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Understanding LV Network Voltage Distribution- UK Smart Grid Demonstration Experience

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***Abstract*—This paper analyses the real-time voltage data acquired at Low Voltage (LV) distribution network substations to understand their distributions. It is a part of a smart grid demonstration project 'Low Voltage Network Templates' conducted in the UK by the local distribution network operator (DNO) for South West and South Wales of UK. This work for the first time provides the visibility of voltage distributions at LV network substations which previously was impossible due to lack of metering equipment. The voltage distributions are divided into two scenarios: over and under statutory limits. The paper first identifies the voltage magnitude distributions, which are then linked with locations and load compositions. Both voltage at substations at feeder ends are investigated to understand the capability to accommodate low carbon technologies. The work complements the current practice of understanding the conditions of LV networks that are not properly monitor from voltage aspect.**

***Index Terms*--Smart grids, low voltage network, low carbon technologies, smart metering, voltage profiles**

I. INTRODUCTION

Due to the ambition to reduce greenhouse gas emissions, the UK government is actively encouraging the development and utlisation of low carbon technologies (LCTs). These new technologies, such as electric vehicles (EVs), heat pumps (HPs), photovoltaics (PVs), and other smart appliances (SAs) are largely deployed at distribution level. [1, 2]. According to recent study, small-scale embedded generators could generate up to 30% to 40% of the UK's electricity demands by 2050 [3]. In addition, report [4] points out that by 2030, the number of electric vehicles will reach to 2.142 million in the UK. Characterised by seasonal or even daily variation, such technologies might pose different impact to the distribution networks, particularly low voltage (LV) networks. [reference of effect]

However, constructed half century ago, a large part of LV networks were designed to primarily take power from higher voltage level networks and then distribute to homes, schools and hospitals, etc. For cost efficiency reasons, little protection and control devices have been installed in LV network [5] because of its huge scale. In the conventional radial networks, by monitoring and controlling higher voltage networks, the LV network power and voltage are expected to stay within the statutory limits empirically. But, the situation is changing because of the decarbonisation initiatives. The current operating frameworks for LV networks are not conceived with LCTs in mind and thus the LV distribution network would face many problems with the growing number of LCTs. Consequently, distribution network operators (DNOs), who are responsible to maintain network security and power quality, are facing the challenge to facilitate the increased penetration of demand from LCTs. The LV distribution networks in the UK were designed with little monitoring equipment, resulting in significant gaps in understanding stress and their margins. Therefore, reliable and economical accommodation of LCTs is difficult because there is a lack of real-time LV network visibility.

In order to understand the capabilities of LV networks to support the low carbon technologies , Western Power Distribution (WPD) in the UK has initiated one of the Low-Carbon Network (LCN) Projects - Low Voltage Network Templates through the funding from the Office of Gas and Electricity Markets (Ofgem) [6]. In the project, WPD installs monitors at selected LV distribution substations and feeders in South Wales, spanning from Newport to Swansea. These monitors collect real-time network data for: i) to find the actual demand and voltage headroom available in LV network; ii) to understand the distribution of LV network voltages; iii)to develop LV network templates by using statistical approaches that may be applicable for the entire UK LV networks [7]. This paper is particularly concentrated on voltage magnitude stress and headroom analysis.

The voltage characteristics on LV network heavily influence the energy quality of end customers. The variations of the voltage characteristics and long-time over/under voltage can cause adverse consequences on end customers' energy use, degrading the performance and lifespan of electrical equipment [8, 9]. The UK voltage standard is based on British Standard BS 7697: nominal voltages for LV public electricity supply systems should be set between 230V +10%/-6% limits[10], i.e. ranges from 253V to 216.2V. Voltage magnitudes within this range are esteemed to be normal, but otherwise the statutory limits are breached. In the UK, voltage control ability is at primary substations. DNOs only have a

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The work is sponsored by Western Power Distribution in the UK under the 'LV Network Templates' project.

snapshot that majority of the voltage magnitudes at LV network should be within the statutory limits, which is achieved by the tap-change transformers in the primary substation. Now with the increasing penetration of LCTs, risks on power quality are increasing due to that the load profiles would have more variations, thus affecting the voltage profiles. Under this condition, a better understanding of the voltage characteristics of the current LV distribution network is necessary. This paper reports the key findings in this smart grid project from a voltage perspective by analyzing the voltage distribution, according to their magnitudes against UK statutory limits. This work, for the first time, provides a visualization of voltages at LV distribution networks that have not been fully monitored. Thereby, this paper measures the headroom of voltages to limits against various voltage ranges, illustrating the beyond limit situations and giving an illustration of voltage stress in different topographies and customer mixes. Finally, suggestions on voltage control, voltage legislation and LCTs accommodation strategy are discussed to enable DNOs to better use the findings.

By knowing the actual voltage characteristics of LV networks, we can gain the following benefits: i) the insight of headroom within the statutory constraints could be gained; ii) a clear picture of the voltage distribution in different topographies and customer mixes with daily and seasonal variation is achieved; iii) adjustment of voltage control can be designed; evidence of policy or legislation on LV network voltage is provided; and iv) stress that LCTs might imposed to the LV network can be predicted and accommodation and operation strategies of LCTs could be planned.

The paper is organized as follows. Section II introduces the project. Section III gives overall voltage distribution of the LV networks. Section IV analyzes the detailed out of statutory voltage problems. Section V discusses the voltage control strategy, potential legislation modification and network capability of connecting low carbon technologies. Section VI draws the conclusion.

II. PROJECT DESCRIPTION

A. Project Vision

The overall aim of this project is to develop a number of common LV substation templates and classify each substation in other areas in the UK to a template with certain statistical confidence [11, 12]. Based on these templates, the available "headroom" in terms of thermal and voltage over time of day and other network will be quantified as to whether further demand and low carbon technologies can be accommodated into these. The research will interrogate the extensive data using statistical approaches with an aim to inform critical conditions in networks in relation to the low carbon technologies, allowing operators to have targeted interventions as required maintaining their quality of supply.

B. Practical Arrangements

In this smart grid demonstration project, WPD deployed monitoring equipment at over 800 HV/ LV substations and over 3500 ends of LV feeders collecting network performance data. A selection of areas and networks will be involved in the project containing a good mix of geographical characteristics, customer composition and network topologies. For example, Cardiff is selected as inner city with a larger number of commercial customers and loads. Rural areas will be represented by places like Monmouthshire. Suburbia areas with more domestic loads between Cardiff and Newport are also included. The Valleys, as ex-industrial areas, is designed to deliver representatives for industry customers.

Two sets of data are received: fixed data and variable data. The flowchart of collecting and transferring the data is given in Figure 1. Fixed data include: i) the information of each chosen LV substation, its capacity, serving customer types and numbers, PV numbers in its serve customer, and the outgoing LV feeder numbers; ii) distributed generation data, which are mainly PV, and the linkage between generation data and LV substations; and iii) LV feeders' information, including: feeder types and length. The fixed data do not change during the research period and they are used to classify LV substations and to form typical LV networks to conduct topology and energy flow analysis. The variable data collection is on a 10-minute interval. The data include: i) real-time voltage, current, power received and delivered at LV substations; ii) PV output data; and iii) voltages at feeder ends. The variable data are used for mathematical clustering analysis to identify the embedded patterns in real power delivered and voltages. Figure 2 presents the general data acquired at a sample substation 553016.

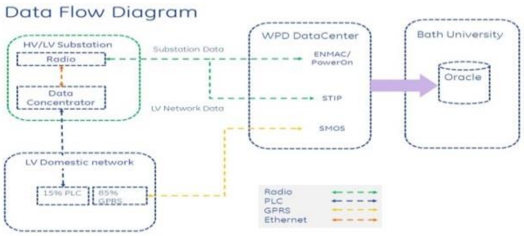


Figure 1 Data flow diagram

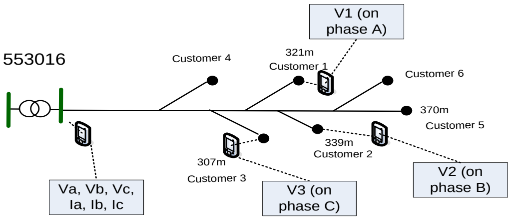


Figure 2 Sample of data Acquisition

III. OVERALL VOLTAGE DISTRIBUTION

The overall voltage distribution in 828 substations and 3609 remote feeder phase monitors are investigated. The real time voltage data collection is taken on a 10 min interval on each phase. The short interval data collection leads to in total 84 million and 98 million of voltage data in substation and remote feeder ends. Given large amount of raw data, the errors can appear at any stage of acquiring and transmitting from filed substations to the university. There might be some bad data that does not make any sense and could interfere with the analysis. As a result, thresholds to filter out bad data are concluded to: the voltage values out of 230V+20%/-20% band. Any voltage data out of this range is considered to be bad and not included in the analysis.

In detail, the voltage magnitude distribution at substations is shown in table I. Voltage values at seven ranges are recorded and compared. It is found that 99.31% of the voltage values at substations are within the standard voltage range. The majority problem is voltage beyond upper limit. Over half of time, 56.15%, voltage values are within 243.8V (+6%) to 253V (+10%) range, locating closely to the upper limit. It can be deduced that the voltage magnitudes at substations are generally higher than 230V. There are a few situations when voltage values fall below 230V-2% range. Considering the high percentage of substation number and low percentage of voltage values located below 230V-6% range, the problem of voltage fall out of lower limit is negligible.

Table I DISTRIBUTION OF VOLTAGE MAGNITUDE AT SUBSTATIONS

Range: 230 V+/- given percentage	Percentage of substation number located at range	Percentage of voltage values located at range
>10%	14.61%	0.6890%
8 to 10%	79.11%	6.9808%
6 to 8%	99.28%	49.1730%
----	----	----
-2 to -4 %	10.02%	0.00076%
-4 to -6 %	9.78%	0.00025%
-6 to -10%	9.90%	0.00025%
<-10%	24.52%	0.00053%

Table II shows the voltage magnitude distribution at customer connected points. There are more voltage values staying within the standard range: 99.62% are within the UK limits 216.2-253V and 0.38% outside. The number of higher voltage values decrease because of the voltage drop on the network. However, there is still a large percentage of voltage magnitudes, 37.52%, in the range between 243.8-253V. Accordingly, voltage values below 230V-6% range become more, but the total number is still negligible. The low percentage of monitor number located below 230V-6% indicates that the problem of low voltage mainly happens in individual feeders.

Table II DISTRIBUTION OF VOLTAGE MAGNITUDE AT REMOTE FEEDER ENDS

Range: 230 V+/-	Percentage of monitor number located at range	Percentage of voltage values located at range
>10%	11.47%	0.3543%
8 to 10%	47.63%	5.2196%
6 to 8%	77.78%	32.2961%
----	----	----
-2 to -4 %	14.08%	0.1234%
-4 to -6 %	5.99%	0.0437%
-6 to -10%	3.33%	0.0187%
<10%	0.89%	0.0022%

From the overall voltage distribution, it can be concluded that the voltage magnitudes in LV network is widely larger than nominal voltage both in substation and customer ends, resulting that overvoltage problem is more serious than under-voltage problem in both substation and customer ends. Because of the voltage drop on the networks, voltage magnitudes at remote feeder ends are lower than that at substation ends without LCTs such as distributed generation. It is reasonable that under-voltage problem is more serious at remote feeder ends (0.0209%) than substation ends (0.00078%). Considering the length of the paper, in the following section, overvoltage problems in substation ends and low voltage scenario in remote feeder ends are detailed investigated.

IV. VOLTAGE PROBLEM ANALYSIS

In order to assess to what extend the voltage magnitudes are breached the statutory limits. The detailed voltage magnitude distribution over time, probability, location and composition of the two group data are investigated.

A. Season Classification

In order to understand the problem in more details, one calendar year has been split into five seasons: spring, summer, high summer, autumn and winter. The classification is according to the industrial practical arrangement used in the UK, as given in Table I [13]. The voltages at high summer and winter are analyzed because in these two seasons the distribution networks will undergo two extreme conditions: maximum generation vs. minimum demand and maximum demand vs. minimum generation.

Table III SEASON CLASSIFICATION [13]

Season	Date
Spring	03.31-05.11
Summer	05.12-07.20
High summer	07.21-09.02
Autumn	09.03-10.27
Winter	10.28-03.30

Generally, the data of 746 substations in high summer and of 808 substations in winter are available. If broken down into single phases, the total valuable measurement data points in summer and winter are 11.7 million and 42.9 million respectively.

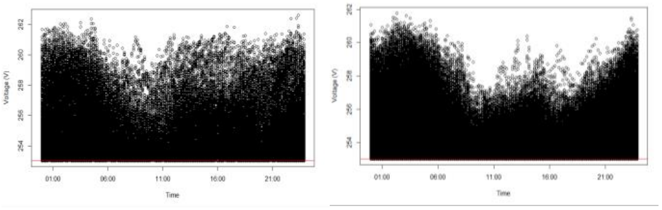
B. Over voltage Scenario (voltage>=253V)at substations

Table IV summarizes the overvoltage percentage among all the measurement. It can be seen that the total over upper limit points are similar in high summer and winter, with only 0.03% higher in high summer. But the lower percentage of substation number in high summer (5.36%) indicating the problems are concentrated on less number of substations.

Table IV OVER LIMIT SCENARIO PERCENTAGE

Season	Voltage point percentage	Substation percentage
High summer	0.74%	5.36%
Winter	0.71%	9.78%

Figure 3 shows the magnitude distribution of overvoltage over time in high summer and winter. In both seasons, the most over limit voltage magnitudes concentrate between 253V and 262V. It is evident that the overvoltage problems at substations are generally less serious during work time especially in morning and evening high demand period. But the high magnitude voltages appear more in high summer than in winter particularly during daytime. In high summer the “above 260V” scenario happens nearly the whole day, while in winter, the morning and evening high demand period obviously has less over upper limit cases, and the voltages between 8:00 and 22:00 are relatively low compared to summer scenario. The overvoltage profile is adverse to demand profile.



(a) (b)

Figure 3 Time distribution of voltage above 253V in high summer (a) and winter (b)

The voltage magnitude probability distributions for the seasons are shown in Figure 4. In both high summer and winter, the largest percentage of over upper limit voltage problem concentrates on the range of 253V-254V with probability of 0.4 and 0.55 respectively. The probabilities both decrease with the increasing of voltage magnitude. Whereas, the voltage in winter decreases more dramatically than in high summer, indicating the average over voltage magnitude in winter is smaller than that in high summer.

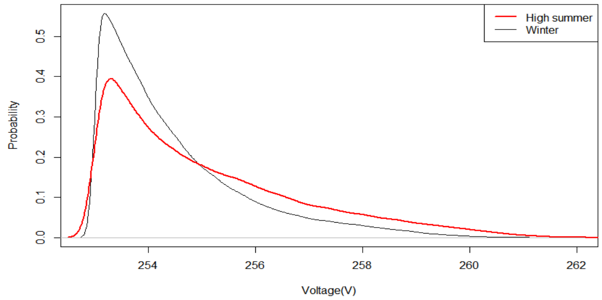
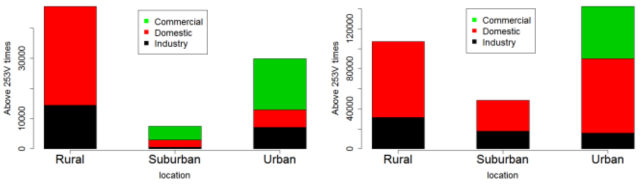


Figure 4 Probability distribution of over voltage in high summer and winter



(a) (b)

Figure 5 Location and customer mix of substation with voltage above 253V in high summer (a) and winter (b)

The locations and customer mix of substations are given in Figure 5. In both high summer and winter, there are more over limit voltage problems allocated in domestic dominant areas than commerical and industrial dominant areas. Additionally, rural and urban substations face more serious overvoltage problems.

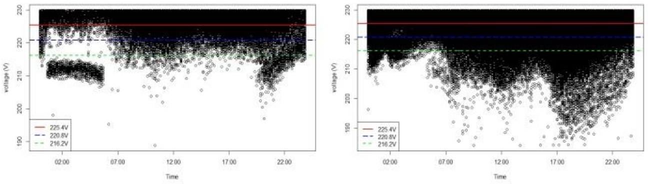
C. Low voltage Scenarioat remote feeder ends

The under-voltage problem at remote feeder ends is not as serious as the over limit problem. The voltage distributions lower than 230V is analyzed. There are less meareurement points below 230V in both seasons shown in table V. The lower remote feeder ends percentage in high summer may indicate the problems are concentrated on individual feeders.

Table V UNDER LIMIT SCENARIO PERCENTAGE

Season	**Voltage point percentage**	**Remote feeder ends percentage**
High summer	0.014%	1.04%
Winter	0.026%	4.87%

Figure 6 displays the magnitude of the low voltages and the appearance time, in each of which the red, blue and green lines represent 225.4V (-2%), 220.8V (-4%) and 216.2V (-6% the lower boundary of UK standard) respectively. In high summer, there are irregular under limit voltage distribution between 1:00-6:00am. The reason might comes from individual feeders that experience low voltage for a long time. It is visible that in winter most voltages below lower limit appear during peak load time. The voltage distribution shows that there are still lots of points falling into the range of 184V-200V and they could cause adverse impact to end customers, such as process disruption or shutdown of electronic and lighting equipment [8]. But, as there are quite few of them, only a few discrete points and not lasting long, their impact would not very significant though.



(a) (b)

Figure 6 Time distribution of voltage below 230V in high summer (a) and winter (b)

The probability distribution of voltage below 230V (Figure 7) gives direct description that a larger number of voltages stay in 220V-230V in both seasons. Additionally, there is a long tail in the low voltage situation –from 190V to 216V, which shows there are very few under limit voltage problems but occupying a wide range. The probability distribution of voltage below 216V (Figure 8) gives the detail of under limit voltage problems. The result shows that in both seasons, the problem mostly appears within the range of 210V-216V.

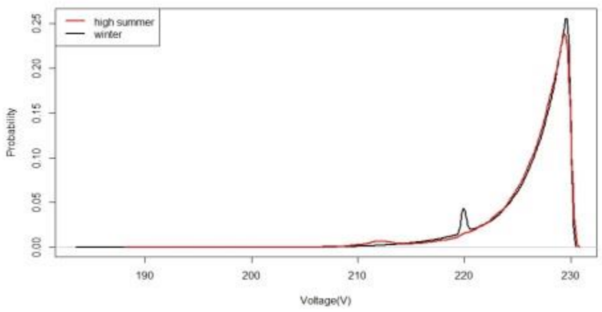


Figure 7 Probability distribution of voltage below 230V in high summer and winter

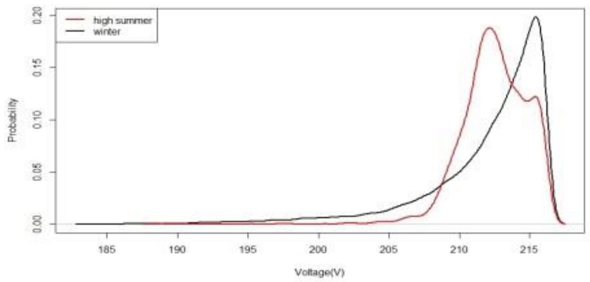
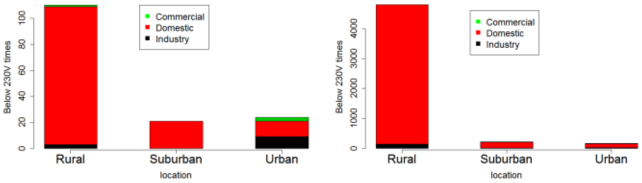


Figure 8 Probability distribution of voltage below 216V in high summer and winter

The low voltage situations in both high summer and winter are mostly distributed in rural area and domestic dominant substations, given in Figures 9. However, the total number of low voltage in substations is much less than the other cases. From the location of the low voltage case distribution, it should be concluded that there is very few low voltage problem on substations especially in urban areas.



(a) (b)

Figure 9 Location and customer mix of remote feeder ends with voltage below 230V in high summer (a) and winter (b)

V. APPLICATION DISCUSSION

The results from this research have important implications for DNOS to conduct voltage control and network investment. The overall voltage distribution shows that generally in widely LV networks, voltage magnitudes at customer ends are higher than nominal voltage 230V. The customer mix analysis indicates that some of the overvoltage problems happen in domestic dominated areas. In the long run, the high voltage will reduce the equipment life of end customer. Generally customer appliances can be classified into two types [14]: voltage independent, and voltage and time dependent. The voltage independent loads consume power with a limitation, such as kettle and hot water cylinder. On the other hand, voltage and time dependent loads consume power whenever they are turned on without limitations, such as lights and heating. They can be seen as resistance, for which, the power consumed is related to voltage. Based on the following formula in (1) and (2), if voltage increases 6%, the related power consumed will increase 12.36%.

$$U = IR \tag{1}$$

$$P = UI = U^2/R \tag{2}$$

As a result, the finding in this paper can guide DNOs to conduct appropriate control actions to manage voltages in order to reduce customer demand. Moreover, the findings provide strong evidence for a change in legislation to the EU 230V +/-10% voltage range. On the other hand, the under-voltage problems are negligible in the current networks. If the wholesale voltage drops by a carefully designed percentage, not only customers can receive a reduced energy bill, but also DNOs can achieve deferment in the network investment as the drop in peak power Additionally, white goods have, for many years, been manufactured to be compliant with the wider EU voltage limits in the UK.

Finally, considering the high voltage in substations and customer ends, the accommodation capability of LCTs can be further analyzed. The distributed generation, such as PVs, that would increase voltage should be properly handled, especially in high summer, since high summer voltage is generally higher than that in winter PV output is also higher. EVs consume energy during charging period and provide energy to the grid by discharging the battery. Charging is more suitable overnight in all areas because it will help to mitigate high percentage of over voltage. Discharging can support part of the local load and therefore can increase voltage, which is beneficial for network operation during peak time when voltage is low. Heat pumps (HPs) can be regarded as normal load to the network.

VI. CONCLUSION

This paper reports the key findings in voltage aspects of a smart grid demonstration project –'Low Voltage Network Templates'. By analyzing the large number of real-time voltage data, network pressures for widely LV system, magnitude problem in high summer and winter of different topographic areas and customer mix are investigated. This work can significantly increase LV network voltage visibility, which is not properly monitored currently. The results in this paper can be used as guide for network operation and voltage control, evidence for policy modification, and reference to LCTs accommodation and investment of other cost-effective planning as well. The implications of the findings will help to increase supply power quality, low carbon technology integration and cost savings for both customers and DNOs.

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