voltage settings for the relay.

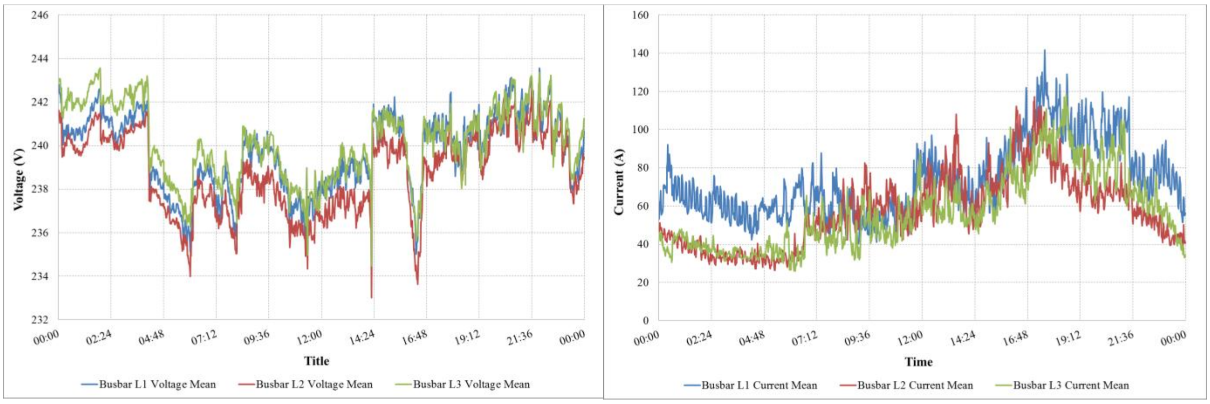


Figure 65: Landgate busbar voltage and current on 03/01/2013

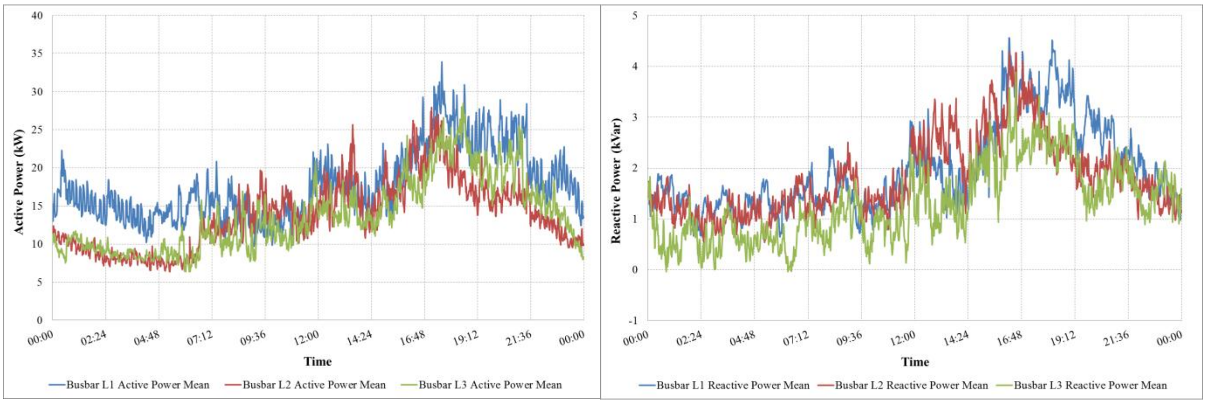


Figure 66: Landgate busbar active and reactive power on 03/01/2013

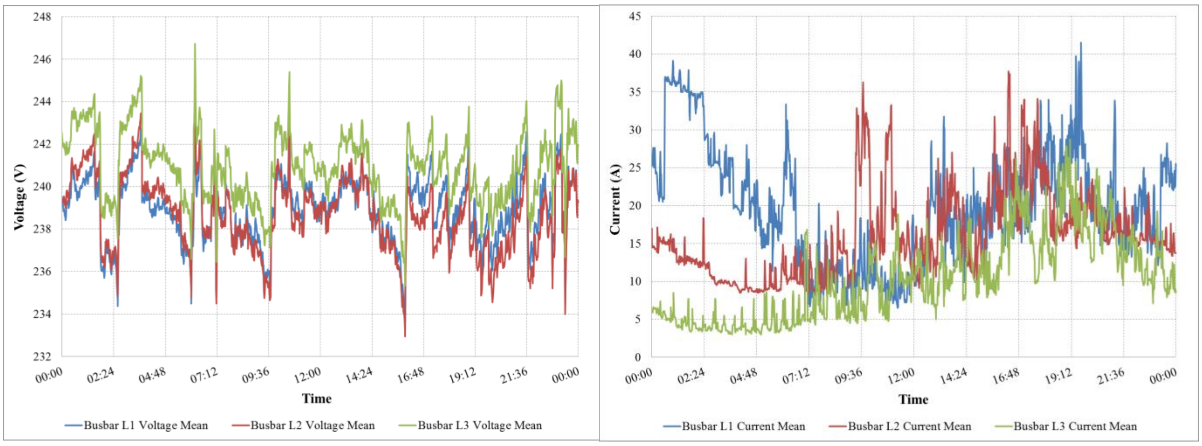


Figure 67: Leicester Av busbar voltage and current on 03/01/2013

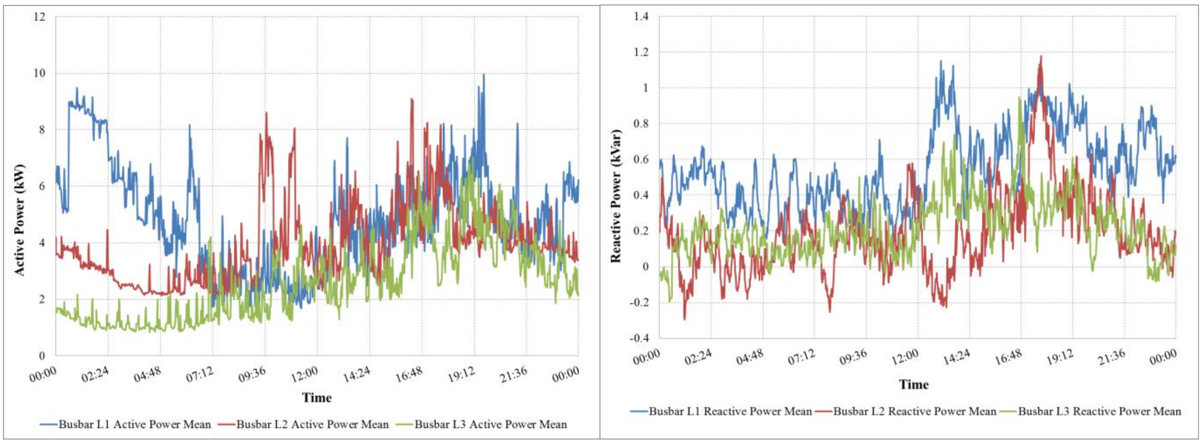


Figure 68: Leicester Av busbar active and reactive power on 03/01/2013

The substations selected for site trial are Landgate and Leicester Avenue, the main trial action are as follows:

- Pre-installation monitoring at substation, mid-point and end-point, information such as voltage, current and THD to be monitored and recorded.
- Set the TAPCON 230 in automatic tuning mode, record the voltage level at various point in the network.

- Set the TAPCON 230 in manual tuning mode, manually change the tap setting to record the voltage level.

5. Conclusion

This report carried out the voltage profile studies for all six trialled network, the voltage profile of each feeder is plotted. The voltage profile and power flow provide the important knowledge in order to decide the most appropriate voltage control method for each substation, based on their different network conditions.

The merged networks are used to study the effect of voltage control equipment on change of the network capacity. This study is to investigate the amount of additional load that can be added onto the network.

There are also large amounts of the monitoring data that being collected throughout the project, these data will help to assess the performance of each voltage control device. Based on the monitoring data collected, the devices were able to effectively regulate voltage within a desired threshold. The voltage reference setting can be altered based on the network conditions.

Appendix

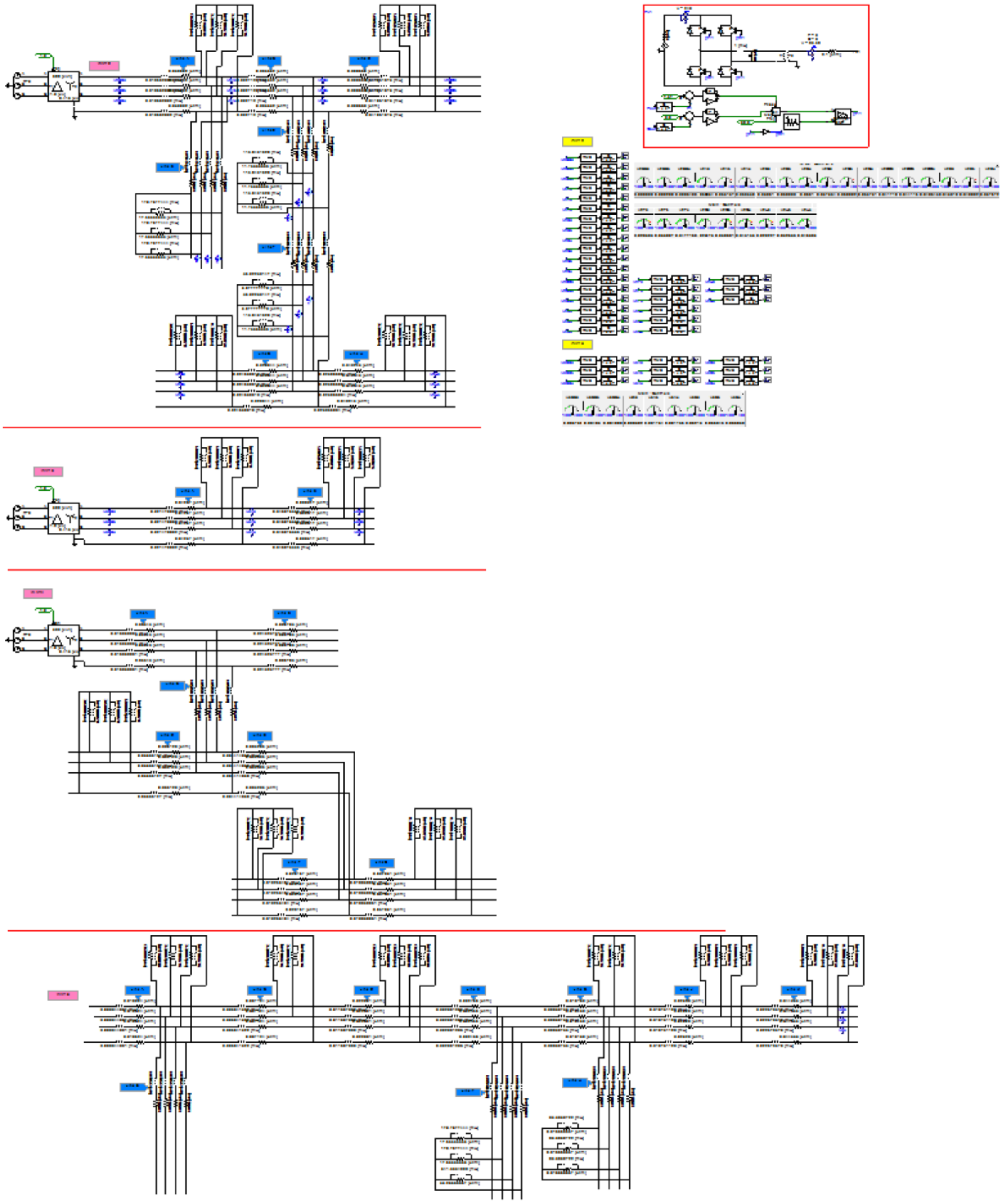


Figure A: Dunton Green network in EMTDC

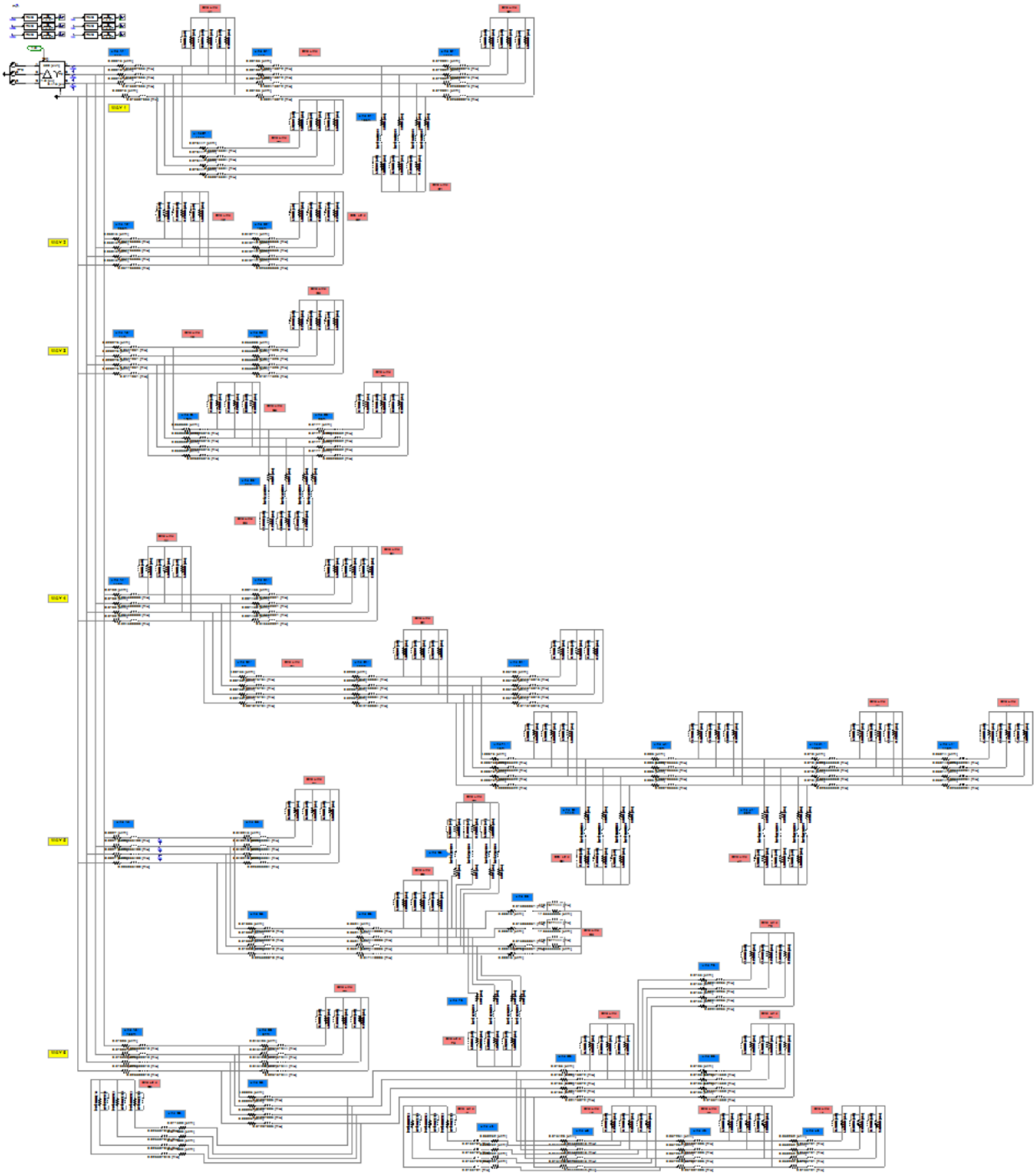


Figure B: Landgate network in EMTDC

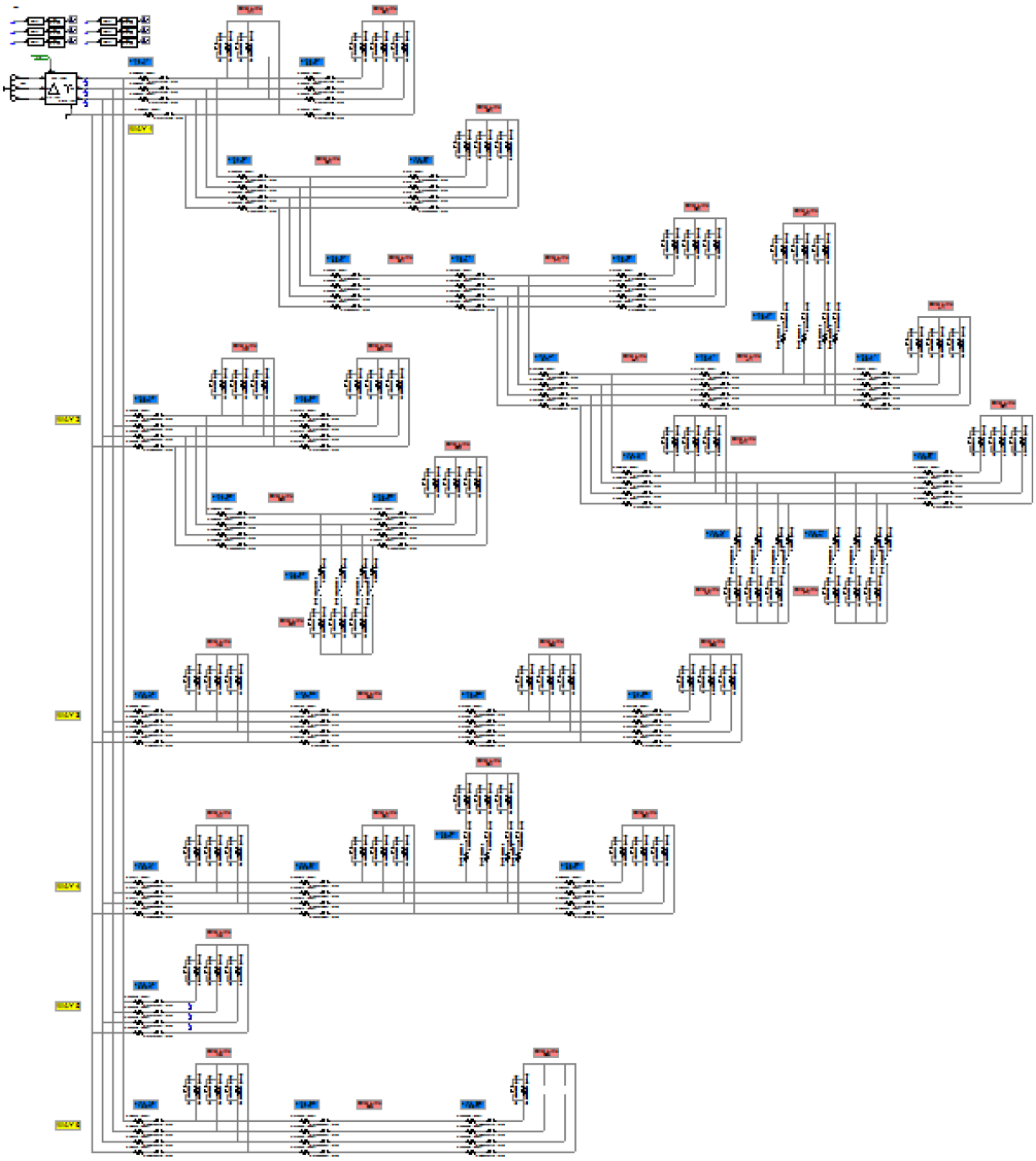


Figure C: Leicester network in EMTDC

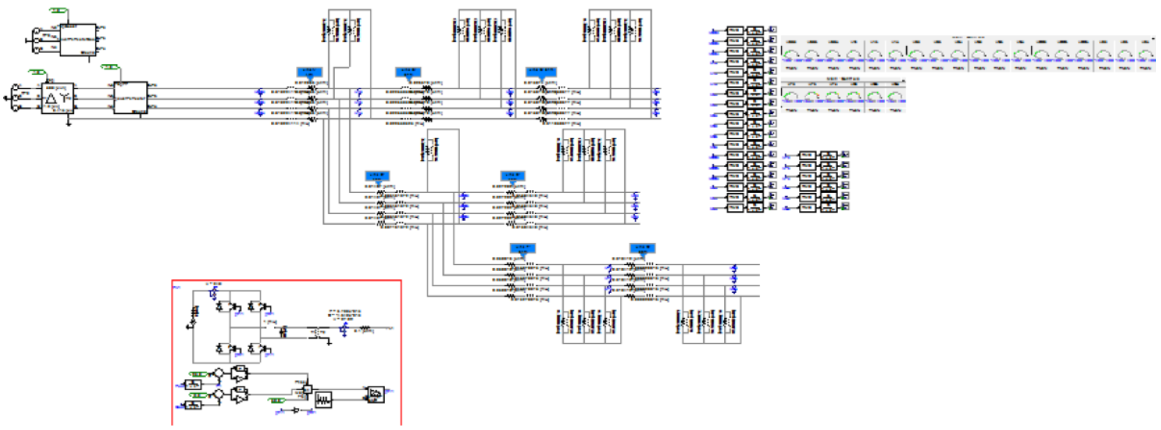


Figure D: A single feeder of Edge Green network in EMTDC

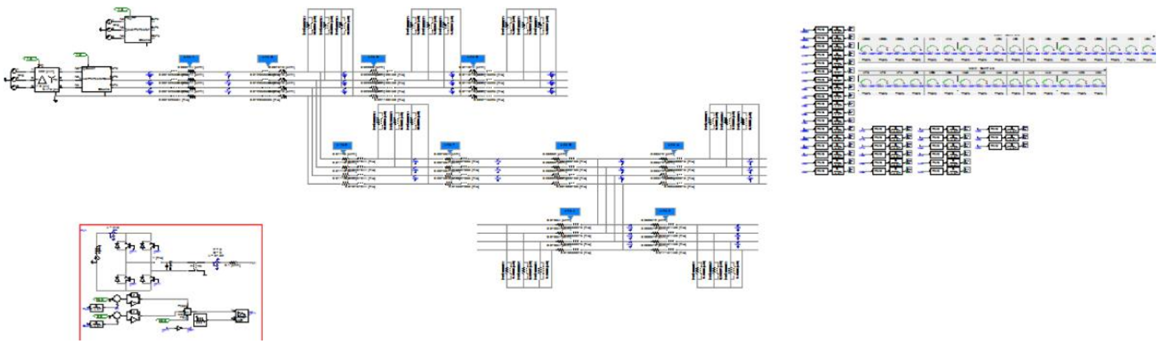


Figure E: A single feeder of Greenside network in EMTDC

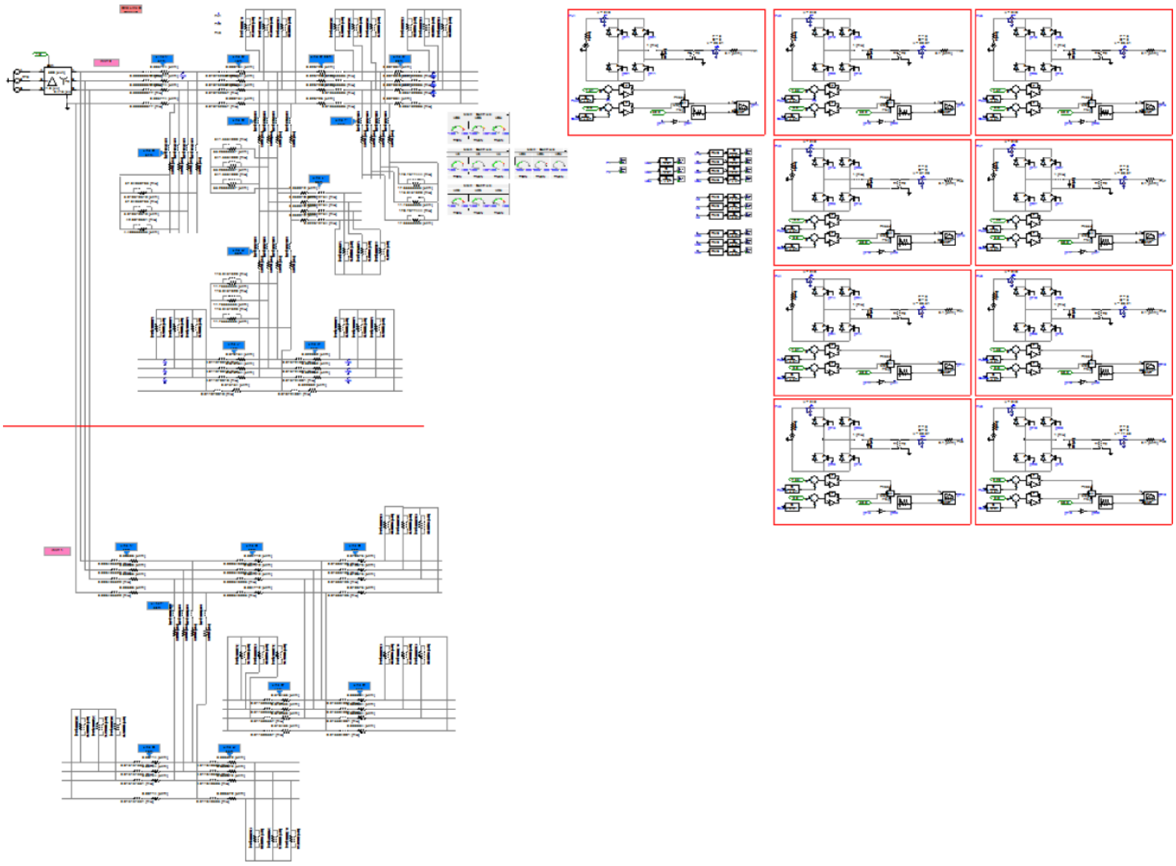


Figure F: Howard Street network in EMTDC