DATA ANALYSIS OF LV NETWORKS: KEY PARAMETERS FROM ONE YEAR OF MONITORING OVER HUNDREDS OF UK LV FEEDERS

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ABSTRACT

Understanding the current behaviour of low voltage distribution feeders is crucial to assess the impacts of low carbon technologies (LCTs) in low voltage (LV) distribution networks. Only by knowing the main parameters in the base case, i.e., without LCTs, it is possible to estimate the potential effects of adopting these technologies. However, the knowledge about the infrastructure at this voltage level is limited. In fact, most of Distribution Network Operators (DNOs) do not monitor LV networks, mainly because of the historic passive nature of these circuits and the assumption that demand and diversity would not change dramatically. Nonetheless, this historic framework is challenged by the increasing adoption of LCTs. In this context, this work analyses real 10-minute resolution data from more than 100 UK LV substations (500+ feeders), considering two seasons (winter and summer), and the presence of photovoltaic systems. In particular, three key parameters are investigated: voltage at the busbar, power factor, and imbalance level for all the cases under analysis. This analysis increases the understanding of current UK LV networks that can then be used to improve modelling and design approaches.

INTRODUCTION

The emissions of greenhouse gases related to human activities have grown considerably in the last century leading to the highest concentrations in thousands of years. These unprecedented levels are likely to be the cause of the current global warming [1]. The reduction of these emissions is the main driver in many countries for the promotion of low carbon technologies (LCTs) (e.g., photovoltaic systems, electric heat pumps, electric vehicles, micro combined heat and power, etc.) at residential level. However, residential customers are connected to low voltage (LV) distribution networks, and therefore the impacts of LCTs are likely to appear first on these circuits. Indeed, high LCT penetrations can produce technical issues such as voltage rise/drop, overloading of cables and/or transformers, etc. [2], [3].

To comprehensively and fairly assess these LCT impacts, it is fundamental to truly understand the real behaviour of LV networks, in particular those designed for dozens to hundreds of customers such as in Europe. In fact, key parameters must be known to feed the potential models of LV feeders. The adoption of historical values, for instance, to model the power factor of residential loads, could –if far from reality– under or overestimate voltage profiles with or without LCTs and thus lead to misleading assessments.

The complete understanding of the main parameters that define the behaviour of LV networks is not yet part of the core business of many Distribution Network Operators (DNOs). In fact, these LV circuits are not monitored or further analysed because of the traditional "fit and forget" approach, mainly driven by the passive nature of these networks and the assumption that demand and diversity would not change dramatically. Nonetheless, this historic framework is challenged by the increasing adoption of LCTs. For example, electric vehicles are likely to increase our peak demand whilst photovoltaic (PV) systems could result in significant reverse power flows.

In this new context, DNOs require a greater understanding of the characteristics and behaviour of LV distribution networks. For that reason, the UK DNO Electricity North West Limited (ENWL), through the Low Carbon Networks Fund Project "LV Network Solutions" [4] carried out an extensive monitoring trial of residential, underground LV networks (multiple feeders, three-phase four-wire designs, predominantly single-phase connection of customers). Two hundred substations were monitored acquiring voltage, current, and active and reactive power at the head of each feeder and for each of the phases (and the neutral) using a sampling interval of 10 minutes. Specifically, this work analyses the data corresponding to 120 substations. Three key parameters that characterise the operation of real residential LV networks are thoroughly investigated: voltage at the busbar, power factor and load imbalance level.

DATA ANALYSIS: FRAMEWORK

The monitors for the substations were installed during 2012 and 2013 at the head of each feeder, recording information from the three phases and the neutral. The installation of these devices was done without any customer interruption by using Rogowski current coils and the adequate voltage connections. The recorded information was continuously sent to ENWL over GPRS (General Packet Radio Service) and then collected by The University of Manchester for further analysis.

Initially, the information was measured with 1-min resolution. Nonetheless, to avoid the massive amount of information being stored and the fact that this resolution did not bring significant benefits to assess the impacts of LCTs in comparison with 10-min resolution data [3], the latter was finally adopted. This is also consistent with the standard BS EN 50160 [5] which establishes a 10-min mean RMS values to check compliance at residential level. Therefore, to uniform the data, 1-min values were averaged accordingly.

The analysed 120 substations correspond to the ones with available information about the presence or not of distributed generation (particularly PV systems) per feeder. It is worth mentioning that this information must be provided to the DNO by PV installers but in many cases it does not happen in a timely manner or at all. Nonetheless, the available information allows comparing the data between feeders with and without PV systems. In addition, only those days with valid data for all the corresponding 10-min periods were considered. This ensures avoiding the under or over representation of period (e.g., night time) with more data availability.

Based on the above, a total of 6.13 million records from the 120 substations (i.e., 515 feeders) are used in the analysis. Each record corresponds to a single 10-min measurement and includes all the information associated to that period (time stamp, date, feeder identification, voltages, currents, active and reactive power, etc.). These records are not distributed uniformly along the year as it can be observed in Fig. 1. A more constant flow of data was only reached after different adjustments were carried out during the first part of the trial (Mar to Aug 2013). In addition, Fig. 1 shows that most of the available data corresponds to the UK winter time (October to January). Only July presents enough data to adequately study the summer period.

Given the available data, two PV cases (with and without) and two seasons (winter and summer) are examined.

DATA ANALYSIS: WITH AND WITHOUT DG

For each of the cases under analysis, the histograms of the key parameters (voltage, power factor and load imbalance) are calculated using all the available records with the purpose of identifying the median (i.e., the middle value that separates the higher and lower half of

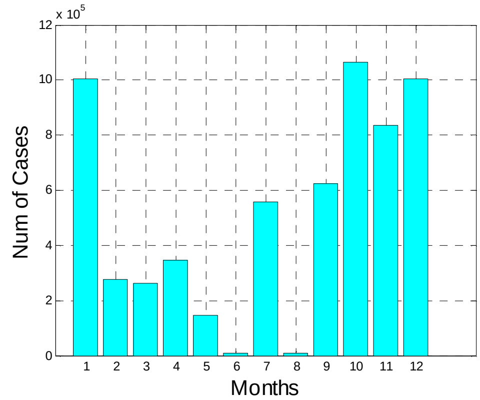

Fig. 1. Data considered in this analysis

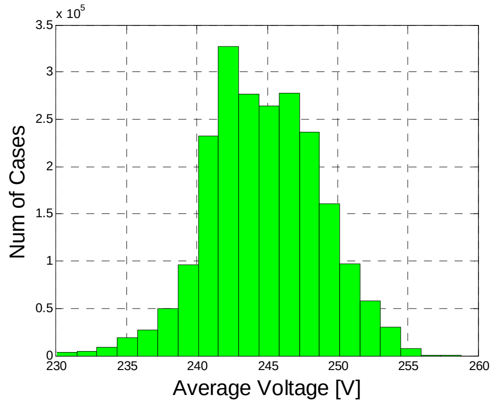

Fig. 2. Phase-to-neutral voltage at the busbar – Winter no PV

the sample) and the range where 80% of the data is concentrated (i.e., difference between the 90th and 10th percentiles). These metrics help to statistically understand the 'typical' values for these key parameters during the year of monitoring.

Winter Period

The months considered in this part of the analysis are November to January, representing 118 substations and 509 feeders (about 3.4 millions of records). Among these feeders, a high proportion (333 feeders; about 2.2 millions of records) do not have PV systems. For this case, Fig. 2 shows the histogram of the phase-to-neutral voltage at busbar (average among the three phases).

From Fig.2 it is possible to observe a median of 245V and an 80% data range between 240.1 and 249.9V. Therefore, given that the nominal phase-to-phase voltage is 400V (i.e., ~230V phase-to-neutral), a typical busbar voltage can be considered to be between 1.04 and 1.08 p.u.

The power factor histogram is presented in Fig. 3. All the values correspond to an inductive behaviour and most of the data is close to unity. In fact, in this case, the median is equal to 0.993 and the 80% data range is between 0.967 and 0.999. This value is higher than the common assumption of 0.95 in LV networks.

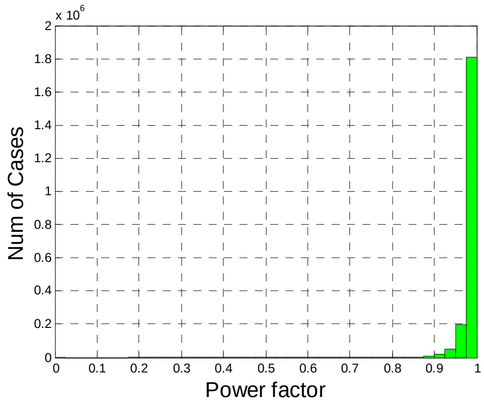

Fig. 3. Inductive Power Factor at the busbar – Winter no PV

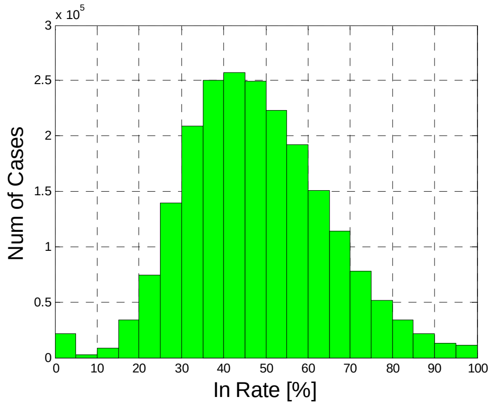

Fig. 4. Neutral current rate – Winter no PV

Even though the monitoring trial carried out constitutes a step ahead in the understanding of UK LV distribution networks, unfortunately, some elements were not considered. Particularly, the phase angles for the voltages were not measured and therefore the calculation of the voltage unbalance cannot be implemented according to the BS EN 50160 [5] (ratio between the negative and positive phase sequence component). Hence, to have a proxy about the imbalance level of LV feeders, two metrics are implemented: the neutral current rate and the load imbalance level.

The neutral current rate is calculated as the ratio between the neutral current and the maximum current among the three phases. It is worth recalling that the neutral current is zero in an ideally balanced system. The histogram for the neutral current rate is presented in Fig. 4. It can be observed that in most cases the neutral current is different from zero, reaching values as big as the phase currents. The median is 46.4% (i.e., the neutral current is about half of the maximum phase current) and the 80% data range is between 27.9% and 69.8%.

The load imbalance level is defined as the ratio between the load in one of the phases (phase A in this case) and the total load (aggregation of the three phases). Therefore, this value must be 33% at any time in an ideally balanced system. Fig. 5 shows the histogram for

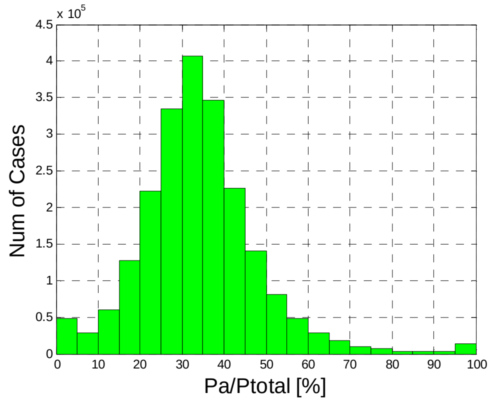

Fig. 5. Load Imbalance Level – Winter no PV

Table I. Summary of key parameters during winter

	Without PV		*With PV*	
Parameters	*Median*	*80% data range*	*Median*	*80% data range*
Voltage [V]	244.6	240.1-249.9	245.9	240.2-251.1
Power factor	0.993	0.968-0.999	0.994	0.973-0.999
Neutral current rate [%]	46.4	27.9-69.8	46.4	28.4-70.4
Load imbalance [%]	33.2	18.5-50	33.8	18.5-50

this metric, indicating a median of 33%. However, there are many cases different to this ideal value. In fact, the 80% data range is between 18.5 and 50%, meaning that most of the time, the load in one phase is between 20 and 50% of the total load in the feeder.

The neutral current rate and the load imbalance level show the truly unbalanced nature of LV feeders and therefore highlight the importance of using power flow engines able to run unbalanced systems (i.e., three-phase four-wire).

The analysis above is repeated for the case with PV systems. The median and the 80% data range for each of the metrics are summarised in Table I (including the case without PV systems). This table shows no significant differences between both cases during winter. In fact, only the median voltage in the PV case is slightly higher (~1.5V). The absence of significant differences between both cases is likely to be due to the unfavourable weather conditions for PV systems during the UK winter, i.e., the corresponding generation is reduced, but also given the higher levels of demand during the day.

Summer period

The months considered for this period are June, July and August; nonetheless, as stated before, most of the data is concentrated only during July (Fig. 1). The number of substations and feeders available are 69 and 277, respectively, representing about 0.6 million records.

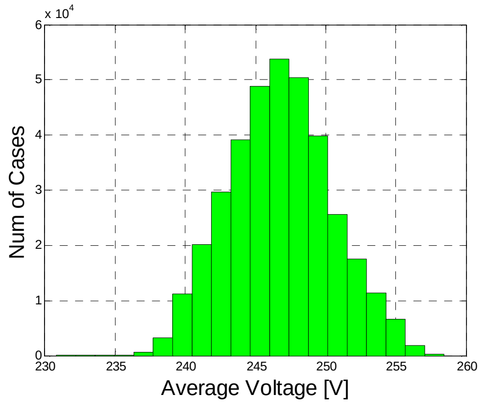

Fig. 6. Phase-to-neutral voltage at the busbar – Summer no PV

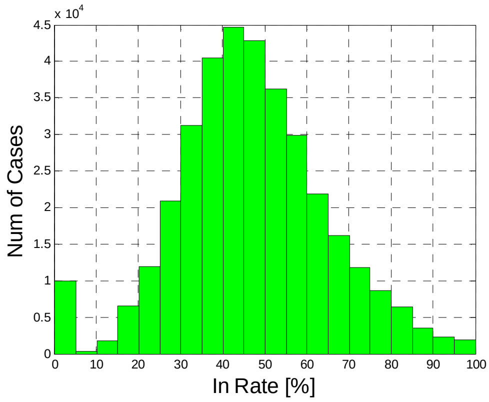

Fig. 8. Neutral current rate – Summer no PV

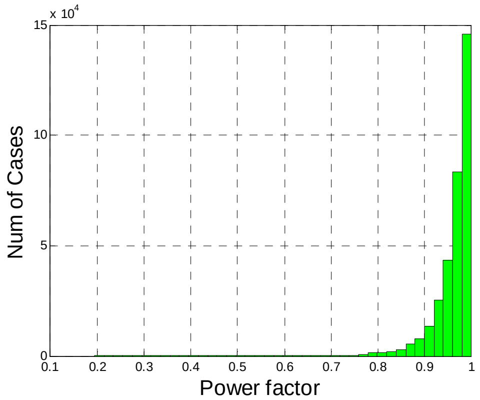

Fig. 7. Inductive Power Factor at the busbar – Summer no PV

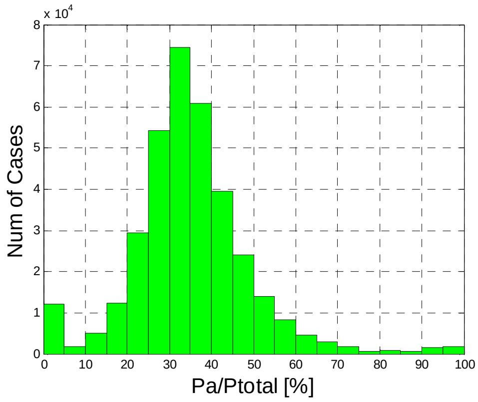

Fig. 9. Load Imbalance Level – Summer no PV

From this information, the feeders with registered PV systems are 170 (about 0.4 millions of records) and the feeders without PV are 107 (about 0.2 millions of records). Following the same structure as the previous winter analysis, the histograms are presented for the case without PV systems. The main metrics for both cases are summarised in Table II.

The histogram of the voltage at the busbar for the cases without PV systems is presented in Fig. 6. From this data, the median is 246V and the 80% data range is concentrated between 241.8V and 251.6V. On the other hand, the histogram for the power factor is shown in Fig. 7. In this case, the values are also close to unity but with a deviation larger than winter; indeed the median is about 0.98 with 80% of the data between 0.912 and 0.997. In respect of the imbalance metrics, the median for the neutral current rate (Fig. 8) and the load imbalance level (Fig. 9) for the case without PV systems are 45.8 and 34%, respectively.

To complete the analysis, the median and the 80% data range for each of the parameters with and without PV are summarised in Table II for the summer period. Thus, for this season, due to the presence of PV systems, it is possible to observe differences between both cases. As expected, the voltage at the busbar is higher in the case with PV, but also the imbalance metrics are higher.

Table II. Summary of key parameters during summer

	Without PV		*With PV*	
Parameters	*Median*	*80% data range*	*Median*	*80% data range*
Voltage [V]	246.6	241.8-251.6	247.5	242.9-252.6
Power factor	0.976	0.912-0.997	0.979	0.920-0.998
Neutral current rate [%]	45.87	26.3-69.9	48.9	27.3-76.5
Load Imbalance [%]	34.07	20.9-50.5	35.5	19.7-52.6

In fact, the median for neutral current rate is about 49% (i.e., the neutral current is almost half of the phase current) in the PV case in comparison with the 46% without PV. In addition, the 80% data range is larger in the PV case, starting 1% before and finishing 7% after the case without PV. The same phenomenon can be observed for the load imbalance level (ideally 33%), where the median is 35.5% with PV and 34% without PV. Furthermore, the 80% data range has a larger dispersion in the PV case, starting 1% earlier and finishing 2% later.

From the analysis above, it is possible to conclude that the presence of PV systems increases the already unbalanced nature of LV distribution networks.

Table III. Winter v. Summer Comparison – without PV

	Winter		*Summer*	
Parameters	*Median*	*80% data range*	*Median*	*80% data range*
Voltage [V]	246.2	242.1-251.0	246.6	241.8-251.4
Power factor	0.992	0.958-0.999	0.976	0.913-0.997
Neutral current rate [%]	44.6	26.3-71.0	45.6	26.3-69.0
Load Imbalance [%]	32.8	18.5-50.0	34.0	21.1-50.5

Table IV. Winter v. Summer Comparison – with PV

	Winter		*Summer*	
Parameters	*Median*	*80% data range*	*Median*	*80% data range*
Voltage [V]	246.8	241.4-252.2	247.5	242.9-252.6
Power factor	0.976	0.912-0.997	0.979	0.920-0.998
Neutral current rate [%]	45.87	26.3-69.9	48.9	27.3-76.5
Load Imbalance [%]	34.07	20.9-50.5	35.5	19.7-52.6

DATA ANALYSIS: WINTER AND SUMMER

The comparison between Table I and Table II can provide some insights about potential differences of the key investigated parameters for the winter and summer periods. However, that comparison can be used only as a reference, because the two samples are not necessary the same. Therefore, to have a fairer analysis, only the feeders with available data for both periods are considered in this section. Thus, the matching winter and summer samples results in a subset of 60 substations and 167 feeders without PV systems (about 0.95 and 0.35 millions of records for winter and summer, respectively) and 48 substations and 107 feeders with declared PV (about 0.71 and 0.21 millions of records for winter and summer, respectively).

Table III presents the comparison between winter and summer for the load-only case. The median for the voltage at the busbar is quite similar between both seasons. The difference in the imbalance level cannot be conclusive since the median values for the neutral current rate and for the load imbalance level are larger in the summer period, but the 80% data range of these metrics are smaller. The power factor exhibits a clear difference between the two periods, having a median close to unity (i.e., most of the data between 0.96 and 1.0) during winter and about 0.98 during summer.

On the other hand, Table IV, as expected, shows an increase in voltage due to the increase in PV generation during summer. More importantly, Table IV ratifies a higher level of imbalance in summer due to the presence of PV systems. In fact, the neutral current rate and the load imbalance level present higher median values and larger 80% data ranges during summer.

All this information is crucial to model adequately the actual nature of residential, underground UK LV distribution networks.

CONCLUSIONS

This paper carried out a statistical analysis of 10-minute resolution data collected over a year from more than 100 residential, underground UK LV feeders. The measurements were done per phase in each of the corresponding 500+ LV feeders. Three key parameters to understand the real behaviour of LV feeders were investigated: voltage, power factor and imbalance level.

The analysis considered two seasons (winter and summer), and two cases (with and without residential-scale PV systems). The main results indicate that the voltage at the busbar is mainly concentrated in all the cases around 241V and 251V. Interestingly, the median power factor during winter, without PV, is close to unity, i.e., different from traditional values around 0.95 adopted by DNOs. During summer, the power factor decreased to about 0.98 irrespective of the presence of PV systems. The analysis also highlighted the increase in the already unbalanced nature of LV networks due to the presence of PV systems.

ACKNOWLEDGMENTS

This work has partly been funded by Electricity North West Limited, UK, through Ofgem's Low Carbon Networks Fund Tier 1 Project "LV Network Solutions", 2011-2014.

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