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Title: **Deliverable 3.3 "(Updated) Performance evaluation of the monitored LV networks"**

Synopsis: This report presents the updated findings on the busbar and feeder performance evaluation of the LV networks monitored as part of the LV Network Solutions project. This has been done from 136 substations with monitoring data from January 2013 to January 2014. Key parameters include transformer usage, voltage, voltage unbalance, power factor. For 430 feeders, neutral currents and current THD are also analysed.

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Executive Summary

This report corresponds to an updated version of Deliverable 3.3 "Performance evaluation of the monitored LV networks" part of the Low Carbon Network Fund Tier 1 project "LV Network Solutions" run by Electricity North West Limited (ENWL).

The aim of the LV Network Solutions project is to provide ENWL with greater understanding of the characteristics, behaviour, and future needs of their low voltage networks. This will be based on the analysis of data gathered by appropriate monitoring schemes to be deployed on hundreds of LV feeders and substations, and the assessment of the corresponding computer-based network models in current and future scenarios.

In particular, this report presents the updated findings on the performance evaluation of the LV networks monitored as part of the LV Network Solutions project. This has been done from 136 substations with monitoring data from January 2013 to January 2014. This has been separated into two parts; busbar and feeder performance evaluation. Key parameters for busbar performance include transformer usage, voltage, voltage unbalance and power factor. For feeder performance, neutral currents and current THD are considered.

From the data analysis, it is important to highlight the following:

Transformer loading

- Overall load factors (i.e., over the analysed period) of all the substations do not exceed the 83.3% of the ENWL Code of Practice 382.
- Most substations (83%) have overall load factors between 10% and 50%.

Voltage Performance at the Busbars

- 7% of the substations have voltages above 253V (1.1pu).
- Daily average voltages for all substations vary between 237V (1.03pu) and 253V (1.10pu).
- Most substations (63%) have daily average voltages between 241V (1.05pu) and 248V (1.08pu).

Power Factor Performance

- More than half of the substations (54%) have a purely inductive power factor behaviour.
- More than a third of the substations (37%) have minimum power factor above 0.90 all the time and an average higher than 0.98.
- 29% of the substations have capacitive behaviour for less than 30 minutes during the day.

Feeder Neutral Currents

- The average neutral current per feeder (of 430) does not exceed 70A. The maximum, however, can be as high as 255A.
- Two thirds of the feeders have average neutral currents between 10A and 40A, and a maximum current of 174A.
- The ratio of maximum neutral current and rating capacity (cable at the head of the feeder) was found to be between 10% and 50% for most of the feeders (80%).

Feeder Current THD

- The average THD per feeder varied between 2 and 98%. The maximum THD is 278%.
- Most feeders (65%) were found to have between 10 and 20% average THD.
- In general, the proportion of feeders without PV that have a low average THD (less than 10%), was much larger than that with any PV penetration.
- Average THD increases significantly (above 20%) in feeders with PV penetration, particularly above 30% of penetration.

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1 Introduction

As part of the transition towards a low carbon economy, Electricity North West Limited (ENWL), the Distribution Network Operator of the North West of England, is involved in different projects funded by the Low Carbon Network Fund. The University of Manchester is part of the Tier 1 project "LV Network Solutions".

The objective of this project is to provide ENWL with greater understanding of the characteristics, behaviour, and future needs of their LV networks. This will be based on the analysis of data gathered by appropriate monitoring schemes to be deployed on hundreds of LV feeders and substations, and the assessment of the corresponding computer-based network models in current and future scenarios.

This report presents the updated findings on the performance evaluation of the LV networks monitored as part of the LV Network Solutions project. This has been done from 136 substations with monitoring data from January 2013 to January 2014. This has been separated into two parts; busbar and feeder performance evaluation. Key parameters for busbar performance include transformer usage, voltage, voltage unbalance and power factor. For feeder performance, neutral currents and current THD are considered.

The active and reactive power data was used to assess their load factor (*LF*) throughout the studied period. All voltage related factors were calculated. This includes the daily calculation (or for the whole studied period) of the average of 10-minute voltages as per EN50160 (*avgV*), compliance with the standard, the difference between min and max recorded voltages (*Vmin-max*), and the voltage unbalance factor (*VUF*). The capacitive or inductive nature of the power factor (*pf_cap*, *pf_ind*) throughout the day is also investigated considering periods such as midday, early morning and evening (peak).

1.1 Summary of Findings

In order to summarise the findings and try to characterise the studied LV networks, these were grouped by transformer capacity. The results are presented in Table 1.

Table 1 Network characterisation based on transformer capacity (Jan 2013-Jan 2014)

	Percentage (%) of Substations				
Transformer loading	**50, 100, 200 kVA**	**300, 315 kVA**	**500 kVA**	**750, 800 kVA**	**1000, 1250 kVA**
LF < 10%	1.5	0.7	2.9	0.7	0.7
10% < *LF* < 50%	14.0	26.5	25.7	12.5	4.4
LF > 50%	0.0	3.7	4.4	2.2	0.0
Voltage Performance					
EN50160 compliant	14.0	28.7	32.3	14.0	4.4
EN50160 non-compliant	1.5	2.2	0.7	1.5	0.7
Vmin-max < 11.5V (0.05pu)	15.4	30.1	28.7	13.2	5.1
Vmin-max > 11.5V (0.05pu)	0.0	0.7	4.4	2.2	0.0
1.05pu < *avg Vabc* <1.08pu	9.6	22.1	25.7	9.6	1.5
avg Vabc > 1.08pu	5.1	5.1	2.9	2.2	2.9
avg Vabc < 1.05pu	0.7	3.7	4.4	3.7	0.7
VUF < 2%	14.7	29.4	33.1	12.5	5.1
VUF > 2%	0.7	1.5	0.0	2.9	0.0

Power Factor Performance

min *pf_ind* > 0.9	7.4	11.8	13.2	4.4	0.7
min *pf_ind* < 0.9	2.2	5.1	2.2	3.7	1.5
min *pf_ind* < 0.9 (reverse power flow)	0.0	1.5	0.0	0.7	0.0
pf_cap & *pf_ind*	5.9	10.3	10.3	4.4	2.2
pf_cap & *pf_ind* (reverse power flow)	0.0	2.2	7.4	2.2	0.7
pf_cap %time = 0 all time	9.6	18.4	15.4	8.8	2.2
pf_cap %time < 2%	2.9	8.8	8.8	5.9	2.2
pf_cap %time > 60% early morning	0.7	0.7	1.5	0.0	0.0
pf_cap %time > 90% all time	0.7	0.0	1.5	0.0	0.0
pf_cap %time > 50% midday	0.0	0.7	0.7	0.7	0.7
20% < *pf_cap* %time < 50%	0.7	2.2	5.1	0.0	0.0

The next section of the report will present network details such as number of customers, corresponding PV systems (if any), customer types and transformer capacity. The methodology to characterise the transformer loading, voltage performance and power factor performance will also be presented. Conclusions are drawn in section 4 of this report.

2 Busbar Performance Evaluation

Monitoring data (9567 daily files) from 136 substations collected from January 2013 to January 2014 was used in this report. The performance evaluation to be carried out here includes key parameters such as transformer loading, busbar voltage, voltage unbalance, and power factor.

The active and reactive power data was used to assess their load factor throughout the studied periods. All voltage related factors were calculated. This includes the daily calculation (or for the whole studied period) of the average of 10-minute voltages as per EN50160 (*avgV*), the range of voltage within 95% times in a day, the minimum, maximum and average voltage (*minV, maxV* and *avgV*), respectively, compliance with the EN50160 standard, the difference between min and max recorded voltages (*Vmin-max*), and the corresponding voltage unbalance factor (*VUF*). The capacitive or inductive nature of the power factor (*pf_cap*, *pf_ind*) throughout the day is also investigated considering periods such as midday, early morning and evening (peak).

Data from 9567 daily files corresponding to 136 LV substations was analysed. Each LV substation has different number of daily files (varying between 3 and 155 files). Data comprises of winter, spring and summer daily files; winter files are the majority (65%).

2.1 LV network characteristics

Technical aspects of 136 substations were considered, including transformer capacity, number customers and PV systems (if any). These substations were also categorised according to type of customers such as profile class (as defined by Elexon, i.e., PC1 to PC8) and Economy 7 (which corresponds to PC2 and PC4). In this section, network characteristics are given based on the proportion of substations.

Substation capacities vary between 50 and 1250kVA. The capacities of most of the substations (64%) are between 500 and 800kVA. 5% of the substations have capacities less than 300kVA (Table 2).

Table 2 Transformer capacity

kVA	50, 100, 200	300, 315	500	750, 800	1000, 1250
% Substations	5.1	15.3	31.4	32.8	15.3

Numbers of customers per substations vary between 3 and 970. Most substations (75%) have between 100 and 500 customers. 19% of the substations have less than 100 customers. However, 6% of the substations have more than 500 customers (Table 3).

Table 3 Number of customers

MPANs	# MPANs < 100	100 ≤ # MPANs < 250	250 ≤ # MPANs < 500	500 ≤ # MPANs
% Substations	19.1	40.4	34.6	5.9

Customers are classified in terms of profile class. 2% of the substations have only domestic unrestricted customers (PC1) and 10% have only domestic customers (PC1 and PC2), i.e., 12% of the substations with only domestic customers. 42% have a combination of domestic and small non-domestic customers (PC1-PC4). One substation, however, has only non-domestic customers (PC3-PC8, PC0) as seen in Table 4.

Table 4 Customer types

MPAN Type	PC1	PC1, PC2	PC1-PC4	PC1-PC8, PC0	PC3-PC8, PC0
% Substations	2.2	10.3	41.9	44.9	0.7

The customers of substations are also classified in terms of Economy 7 customers: domestic (PC2) and non-domestic (PC4). Most substations (96%) have Economy 7 customers. 40% have only PC2 whereas 53% have a mix of PC2 and PC4. In addition, 4% of the substations have more than 60% Economy 7 customers. 85% substations have less than 20% Economy 7 customers (Table 5).

Table 5 Economy 7 customers

Economy 7	No Economy 7	PC2	PC4	PC2, PC4
% Substations	4.4	39.7	2.9	52.9

% Economy 7 (# MPANs)	No Economy 7	%Eco < 20	20 ≤ %Eco < 60	%Eco ≥ 60
% Substations	4.4	84.6	7.4	3.7

In terms of PV systems, 61% of the substations have penetrations (i.e., percentage of houses with PV systems) varying between 0.2% and 49%. 21% of the substations have less than 1% PV penetration. 7% of the substations have more than 20% PV penetration (Table 6). The average PV installed capacity is 3kW.

Table 6 Penetration of PV systems

% PV (# MPANs)	No PV	%PV<1	1 ≤ %PV < 5	5 ≤ %PV < 20	20 ≤ %PV < 50
% Substations	39	21.3	18.4	14.7	6.6

As a summary of the network characteristics from 136 substations, it is important to highlight the following:

- Most substations (65%) have capacities between 500 and 800kVA.
- Most substations (75%) have between 100 and 500 customers.
- 13% of the substations have only domestic (PC1). The rest are mixed profile classes: 42% of the substations have domestic and small non-domestic customers (PC1-PC4), 45% have domestic and non-domestic customers (PC1-PC8, PC0).
- Most substations (96%) have Economy 7 customers. 53% of the substations have domestic and non-domestic Economy 7 customers. 85% of the substations have less than 20% Economy 7 customers, 4% have more than 60%.
- 61% of the substations have PV penetrations between 0.2 and 49% (percentage of houses with PV systems). 7% of the substations have more than 20% PV penetration.
- The average of PV installed capacity is 3kW.

2.2 Seasonal Transformer Loading

To understand how transformers are loaded, this section evaluates the apparent power through the asset and the corresponding load factor. In order to check compliance of the load factor with ENWL Code of Practice 382 this is compared against the 83.3% value required to make the normal cyclic ratings possible. The actual values of apparent power (maximum and average) are also compared to the nominal and normal cyclic ratings.

Figure 1Figure 13 presents the seasonal load factor for each substation considering winter, spring and summer. Due to the different availability of data per substation, summer load factors could be calculated only for 50% of the substations. Spring load factors were computed for only 35% of the substations. However, 135 substations (99%) had their winter load factors calculated.

From Figure 1Figure 13 it can be seen that, in general, significant differences between winter and spring load factors do not exist (average of 2% across substations). Nonetheless, *Larch Close* had its spring load factor 6% higher than winter.

On the other hand, winter load factors are 10% higher than summer load factors in average. *Leicester Ave* had a largest difference between winter and summer (24% higher during winter). It is important to highlight that this substation has 21% penetration PV systems and more than 20% Economy 7 customers.

Considering the winter load factor, it can be seen that all the substations have load factors within the 83.3% limit (to be able to use the normal cyclic rating). The highest load factors are found in *Lever St* and *Pinewood Rd* with 62%. On the contrary, *Cutler Cl* and *Lindisfarne Drive* are substations with load factors lower than 3%. The average load factors for all substations are 30%. Most substations (83%) have load factors between 10% and 50%. 10% substations have load factors higher than 50%.

Figure 2 presents the transformer maximum and average hourly loadings for all substations during winter. The hourly values were calculated with a moving hourly window rather than actual hours (e.g., 10am-11am). The nominal rating and two normal cyclic ratings (for ambient temperature 0°C and 15°C) for each substation are also presented. It can be observed that the maximum hourly loading of *Pinewood Rd* and *Greenside Ln Fiveways* exceeded their nominal ratings. For both substations, the maximum loadings occurred during winter, i.e., are within their normal cyclic ratings for 0°C and 15°C. In addition, their average hourly loadings are more than 58% and maximum hourly loadings are 103% (of nominal capacity).

Comparing with maximum and average hourly loadings, 10% of the substations have average hourly loadings higher than 50%. Their maximum loadings are between 62% and 103%. 7% of the substations have average hourly loadings less than 10%, and maximum loadings between 5% and 17%. The average difference between the maximum and average hourly loadings for all substations was 20%. *Greenside Ln Fiveways* showed a particularly high difference reaching 44%.

Summarising transformer loading findings, it is important to highlight the following:

- Overall load factors (i.e., over the analysed period) of all the substations do not exceed the 83.3% of the ENWL Code of Practice 382.
- Most substations (83%) have overall load factors between 10% and 50%.
- *Lever St* and *Pinewood Rd* are substations with the highest overall load factors (62%).
- *Cutler Cl* and *Lindisfarne Drive* are substations with overall load factors lower than 3%.
- *Leicester Ave* shows a 24% absolute difference between winter and summer load factors. It has 21% penetration PV systems and more than 20% PC2 customers.
- *Pinewood Rd* and *Greenside Ln Fiveways* are substations whose maximum hourly loadings exceed their nominal ratings but are within their normal cyclic ratings.

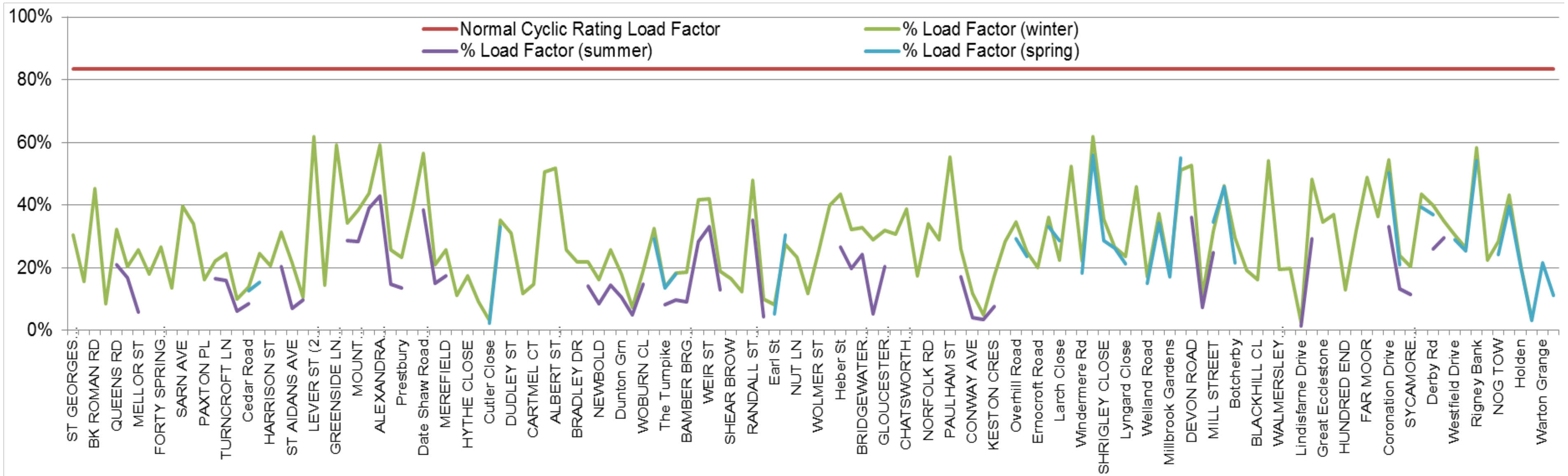

Figure 1 Seasonal Load Factors per Substation

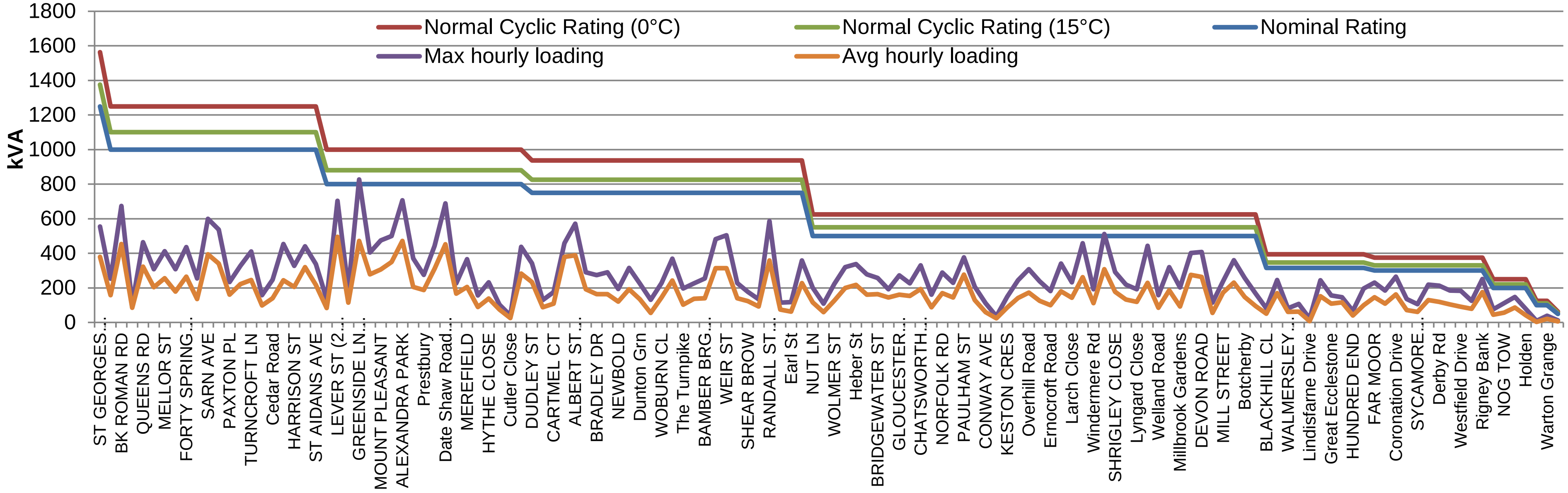

Figure 2 Maximum Transformer Loading per Substation (Winter)

2.3 Voltages at the Busbars

One of the first analyses is the compliance of busbar voltages with the standard BS EN50160. This is used as a proxy to determine whether the voltage at the connection point of the corresponding customers is likely or not to be compliant. Then, other performance parameters are investigated such as daily min-max difference and voltage unbalance. The following has been considered.

- EN50160 compliance means that all 10-minutes average voltages must be within the range of +10% / -15% of nominal voltage, and 95% times of a week (here considered per day) must be within the range +10% / -6%.
- To capture certain voltage characteristics throughout the day, values such as the daily minimum, maximum and average –all for 10-minute samples- are considered.
- For voltage profiling, daily minimum, maximum and average voltage values (average of the three phases) with 10 minute resolution are evaluated. In addition, to show the range of voltages that more frequent, the 2.5th percentile extremes are excluded. This range is presented with the parameters *97.5% avg Vabc* and *2.5% avg Vabc*.
- For the voltage unbalance factor, the differences between the phase voltages and average phase voltages are determined, and the largest value chosen. The ratio of the largest value to an average voltage is identified as the voltage unbalance factor (*VUF*). This is done for every 10 minutes. The daily value corresponds to the daily average. Note that although voltage unbalance factor according to EN50160 needs be calculated with symmetrical components, here this is only done using the voltage magnitudes.

Figure 3 presents the above parameters for all substations (136) and all data (9567). Results for 63% substations suggest that the corresponding customers have EN50160-complaint voltages at their connection points for each of the analysed days. The remaining 37% of the substations, however, could potentially have customer connection points that are non-compliant with the standard. These are presented (with more detail) in Figure 4**Error! Reference source not found.**. In this figure, it can be seen that their maximum 10-minute average voltages go beyond 253V (1.1pu) some times. However, voltages of only nine substations (7%) always go beyond 253V (1.1pu). These nine substations have mixed customers with more than 20% of Economy 7 customers.

Figure 5 presents voltage parameters for each substation. The parameters *97.5% avg Vabc* and *2.5% avg Vabc* are the averages of all available data at each substation. The parameters *min Vabc* and *max Vabc* are minimum and maximum voltage values of all available data at each substation. In this figure, it can be seen that maximum voltage values vary between 242.5V (1.05pu) and 264V (1.14pu). Minimum values vary between 203V (0.88pu) and 252V (1.09pu). The average voltages vary between 237V (1.03pu) and 253V (1.10pu). Most substations (63%) have average voltages between 1.05pu and 1.08pu.

Considering the maximum and minimum voltage value for each substation, the maximum min-max voltage difference was found to be 18V (0.078pu). The minimum difference was 5V (0.021pu) and the average was 9V (0.04pu). Most substations (93%) have min-max voltage differences less than 11.5V (0.05pu).

To understand the most frequent voltage variations, the difference between *97.5% avg Vabc* and *2.5% avg Vabc* is also examined. Most substations (82%) have voltage variations less than 7V (0.03pu). In this case, the voltage variation found to be between 3V (0.013pu) and 9V (0.04pu).

Figure 6 presents the daily average voltage unbalance factors calculated for each substation. The VUF is found to be between 0.2% and 10%. Seven substations potentially exceed the 2% limit established by EN50160 (although here the average for the whole day is considered rather than 95% of the time). Out of the seven,

- Three substations (*Holden*, *Woburn Cl* and *Ashwood Crescent*) exceed the 2% limit, but only on one monitored day;
- One substation (*Dickens Place*) has a VUF about 2% most of the time and a maximum VUF of 2.4%; and,

- Three substations (*Dunton Green*, *Ruskin Ave* and *Weir St*) have a VUF of more than 3%. *Ruskin Ave* has a VUF more than 2% most of the time (70%) whereas *Weir St* has a VUF more than 2% a fifth of the time. *Dunton Green* has a high VUF between April and August, but after August it decreases to 2%. It is important to highlight that *Weir St* has no PV systems, *Ruskin Ave* has 1% of PV penetration and *Dunton Green* has 40% of PV penetration.

As a summary, it is important to highlight the following:

- 7% of the substations have busbar voltages above 253V (1.1pu).
- Daily average busbar voltages for all substations vary between 237V (1.03pu) and 253V (1.10pu).
- Most substations (63%) have daily average busbar voltages between 241V (1.05pu) and 248V (1.08pu).
- The busbar voltage variations (i.e., max minus min voltage) throughout the analysed period are between 5V (0.021pu) and 18V (0.078pu).
- Most substations (93%) have voltage difference less than 11.5V (0.05pu).
- Most voltage variations (95% of the time during the day) are between 3V (0.013pu) and 9V (0.04pu).
- *Ruskin Ave, Weir St* and *Dunton Green* are the substations with the highest voltage unbalance factor.
- After August 2013, *Dunton Green* improved its unbalance factor from 4% to less than 2%.

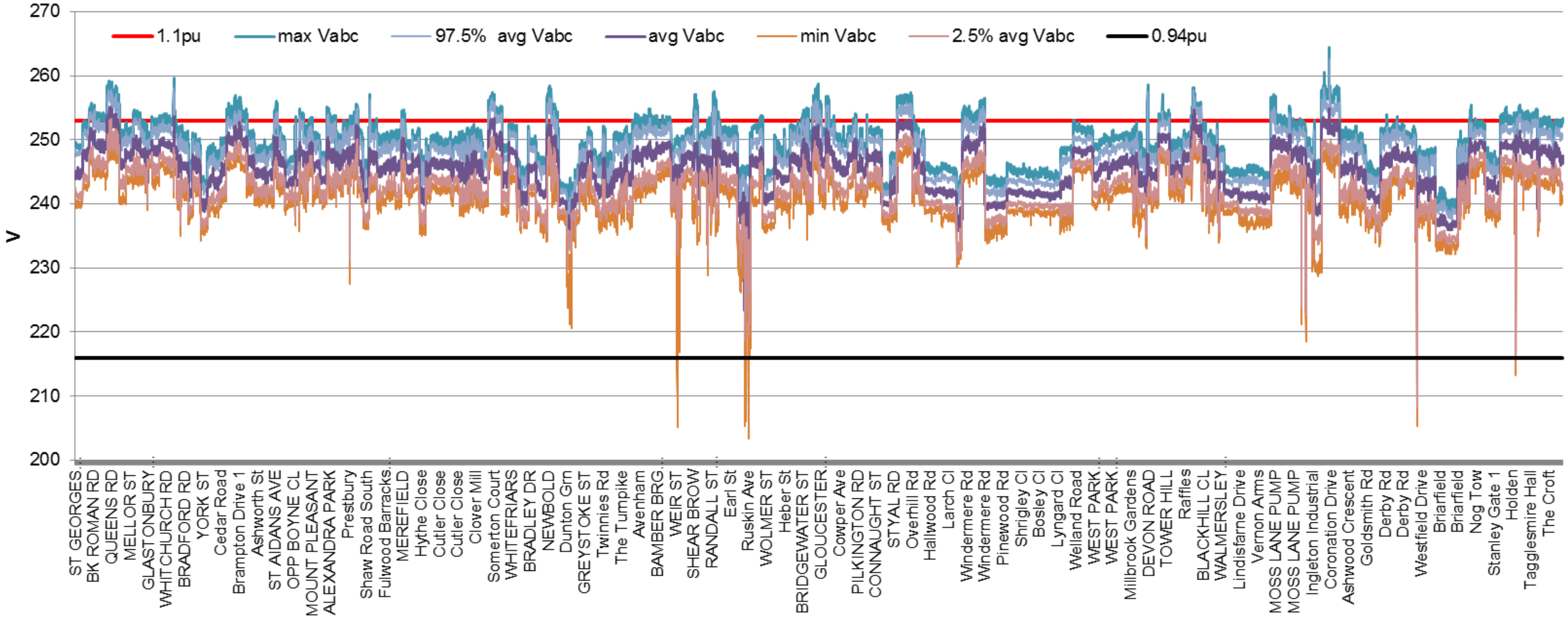

Figure 3 Voltage profiles for all substation and all daily data

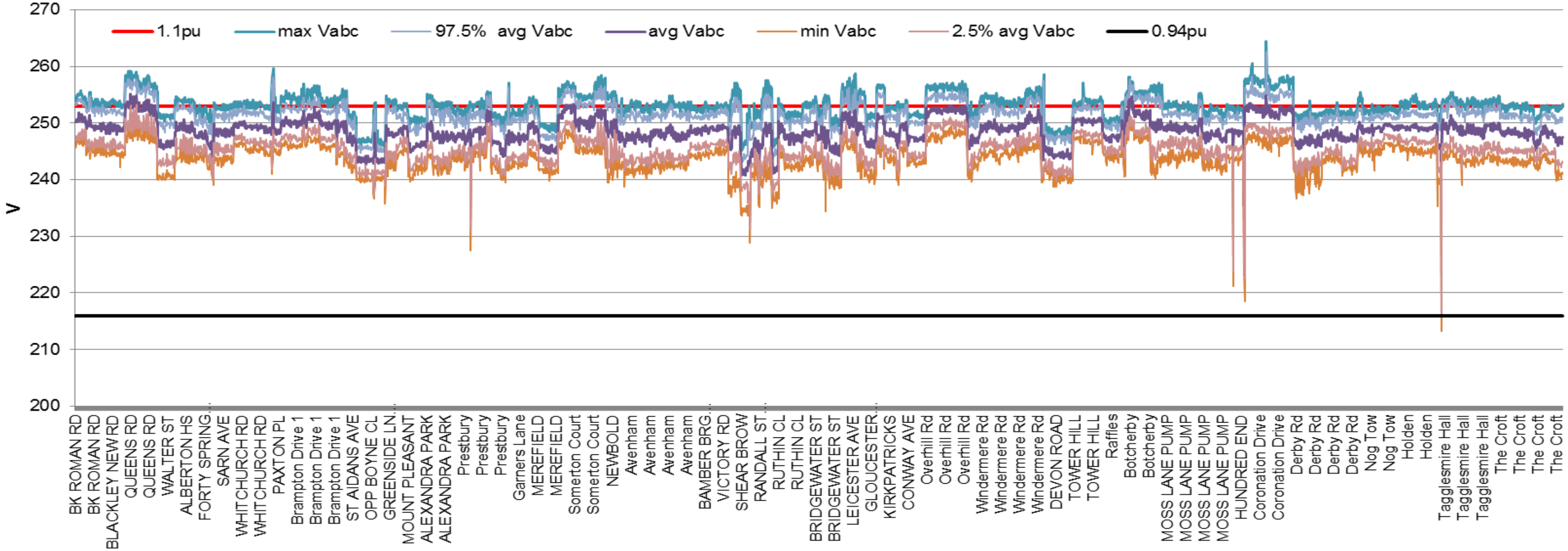

Figure 4 Substations potentially non-compliant with EN50160 (daily basis)

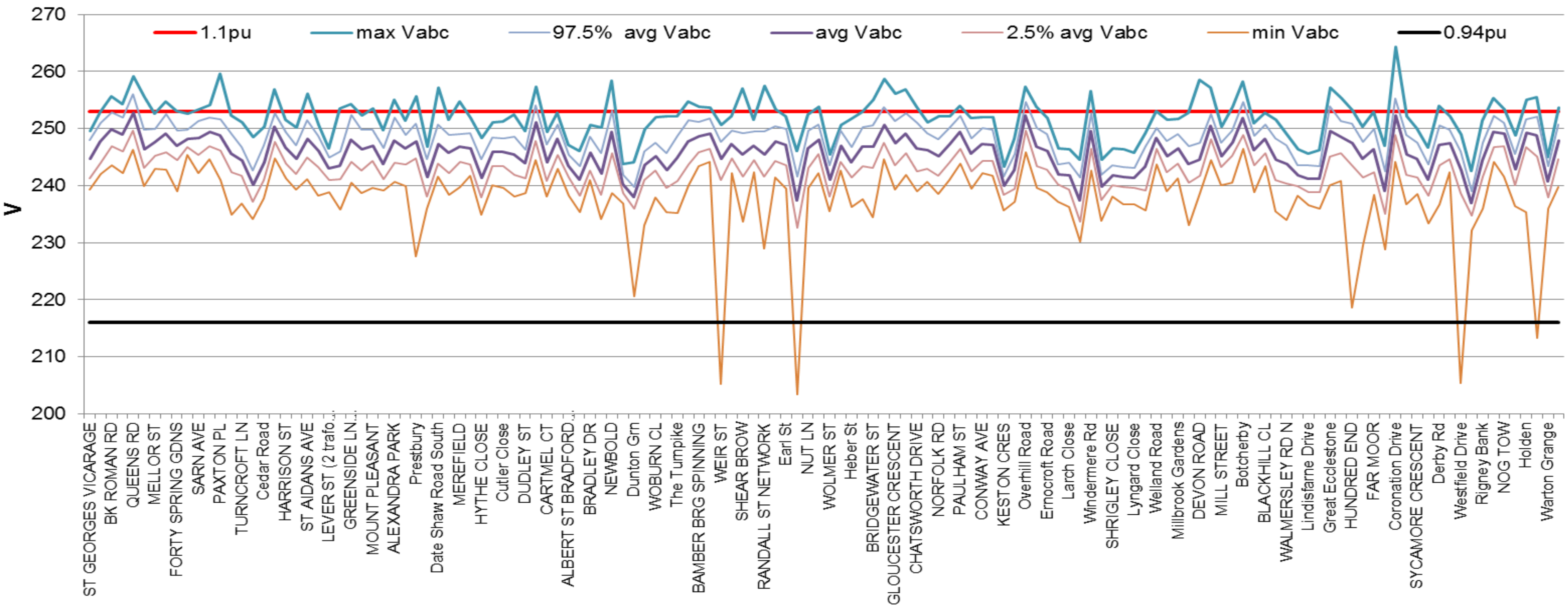

Figure 5 Voltage profile for each substation

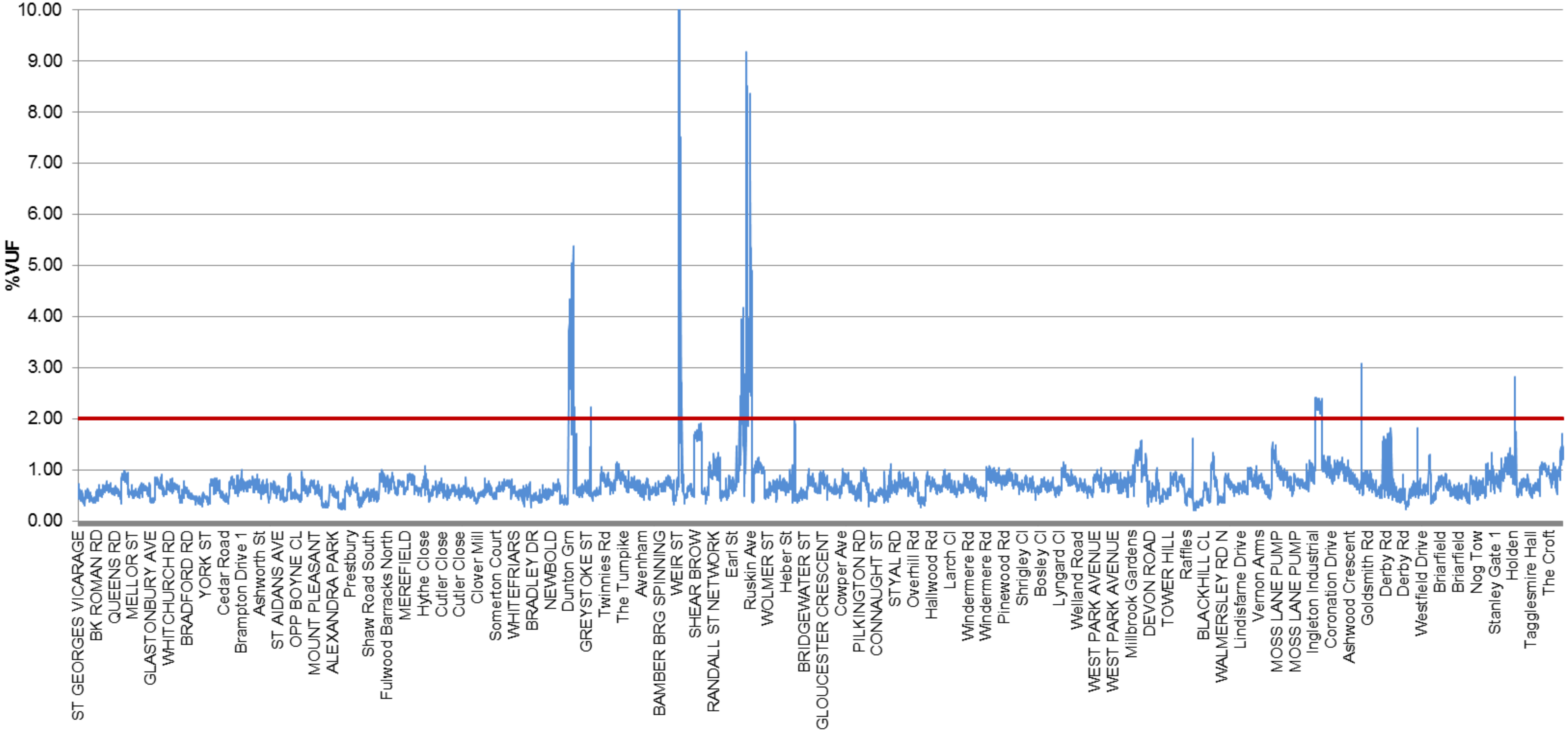

Figure 6 Voltage unbalanced factor (VUF)

2.4 Power Factor

This section investigates the behaviour of the power factor in all substations. In particular, it differentiates between purely inductive substations and those that have a mixed behaviour, i.e., inductive and capacitive. Specific time intervals during the day are also analysed, this includes midday (10am–2pm), early morning (0am-3am), and peak (5pm-8pm).

Key parameters that will be calculated and presented here are the daily minimum, maximum and average power factors. The corresponding angles are also presented. In addition, to understand how often capacitive power factor appear in those substations with mixed behaviour, the corresponding frequency is also computed for each of the above specified intervals.

2.4.1 Purely inductive substations

74 substations (54%) have shown an inductive behaviour throughout all the monitoring data. The corresponding daily average power factors (*avg pf*) ranged from 0.74 to 0.998 (Figure 7). These substations are examined in detail in this subsection.

51 of these substations (37% of the total) have 10-minute power factors above 0.90 all the time. In addition, their daily *avg pf* are between 0.93 and 0.997. Indeed, *avg pf* for each substation have higher than 0.98.

The other 23 substations have much bigger range of 10-min average power factors and, in general, much lower daily minimum power factors (min *avg pf,* 0.74). In addition, 3 of these substations have some instances with reverse power flows.

To illustrate the power factor behaviour from another perspective, Figure 8 presents the daily power factor angles of 74 substations. This figure can show inductive, capacitive behaviour and also reverse power flows at same time. The points between an angle between 0° and 90° indicate inductive behaviour; between 90° and 180° refer to reverse power flows. The points between 0° and -90° are for capacitive behaviour, and between 90° and 180° are for reverse power flows. From the figure, it can be seen that the average angle varies between 3.43° and 41°. The minimum angle is 0.1° and the maximum is 151°. There are five cases bigger than 90° (reverse power flows) involving three substations.

2.4.2 Substations with mixed power factor behaviour

According to the monitoring data, 62 substations (46% of the total) had a capacitive behaviour during some periods of the day. To illustrate this, inductive and capacitive power factor behaviours are shown separately in Figure 9 and Figure 10, respectively. To show the occurrence of reverse power flows a negative y-axis was added to the figures.

In addition to these figures, both inductive and capacitive power factor behaviours using the corresponding angles are shown in Figure 11. It can be clearly seen that the power factor angles spread in the range of 180° to -180°. The ranges between 90° and 180° as well as -90° and -180° show the reverse power flows with inductive and capacitive behaviours, respectively.

17 of these substations (13% of the total) have some reverse power flows for both capacitive and inductive *avg pf* behaviours. The other 45 substations do not have reverse power flows but also behave inductively (*avg pf* of 0.94) and capacitively (*avg pf* 0.97).

In order to assess in detail the behaviour of the power factor, Figure 12 presents the percentage of time (during the day) that the capacitive power factor occurs. This is also divided by specific periods such as all day, early morning, midday and peak.

39 substations (29% of the total) behave capacitively for less than 30 minutes during the day. 11 substations behave capacitively for less than 5 hours but more than 30 minutes. Some of these 11 substations behave more capacitively during midday, some early in the morning. 9 substations behave

capacitively for more than 5 hours during the day (but less than 17 hours). 4 of them behave capacitively early in the morning and 5 behave capacitively during mid-day. Finally, three substations (*Paxton Pl, Opp Boyne Cl* and*, Lower Hazel Cl*) behave capacitively throughout most of the day (90% of the time).

As a summary, it is important to highlight the following:

- More than half of the substations (54%) have a purely inductive power factor behaviour.
- More than a third of the substations (37%) have minimum power factor above 0.90 all the time and an average higher than 0.98.
- 29% of the substations have capacitive behaviour for less than 30 minutes during the day.
- 15% of the substations have capacitive behaviour between 30 minutes and 17 hours during the day. Some are more capacitive during midday, some during early morning.
- Three substations (*Paxton Pl, Opp Boyne Cl* and*, Lower Hazel Cl*) have an almost constant capacitive behaviour (22 hours during the day).
- 15% of the substations experienced reverse power flows at some point; 3 of them are purely inductive whilst 17 substations have both capacitive and inductive behaviours.

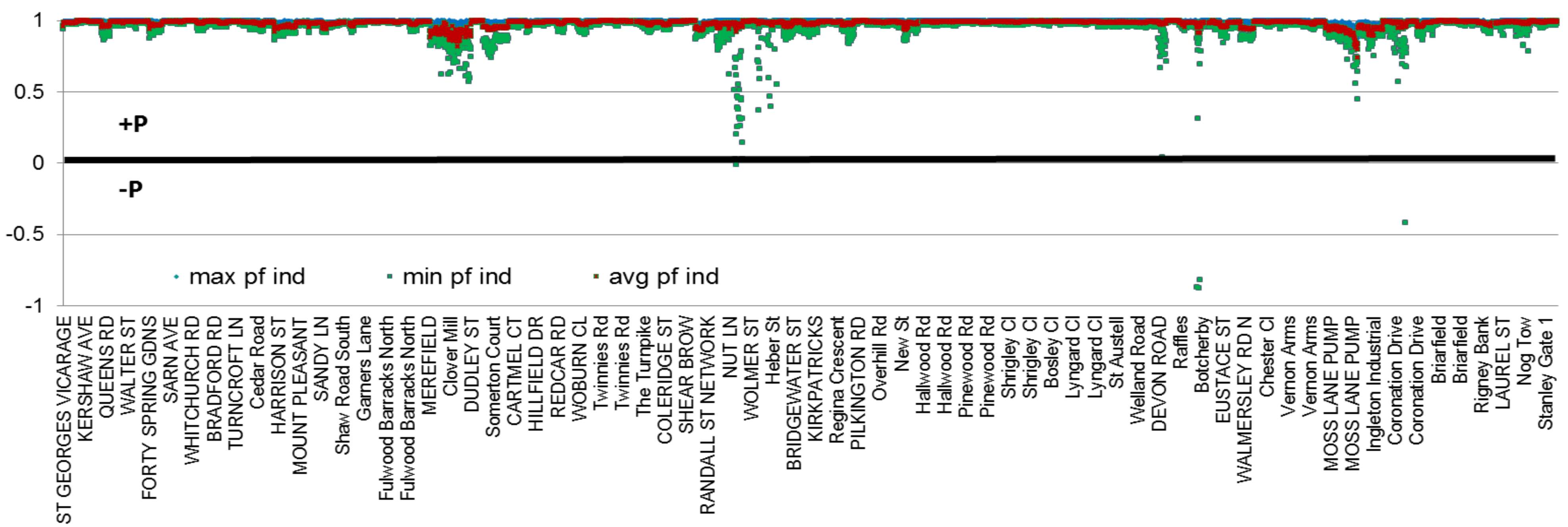

Figure 7 Pure inductive substations' inductive power factors

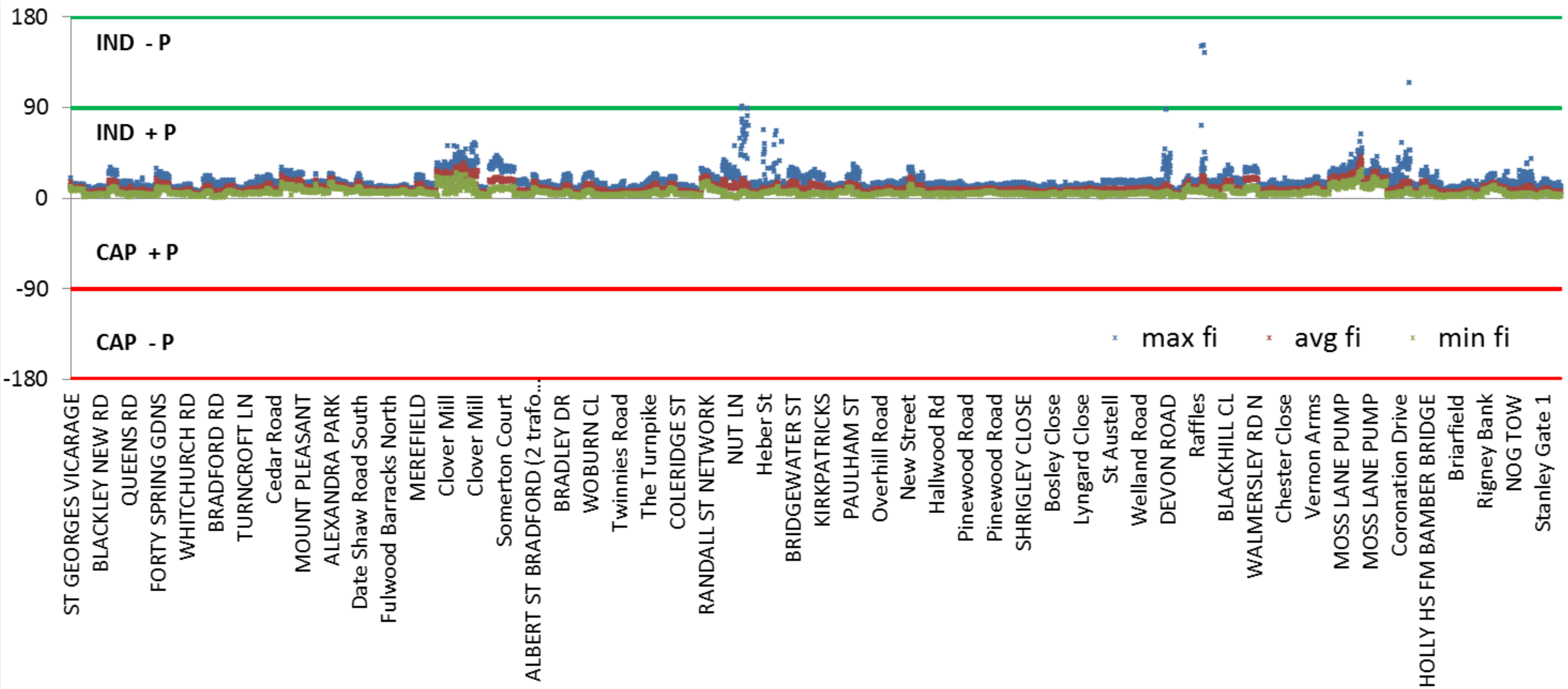

Figure 8 Pure inductive substations' power factor angles

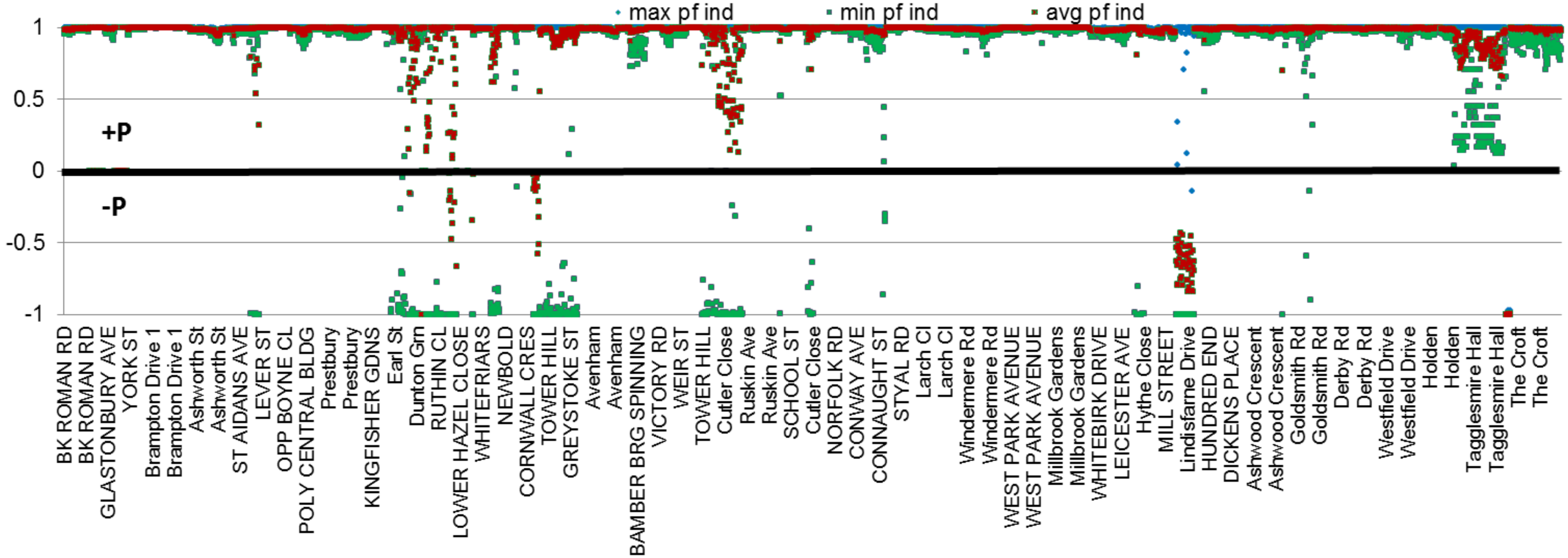

Figure 9 Substations’ (mixed behaviour) inductive power factors

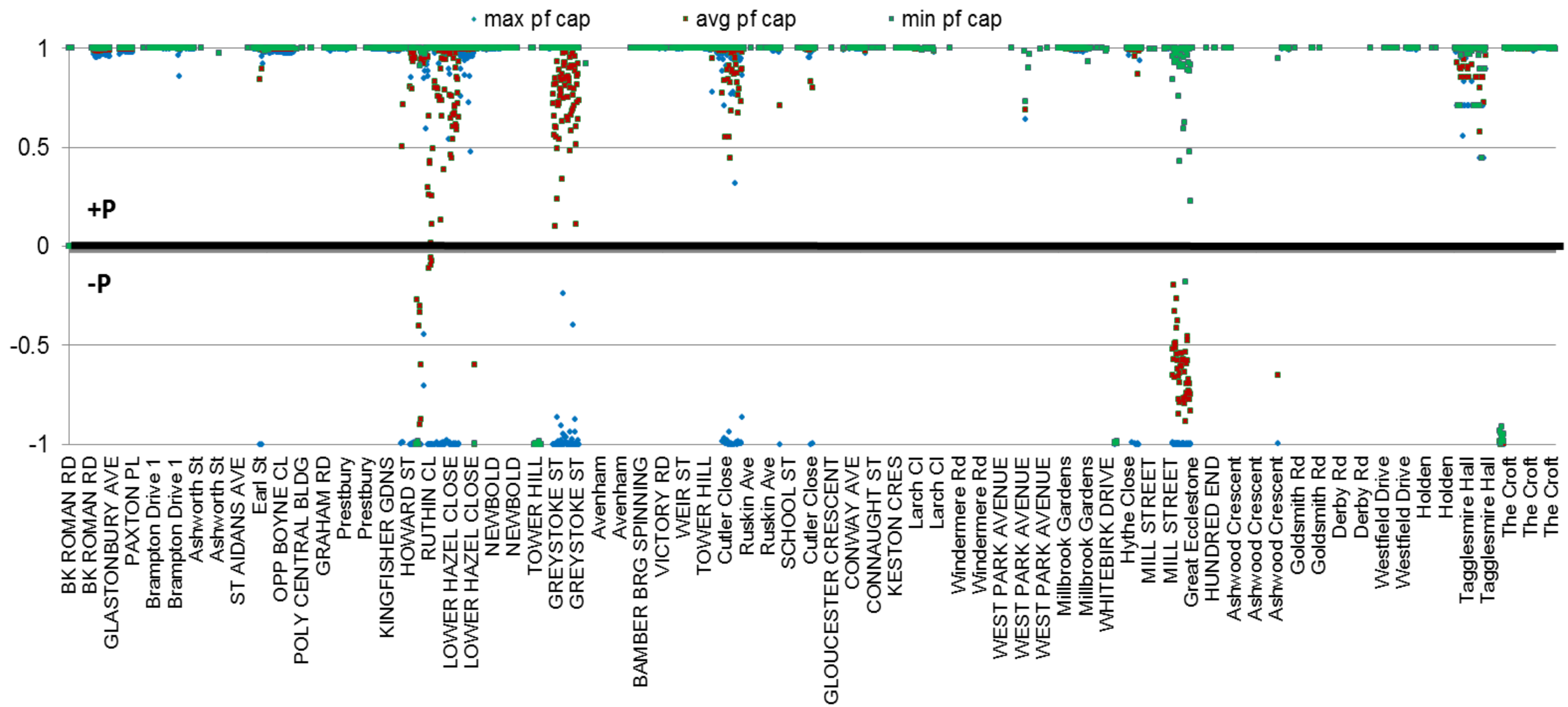

Figure 10 Substations' (mixed behaviour) capacitive power factors

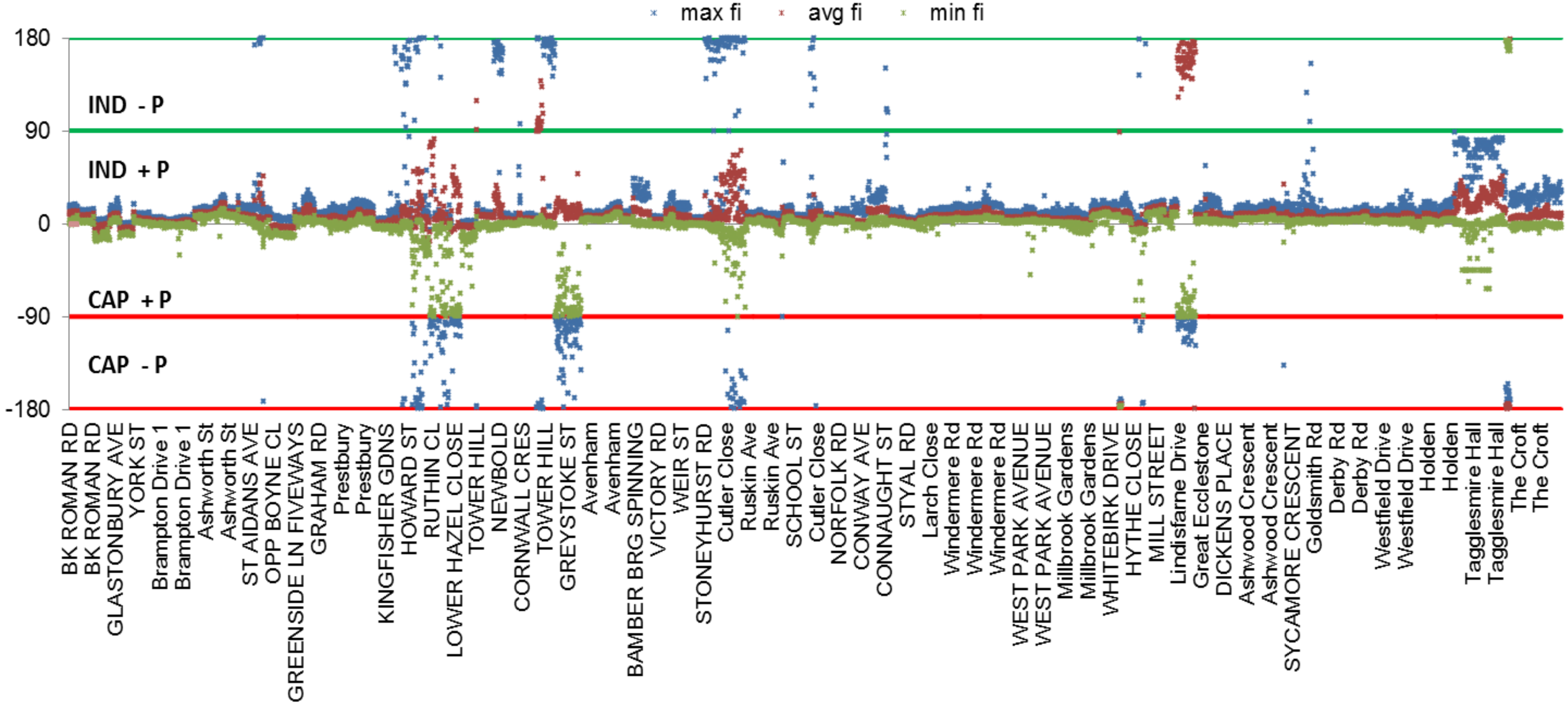

Figure 11 Substations' (mixed behaviour) power factor angles

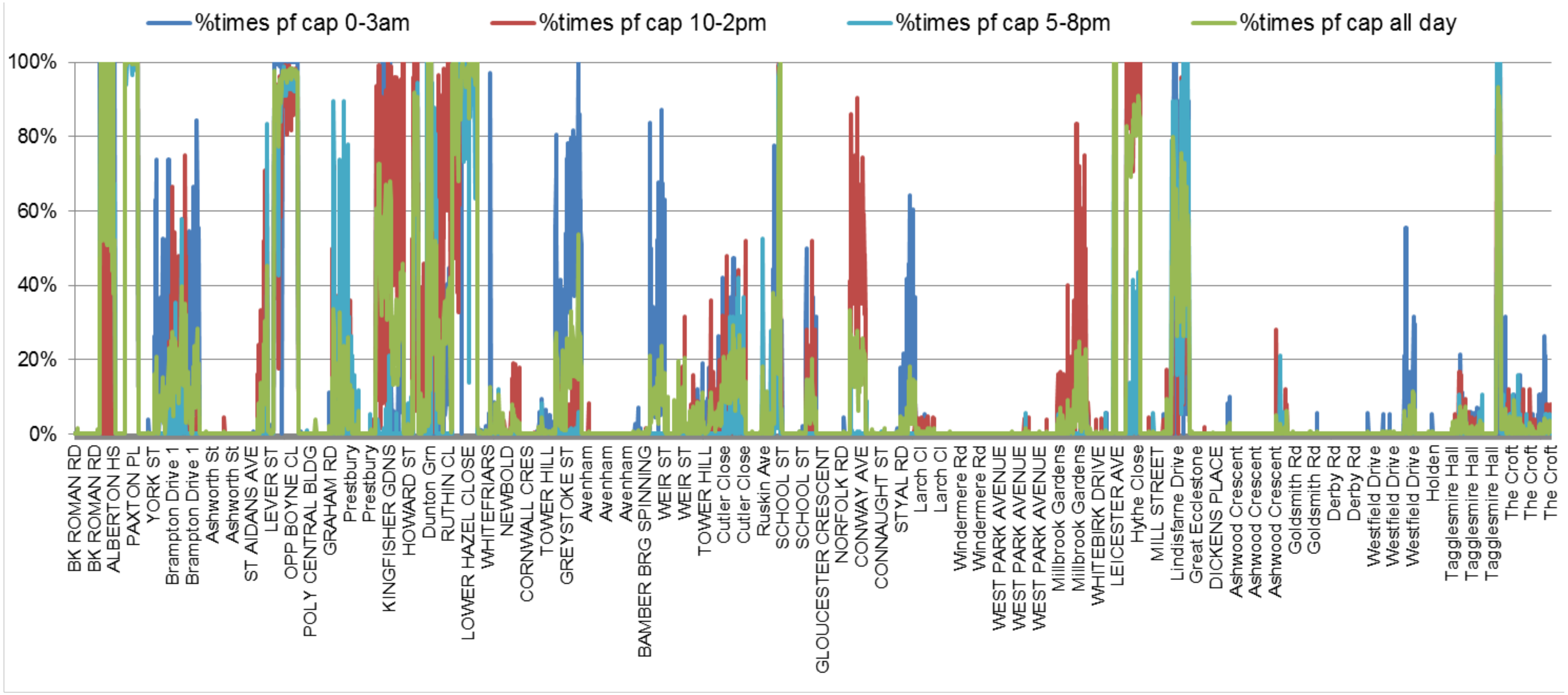

Figure 12 Percentage of time with a capacitive power factor

2.5 Busbar Performance Summary

This section presented the findings on the busbar performance evaluation of the LV networks monitored as a part of the LV Network Solutions project. This has been done for 136 substations with monitoring data from January 2013 to January 2014. Key parameters include transformer usage, voltage, voltage unbalance, and power factor.

The active and reactive power data was used to assess their load factor (*LF*) throughout the studied period. All voltage related factors were calculated. This includes the daily calculation (or for the whole studied period) of the average of 10-minute voltages (*avgV*), compliance with the standard, the difference between min and max recorded voltages (*Vmin-max*), and the voltage unbalance factor (*VUF*). The capacitive or inductive nature of the power factor (*pf_cap*, *pf_ind*) throughout the day is also investigated considering periods such as midday, early morning and evening (peak).

In order to summarise the findings and try to characterise the studied LV networks, these were grouped by transformer capacity. The results are presented in Table 7.

Table 7 Network characterisation based on transformer capacity (Jan 2013-Jan 2014)

	Percentage (%) of Substations				
Transformer loading	**50, 100, 200 kVA**	**300, 315 kVA**	**500 kVA**	**750, 800 kVA**	**1000, 1250 kVA**
LF < 10%	1.5	0.7	2.9	0.7	0.7
10% < *LF* < 50%	14.0	26.5	25.7	12.5	4.4
LF > 50%	0.0	3.7	4.4	2.2	0.0
Voltage Performance					
EN50160 compliant	14.0	28.7	32.3	14.0	4.4
EN50160 non-compliant	1.5	2.2	0.7	1.5	0.7
Vmin-max < 11.5V (0.05pu)	15.4	30.1	28.7	13.2	5.1
Vmin-max > 11.5V (0.05pu)	0.0	0.7	4.4	2.2	0.0
1.05pu < *avg Vabc* <1.08pu	9.6	22.1	25.7	9.6	1.5
avg Vabc > 1.08pu	5.1	5.1	2.9	2.2	2.9
avg Vabc < 1.05pu	0.7	3.7	4.4	3.7	0.7
VUF < 2%	14.7	29.4	33.1	12.5	5.1
VUF > 2%	0.7	1.5	0.0	2.9	0.0
Power Factor Performance					
min *pf_ind* > 0.9	7.4	11.8	13.2	4.4	0.7
min *pf_ind* < 0.9	2.2	5.1	2.2	3.7	1.5
min *pf_ind* < 0.9 (reverse power flow)	0.0	1.5	0.0	0.7	0.0
pf_cap & *pf_ind*	5.9	10.3	10.3	4.4	2.2
pf_cap & *pf_ind* (reverse power flow)	0.0	2.2	7.4	2.2	0.7
pf_cap %time = 0 all time	9.6	18.4	15.4	8.8	2.2
pf_cap %time < 2%	2.9	8.8	8.8	5.9	2.2
pf_cap %time > 60% early morning	0.7	0.7	1.5	0.0	0.0
pf_cap %time > 90% all time	0.7	0.0	1.5	0.0	0.0
pf_cap %time > 50% midday	0.0	0.7	0.7	0.7	0.7
20% < *pf_cap* %time < 50%	0.7	2.2	5.1	0.0	0.0

3 Feeder Performance Evaluation

Monitoring data (9567 daily files) from 430 feeders collected between January 2013 and January 2014 was used in this report. The feeder performance evaluation to be carried out here includes key parameters such as neutral current and current distortion (current THD).

The neutral current behaviour was investigated including the daily calculation of the maximum and average of neutral currents across all feeders based on monitoring data (1 and 10-minute resolution). Daily maximum and average of neutral currents per feeder (*max In* and *avg In*) were also determined. In addition, to compare neutral currents with current rating (*%In/CR*), cable types at the head of the feeders were extracted automatically from GIS network files. Their current ratings (assuming 'laid in duct') were derived from ENWL Code of Practice 203. However, it is important to note that neutral current calculations were carried out considering 1-minute or 10-minute resolution (according to the data), not hourly.

Available current THD data was used to assess the feeders' current distortion throughout the studied periods. Due to the lack of THD data in some of feeders, only 172 of 430 feeders could be analysed. Current THD was investigated considering the daily maximum and average of THD (*max THD* and *avg THD*).

3.1 LV feeder characteristics

Technical aspects of 430 feeders were considered such as number of customers and PV systems (if any). These feeders were also categorised according to type of customers such as profile class and Economy 7. Feeder characteristics for 430 feeders are given based on the proportion of feeders. In addition to these characteristics, tables present the proportion of 172 feeders used for THD analysis. The evaluation of feeder characteristics has been done for all 430 feeders in this section.

In terms of customer numbers, the analysed feeders have between 3 and 304. Most feeders (62%) have less than 50 customers. 27% of the feeders have between 50 and 100 customers, and 11% more than 100 customers (Table 8).

Table 8 Number of customers

MPANs	# MPANs ≤ 50	50 < # MPANs ≤ 100	100 < # MPANs ≤ 150	150 < # MPANs ≤ 304
% Feeders	61.9	27.4	6.7	4.0

Customers are classified in terms of profile class. Most feeders (35%) have domestic and small non-domestic customers (PC1-PC4). 32% of the feeders have domestic customers (PC1, PC2). In addition, 17% of the feeders have only domestic unrestricted customers (PC1). 13% of the feeders have domestic and non-domestic customers (PC1-PC8, PC0). However, 3% have only non-domestic customers (PC3-PC8, PC0) as seen in Table 9. It is important to highlight that 49% feeders have domestic customers.

Table 9 Customer types

MPAN Type	PC1	PC1-PC2	PC1-PC4	P1-PC8, PC0	PC3-PC8,PC0
% Feeders	17.2	31.9	34.7	13.0	3.3

The customers of feeders are also classified in terms of Economy 7 customers: domestic (PC2) and non-domestic (PC4). 75% of the feeders have Economy 7 customers, 25% have no Economy 7 customers. About half of the feeders (55%) have only PC2 whereas 6% have only PC4. In addition, 53% of the feeders have less than 10% Economy 7 customers. 4% of the feeders have more than 50% Economy 7 customers (Table 10).

Table 10 Economy 7 customers

Economy 7	No Economy 7	PC2	PC4	PC2, PC4
% Feeders	25.3	55.1	5.8	13.7

% Economy 7 (# MPANs)	No Economy 7	%Eco ≤ 10	10 < %Eco ≤ 50	50 < %Eco < 100
% Feeders	25.3	52.6	17.7	4.4

Regarding PV systems, 68% feeders have no PV systems. 15% feeders have less than 5% of PV penetration. Only 5% of the feeders have more than 30% of PV penetration. The maximum PV penetration is 83% found in one feeder of *Earl St* substation. This substation has also the highest PV penetration from all the 136 substations. The average of PV installed capacity for the 430 feeders is also around 3kW (as for the 136 substations).

Table 11 Penetration of PV systems

% PV (# MPANs)	No PV	%PV ≤ 5	5 < %PV ≤ 30	30 < %PV ≤ 50	%PV > 50
% Feeders	67.7	14.7	12.1	3.7	1.9

Summarising feeder characteristics from 430 feeders (a subset of the 136 substations), it is important to highlight the following:

- Most feeders (62%) have less than 50 customers.
- Almost half of the feeders (49%) have domestic customers only.
- Three quarters of the feeders (75%) have Economy 7 customers. About half of the feeders have PC2 customers.
- About half of feeders (53%) have less than 10% Economy 7 customers. 4% of the feeders have more than 50% Economy 7 customers.
- 68% of the feeders have no PV penetration. 15% of the feeders have less than 5% of PV penetration. The maximum PV penetration is 83% found in one feeder of *Earl St* substation.
- The average PV installed capacity is 3kW.

3.2 Neutral current

This section evaluates the neutral current per feeder and compares the maximum neutral current with cable current rating at the head of each feeder. Maximum and averages per feeder (*max In* and *avg In*) are taken for the whole studied period. The daily ratios of neutral currents to the corresponding current rating (cable laid in duct), *%In/CR*, are also taken into account. These calculations were carried out considering 1 or 10-minute resolutions (original data) instead of hourly values.

Figure 13 presents the average and maximum neutral currents (*max In* and *avg In*) as well the current ratings for each 430 head of the feeders. It can be seen that *avg In* is always below 70A. The *max In* goes up to 255A. Almost a quarter of the 430 feeders (24%) have *avg In* less than 10A. The maximum neutral current from them is 67A. 67% of the feeders have *avg In* between 10A and 40A and a maximum current of 174A. The other 9% of the feeders (*avg In* less than 70A) have maximum neutral currents between 72A and 255A.

It is important to highlight that neutral current varies between 10A and 40A for most feeders, but these value is correlated with the number of customers. To further analyse this, considering customer type, Economy 7 and PV, all feeders are separated according to *avg In* into the following three segments: *avg In* < 10A, 20A ≤ *avg In* < 40A, and *avg In* > 40A.

Comparing maximum neutral current with current rating (*%In/CR)*, it can be seen that a feeder of *Pinewood Rd* substation exceeds its current rating, with a *%In/CR* of 108%. Three other feeders (from *Heber St, Twinnies Rd* and *Dunton Grn* substations) have also large ratios neutral currents, with *%In/CR* of more than 90%. In summary, 13% of the feeders were found to have *%In/CR* less than 10%. Most feeders (80%) are found with values between 10% and 50%. Only 7% of the feeders have *%In/CR* more than 50%.

To analyse *%In/CR* considering customer type, Economy 7 and PV, all feeders are separated into three segments: *%In/CR* < 10, 10 < *%In/CR* <50, and *%In/CR* > 50. Table 12 presents the proportion of the 430 feeders for each of the *avg In* and *%In/CR* segments considering customer type. It can be clearly seen that all types of feeders have neutral currents mostly between 10A and 40A. Most of the feeders with mixed type of customers (PC1-PC8, PC0) have neutral currents less than 40A. Only a small proportion of the feeders with domestic customers only (PC1-PC2) have neutral currents exceeding 40A. In terms of *%In/CR,* all the types of feeders have almost the same proportion except for feeders with mixed type of customers (a higher *%In/CR* value).

Table 12 Neutral current based on customer type (Jan 2013-Jan 2014)

% Feeders	**PC1**	**PC1-PC2**	**PC1-PC4**	**PC1-PC8,PC0**	**P3-PC8, PC0**
avg In < 10A	22.3	15.9	32.7	50.0	50.0
10A ≤ *avg In* ≤ 40A	68.4	69.8	65.4	50.0	37.5
avg In > 40A	9.3	14.3	1.9	0.0	12.5
%In/CR < 10	12.4	7.9	19.2	25.0	12.5
10 < *%In/CR* <50	80.8	85.7	73.1	62.5	81.3
%In/CR > 50	6.9	6.3	7.7	12.5	6.3

Table 13 presents the proportion of feeders for each of the *avg In* and *%In/CR* segments considering Economy 7. It can be seen that the number of feeders with *avg In* larger than 40A increases with higher penetrations of Economy 7 customers. In terms of *%In/CR*, most of the feeders with 10 to 50% penetration of Economy 7 customers showed ratios between 10 and 50%. The feeders with more than 50% of Economy 7 customers have all *%In/CR* values less than 50%.

Table 13 Neutral current based on Economy 7 (Jan 2013-Jan 2014)

% Feeders (430)	**No Eco**	**%Eco ≤ 10**	**10 < %Eco ≤ 50**	**50 < %Eco ≤ 100**
avg In < 10A	37.6	20.4	17.1	21.1
10A ≤ *avg In* ≤ 40A	60.6	71.2	64.5	57.9
avg In > 40A	1.8	8.4	18.4	21.1
%In/CR < 10	20.2	10.2	7.9	21.1
10 < *%In/CR* <50	77.1	81.9	80.3	78.9
%In/CR > 50	2.8	8.0	11.8	0.0

Table 14 presents the proportion of feeders based on PV penetration. In this case, it is not possible to find a clear correlation between neutral current behaviour and PV penetration.

Table 14 Neutral current based on PV systems (Jan 2013-Jan 2014)

% Feeders (430)	**No PV**	**%PV ≤ 5**	**5 < %PV ≤ 30**	**30 < %PV ≤ 50**	**%PV > 50**
avg In < 10A	22.3	15.9	32.7	50.0	50.0
10A ≤ *avg In* ≤ 40A	68.4	69.8	65.4	37.5	50.0
avg In > 40A	9.3	14.3	1.9	12.5	0.0
%In/CR < 10	12.4	7.9	19.2	12.5	25.0
10 < *%In/CR* <50	80.8	85.7	73.1	81.3	62.5
%In/CR > 50	6.9	6.3	7.7	6.3	12.5

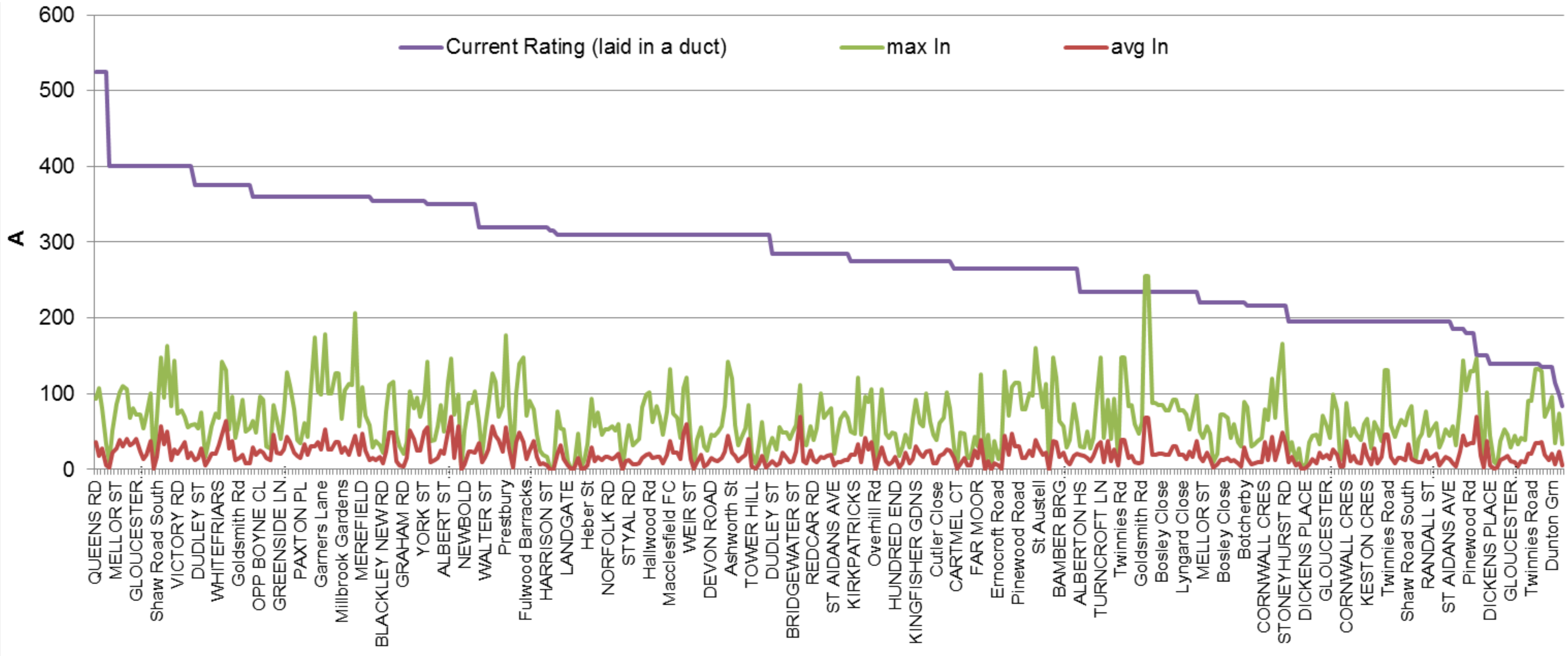

Figure 13 Neutral current per Feeder (whole studied period)

3.3 Current THD

This section evaluates current distortions considering maximum and average of current THD per feeder (*max THD* and *avg THD*) for the whole analysed period. Values are always presented as percentage (%). Due to the lack of THD data in some feeders, only 172 (from 430) are considered. However, these feeders have characteristics covering the whole sample.

Figure 14 presents the maximum and average THD for all the feeders. It can be observed that the average THD vary between 2 and 98%. The maximum THD is 278%. Most feeders (65%) were found to have between 10 and 20% *avg THD*. 10% of the feeders have less than 10% *avg THD*. However, a quarter of feeders have more than 20 *avg THD*.

In Figure 14, it can also be seen that some feeders have significant differences between average and maximum THD. To understand how many feeders have higher current distortion variations during the day, the differences between maximum and average THD (*ΔTHD(max-avg)*) are investigated. About 80% of the feeders are found to have a difference less than 50% (*ΔTHD(max-avg) < 50%*) whereas the maximum difference is 180%.

To further analyse the THD behaviour, customer type, Economy 7 and PV penetrations are considered. Feeders are separated according to *avg THD* into three segments: *avg THD* < 10%, 10% ≤ *avg THD* < 20% and 20% ≤ *avg THD* < 100%. This is also done for THD, separating feeders into two segments: *ΔTHD(max-avg)*≤ 50% and *ΔTHD(max-avg)*> 50%.

Table 15 presents the share of feeders based on customer type. It can be clearly seen that half of the feeders with mixed customers (PC1-PC8, PC0) have less *avg THD.* Most of the feeders with only domestic customers (PC1-PC2) have *avg THD* between 10 and 20%. In terms of *ΔTHD(max-avg)*, all types of feeders show similar proportions except from those purely non-domestic.

Table 15 THD performance based on customer type (Jan 2013-Jan 2014)

% Feeders	PC1	PC1-PC2	PC1-PC4	PC1-PC8,PC0	P3-PC8, PC0
avg THD < 10%	0.0	1.5	15.8	50.0	0.0
10% ≤ *avg THD* < 20%	50.0	78.8	64.9	37.5	0.0
20% ≤ *avg THD* < 100%	50.0	19.7	19.3	12.5	100.0
ΔTHD(max-avg)≤ 50%	71.9	83.3	84.2	87.5	0.0
ΔTHD(max-avg)> 50%	28.1	16.7	15.8	12.5	100.0

Table 16 presents the share of feeders based on Economy 7. More than half of the feeders without Economy 7 had *avg THD* above 20%. With Economy 7, disregarding the penetration, this level of THD is not present in many feeders. Indeed, it can be said that *avg THD* decreases in the feeders with more Economy 7 customers.

Table 16 THD performance based on Economy 7 (Jan 2013-Jan 2014)

% Feeders	No Eco	%Eco ≤ 10	10 < %Eco ≤ 50	50 < %Eco ≤ 100
avg THD < 10%	0.0	9.9	21.6	33.3
10% ≤ *avg THD* < 20%	46.3	74.7	59.5	66.7
20% ≤ *avg THD* < 100%	53.7	15.4	18.9	0.0
ΔTHD(max-avg)≤ 50%	65.9	86.8	83.8	100.0
ΔTHD(max-avg)> 50%	34.1	13.2	16.2	0.0

Table 17 presents the proportion of feeders considering PV penetration. In general, the proportion of feeders without PV that have a low average THD (less than 10%), was much larger than that with any PV penetration. Indeed, THD increases significantly in the feeders with PV penetration, particularly above 30%. In addition, large differences between maximum and average THD, *ΔTHD(max-avg)*, also increases with more PV penetration.

Table 17 THD performance based on PV systems (Jan 2013-Jan 2014)

% Feeders	No PV	%PV ≤ 5	5 < %PV ≤ 30	30 < %PV ≤ 50	%PV > 50
avg THD < 10%	14.0	0.0	4.5	0.0	0.0
10% ≤ *avg THD* < 20%	71.9	76.5	40.9	12.5	25.0
20% ≤ *avg THD* < 100%	14.0	23.5	54.5	87.5	75.0
ΔTHD(max-avg) ≤ 50%	92.6	88.2	45.5	37.5	0.0
ΔTHD(max-avg)) > 50%	7.4	11.8	54.5	62.5	100.0

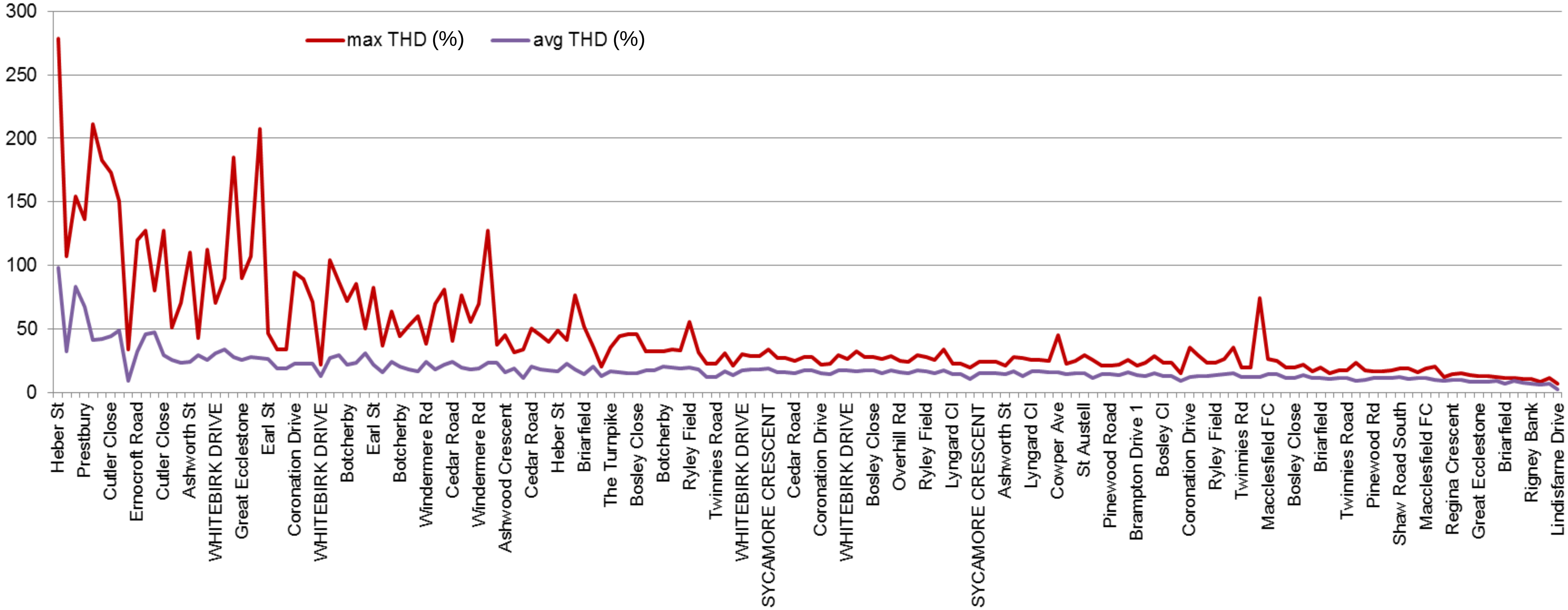

Figure 14 Current THD (%) per Feeder (whole studied period)

4 Conclusions

This report presented the findings on the performance evaluation of the LV networks monitored as a part of the LV Network Solutions project. This has been done for 136 substations with monitoring data from January 2013 to January 2014. Key parameters include transformer usage, voltage, voltage unbalance, and power factor. THD and neutral current have not been considered in this report given that these are feeder-based parameters.

It is important to highlight the following:

Network characteristics

- Most substations (65%) have capacities between 500 and 800kVA.
- Most substations (75%) have between 100 and 500 customers.
- 13% of the substations have only domestic (PC1). The rest are mixed profile classes: 42% of the substations have domestic and small non-domestic customers (PC1-PC4), 45% have domestic and non-domestic customers (PC1-PC8, PC0).
- Most substations (96%) have Economy 7 customers. 53% of the substations have domestic and non-domestic Economy 7 customers. 85% of the substations have less than 20% Economy 7 customers, 4% have more than 60%.
- 61% of the substations have PV penetrations between 0.2 and 49% (percentage of houses with PV systems). 7% of the substations have more than 20% PV penetration.
- The average of PV installed capacity is 3kW.

Feeder characteristics

- Most feeders (62%) have less than 50 customers.
- Almost half of the feeders (49%) have domestic customers only.
- Three quarters of the feeders (75%) have Economy 7 customers. About half of the feeders have PC2 customers.
- About half of feeders (53%) have less than 10% Economy 7 customers. 4% of the feeders have more than 50% Economy 7 customers.
- 68% of the feeders have no PV penetration. 15% of the feeders have less than 5% of PV penetration. The maximum PV penetration is 83% found in one feeder of *Earl St* substation.
- The average PV installed capacity is 3kW.

Transformer loading

- Overall load factors (i.e., over the analysed period) of all the substations do not exceed the 83.3% of the ENWL Code of Practice 382.
- Most substations (83%) have overall load factors between 10% and 50%.
- *Lever St* and *Pinewood Rd* are substations with the highest overall load factors (62%).
- *Cutler Cl* and *Lindisfarne Drive* are substations with overall load factors lower than 3%.
- *Leicester Ave* shows a 24% absolute difference between winter and summer load factors. It has 21% penetration PV systems and more than 20% PC2 customers.
- *Pinewood Rd* and *Greenside Ln Fiveways* are substations whose maximum hourly loadings exceed their nominal ratings but are within their normal cyclic ratings.

Voltage Performance at the Busbars

- 7% of the substations have busbar voltages above 253V (1.1pu).
- Daily average busbar voltages for all substations vary between 237V (1.03pu) and 253V (1.10pu).
- Most substations (63%) have daily average busbar voltages between 241V (1.05pu) and 248V (1.08pu).
- The busbar voltage variations (i.e., max minus min voltage) throughout the analysed period are between 5V (0.021pu) and 18V (0.078pu).
- Most substations (93%) have voltage difference less than 11.5V (0.05pu).
- Most voltage variations (95% of the time during the day) are between 3V (0.013pu) and 9V (0.04pu).

- *Ruskin Ave, Weir St* and *Dunton Green* are the substations with the highest voltage unbalance factor.
- After August 2013, *Dunton Green* improved its unbalance factor from 4% to less than 2%.

Power Factor Performance

- More than half of the substations (54%) have a purely inductive power factor behaviour.
- More than a third of the substations (37%) have minimum power factor above 0.90 all the time and an average higher than 0.98.
- 29% of the substations have capacitive behaviour for less than 30 minutes during the day.
- 15% of the substations have capacitive behaviour between 30 minutes and 17 hours during the day. Some are more capacitive during midday, some during early morning.
- Three substations (*Paxton Pl, Opp Boyne Cl* and, *Lower Hazel Cl*) have an almost constant capacitive behaviour (22 hours during the day).
- 15% of the substations experienced reverse power flows at some point; 3 of them are purely inductive whilst 17 substations have both capacitive and inductive behaviours.

Feeder Neutral Currents

- Throughout the analysed period, the average neutral current per feeder (of 430) does not exceed 70A. The maximum, however, can be as high as 255A.
- Two thirds of the 430 feeders have average neutral currents between 10A and 40A, and a maximum current of 174A.
- The ratio of maximum neutral current and rating capacity (cable at the head of the feeder) was found to be between 10% and 50% for most of the 430 feeders (80%).
- Only a small proportion of the feeders (14%) with domestic customers only (PC1-PC2) have neutral currents exceeding 40A.
- The number of feeder with average neutral currents larger than 40A increases with the penetration of Economy 7 customers.

Feeder Current THD

- The average THD per feeder varied between 2 and 98%. The maximum THD is 278%.
- Most feeders (65%) were found to have between 10 and 20% average THD.
- Half of the feeders with mixed customers (PC1-PC8, PC0) had average THD up to 10%.
- Most of the feeders with only domestic customers (PC1-PC2) had average THD between 10 and 20%.
- More than half of the feeders without Economy 7 had average THD above 20%. With Economy 7, disregarding the penetration, this level of THD is not present in many feeders.
- In general, the proportion of feeders without PV that have a low average THD (less than 10%), was much larger than that with any PV penetration.
- Average THD increases significantly (above 20%) in feeders with PV penetration, particularly above 30% of penetration.