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DOI:

[10.1109/ISGTEurope.2013.6695466](https://doi.org/10.1109/ISGTEurope.2013.6695466)

[Link to publication record in Manchester Research Explorer](#)

Citation for published version (APA):

Lamberti, F., Dong, C., Calderaro, V., & Ochoa, L. F. (2013). Estimating the load response to voltage changes at UK primary substations. In *2013 4th IEEE/PES Innovative Smart Grid Technologies Europe, ISGT Europe 2013|IEEE/PES Innovative Smart Grid Technol. Europe, ISGT Europe*
<https://doi.org/10.1109/ISGTEurope.2013.6695466>

Published in:

2013 4th IEEE/PES Innovative Smart Grid Technologies Europe, ISGT Europe 2013|IEEE/PES Innovative Smart Grid Technol. Europe, ISGT Europe

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Estimating the Load Response to Voltage Changes at UK Primary Substations

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Abstract— The development of Smart Grid technologies and the need to defer investments for expanding and reinforcing distribution networks have attracted new attention to aspects of Conservation Voltage Reduction (CVR). Based on the fact that the demand of certain loads can change with voltage, it is plausible to envisage the active management of voltage regulation devices in order to increase/decrease the demand during certain periods for the benefit of the distribution network (e.g., peak shaving) or the whole system (e.g., fast reserves). The extent of this voltage-driven demand response is however entirely dependent on the instantaneous load composition. In order to quantify the benefits of such a scheme, this work proposes a methodology to estimate the time-varying residential load response to primary substation voltage changes whilst complying with voltage limits at low voltage. This is applied to a small UK distribution network downstream an OLTC-enabled 33kV/6.6kV substation with 351 residential, 2 commercial and 1 industrial customers (total peak demand of 932 kW). The results, only considering part of the residential loads modeled with time-varying ZIP parameters, suggest that – even considering voltage constraints– there is considerable load response that can be unlocked from residential loads. However, this is highly dependent on the time of the day.

Index Terms—active load management, CVR, demand response, ZIP model, voltage management, voltage regulation, smart grids

I. INTRODUCTION

One of the aspects of the transition towards Smart Grids is the ability to manage demand, particularly given the continuous need to defer investments for expanding and reinforcing distribution networks. This is mostly seen from the perspective of the infrastructure needed to integrate participants in demand response schemes (typically involving an economic incentive). However, the advent of advanced capabilities to manage voltages at different distribution levels has attracted new attention to aspects of Conservation Voltage Reduction (CVR).

CVR is based on the simple principle that (certain) loads change with voltage, therefore a reduction in voltage can lead to savings in energy consumption (to customers). This

technique has been performed to different extents since the '70s [1]. Initially, the method did not have much adoption mainly because it was difficult to deploy it over a wide area without causing problems to the network and loads (due to voltage drops below statutory limits). Nevertheless, recent studies on voltage optimization and volt-var control, have drawn more attention on CVR [2-4] given that they could, in the future, allow controlling voltages accordingly.

From the perspective of a distribution network operator (DNOs) subject to unbundling rules (such as in Europe), it is therefore plausible to envisage the active management of voltage regulation devices in order to increase/decrease the demand during certain periods for the benefit of the network (e.g., peak shaving, congestion management) or the whole system (e.g., fast reserves). The extent to which this voltage-driven demand response can actually help in managing the network is however entirely dependent on the instantaneous load composition – that might have small changes minute by minute but is significantly different from day to night and from season to season.

On the other hand, the boundaries to which voltage changes can be applied will also depend on how load changes and the corresponding final voltages downstream, particularly for low voltage-connected consumers. Such final voltages should remain within statutory limits and be compliant with standards such as the BS EN50160 [5].

In order to assess the feasibility of the above scheme, this work first estimates the domestic load response to voltage changes whilst complying with voltage limits at low voltage. This is carried out on a UK HV-LV distribution network in the North West of England with 351 residential, 2 commercial and 1 industrial customers, and with a total peak demand of 932 kW. Focus has been given to residential loads of which certain appliances have been modeled aggregating the corresponding ZIP parameters for each customer. This, combined with the corresponding load profiles, allowed the creation of time-varying ZIP models per residential customer.

Section II contains the analysis of the load profiles and load models, including the time-varying ZIP model. This is implemented on a UK HV-LV distribution network, as described in Section III. Results for 24-hour time-series simulations are the presented highlighting the load response due to the voltage changes on the primary substation. Conclusions are drawn in Section IV.

II. METHODOLOGY

Primary substations in the UK are those typically transforming 33kV to 11kV or 6.6kV. Automatic voltage control systems are used to regulate the voltage target on the secondary using the on load tap changer. These substations are in essence the last elements with controllable voltage capabilities in UK distribution networks. Consequently, they are the most desirable points to assess the effect of voltage changes on (aggregated) load demand.

To model the effects of voltage changes on loads the well-known ZIP model [6] was used to take into account the corresponding relationship. In particular, the analysis carried out here takes into account the profiles of individual appliances for each house. To reduce the complexity of such a detailed model, time-varying (i.e., changing minute by minute) aggregated ZIP parameters are produced per household. This is explained in the following subsections.

A. Load Profiles

In order to achieve a time-series simulation the profiles of industrial and commercial customers are obtained through a historic, aggregated half-hourly yearly load profiles (produced by Elexon [7]).

The profiles of the residential customers are produced using a high-resolution (e.g., minute by minute) model developed by CREST (Centre for Renewable Energy Systems Technology) [8] at Loughborough University. In addition, UK National Statistics were adopted to determine the occupancy of households (29% with 1, 35% with 2, 16% with 3 and 20% with 4 people) [9]. A typical daily profile of a UK residential customer (4 people) for a weekday in December is shown in Fig. 1.

B. ZIP Model

The traditional ZIP model is the sum of three time-invariant terms: constant impedance, constant power and constant current [6]. The active and reactive power consumption in the polynomial formulation is given by (1) and (2). Eq. (3) is a normalized constraint for (1) and (2) that forces the load to consume rated power at rated voltage.

$$P_{load} = P_{nom} * \left(Z_{act} \frac{V^2}{V_0^2} + I_{act} \frac{V}{V_0} + P_{act} \right), \quad (1)$$

$$Q_{load} = Q_{nom} \left(Z_{react} \frac{V^2}{V_0^2} + I_{react} \frac{V}{V_0} + P_{react} \right), \quad (2)$$

$$1 = Z_{act} + I_{act} + P_{act}, \quad (3)$$

$$1 = Z_{react} + I_{react} + P_{react} \quad (4)$$

where P_{load} and Q_{load} are the active and reactive power consumption of the load; P_{nom} and Q_{nom} are the active and

reactive power consumption at nominal voltage; V is the actual terminal voltage; V_0 is the nominal terminal voltage (230 V); Z_{act} , I_{act} , and P_{act} are the active power constant impedance, current, and power parameters, respectively; and, Z_{react} , I_{react} and P_{react} are the reactive power constant impedance, current, and power parameters, respectively.

The parameters considered in this work are shown in Table 1. Column % indicates the percentage of users with a similar residential load according to UK National Statistics [10].

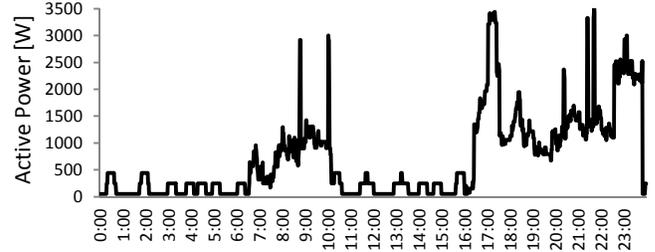


Figure 1. Typical 4-person residential profile (December, weekday).

TABLE 1. ZIP PARAMETERS (230 V) [11],[12]

Name	Appliance Data			Zip Parameters					
	S0 (VA)	pf	%	Active Power			Reactive Power		
				Z%	I%	P%	Z%	I%	P%
Tv(Crt)	150	0.99	0.48	0.00	1.24	-0.24	0.00	0.00	-1.00
Tv(Plasma)	470	0.99	0.50	-0.27	0.44	0.83	-1.95	2.32	-1.37
Dishwasher	1500	0.80	0.34	0.10	0.10	0.80	1.54	-1.43	0.89
Oven	2500	1.00	0.62	1.00	0.00	0.00	0.00	0.00	0.00
Kettle	2000	1.00	0.98	1.00	0.00	0.00	0.00	0.00	0.00
Wash.Machine	1065	0.61	0.93	0.06	0.31	0.63	-0.56	2.20	-0.64
Fridge	225	0.84	0.99	1.19	-0.26	0.07	0.59	0.65	-0.24
PC	150	1.00	0.77	0.00	0.00	1.00	0.00	0.00	0.00
Microwave	1300	1.00	0.85	-2.78	6.06	-2.28	0.00	0.00	0.00
Hob	2500	1.00	0.46	1.00	0.00	0.00	0.00	0.00	0.00
Heater	1500	1.00	0.50	1.00	0.00	0.00	0.00	0.00	0.00
Light Bulb	70	1.00	1.00	0.57	0.43	0.00	0.00	0.00	0.00

C. Time-varying ZIP Model

In order to reduce the number of loads to be modeled (i.e., each appliance per household), a polynomial formulation was developed to aggregate the ZIP parameters at a given instant for each residential customer connected to the LV network.

Considering that the active and reactive power for a customer is equal to the sum of the active and reactive power of all appliances connected at a given instant, then it is possible to derive a mathematical formulation of the aggregated ZIP parameters.

Equations (5)-(10) extend the polynomial formulation of the traditional ZIP parameters (1)-(4), for multiple appliances. P_{tot} and Q_{tot} are the total active and reactive power of the customer taking into account the actual voltage at the connection point. Furthermore, P_0 and Q_0 are the amount of active and reactive power of the same customer considering nominal voltage. They are obtained by adding the nominal active and reactive power of each appliance, P_{nom_i} and Q_{nom_i} .

In order to achieve the same formulation of (1) and (2) for (5) and (6) the aggregated ZIP parameters can be expressed as in (11) and (12), where the upper extreme of the summation N_{load} is the number of the appliances modelled through the

ZIP, and Z_{act_i} , I_{act_i} , P_{act_i} , Z_{react_i} , I_{react_i} and P_{react_i} are the ZIP parameters of the i^{th} appliance with V_i terminal voltage.

$$P_{tot} = P_0 \left(Z_{act_{tot}} \frac{V_i^2}{V_0^2} + I_{act_{tot}} \frac{V_i}{V_0} + P_{act_{tot}} \right), \quad (5)$$

$$Q_{tot} = Q_0 \left(Z_{react_{tot}} \frac{V_i^2}{V_0^2} + I_{react_{tot}} \frac{V_i}{V_0} + P_{react_{tot}} \right), \quad (6)$$

$$P_0 = \sum_{i=1}^{N_{load}} P_{nom_i}, \quad (7)$$

$$Q_0 = \sum_{i=1}^{N_{load}} Q_{nom_i}, \quad (8)$$

$$1 = Z_{act_{tot}} + I_{act_{tot}} + P_{act_{tot}}, \quad (9)$$

$$1 = Z_{react_{tot}} + I_{react_{tot}} + P_{react_{tot}}, \quad (10)$$

$$\begin{cases} Z_{act_{tot}} = \frac{\sum_{i=1}^{N_{load}} (P_{0_i} Z_{act_i})}{P_0} \\ I_{act_{tot}} = \frac{\sum_{i=1}^{N_{load}} (P_{0_i} I_{act_i})}{P_0} \\ P_{act_{tot}} = \frac{\sum_{i=1}^{N_{load}} (P_{0_i} P_{act_i})}{P_0} \end{cases}, \quad (11)$$

$$\begin{cases} Z_{react_{tot}} = \frac{\sum_{i=1}^{N_{load}} (Q_{0_i} Z_{react_i})}{Q_0} \\ I_{react_{tot}} = \frac{\sum_{i=1}^{N_{load}} (Q_{0_i} I_{react_i})}{Q_0} \\ P_{react_{tot}} = \frac{\sum_{i=1}^{N_{load}} (Q_{0_i} P_{react_i})}{Q_0} \end{cases}. \quad (12)$$

With the above procedure to create time-varying ZIP models it is possible to model a customer with 10 appliances with only 6 parameters instead of 60. This reduces considerably the management of data.

III. CASE STUDY

A. HV-LV Network

The studied UK HV-LV distribution network is operated by Electricity North West Limited and is located in the North West of England. The single-line diagram is shown in Fig. 2. There are four feeders connected to the busbar of the on-load tap changer-enabled primary substation (33kV/6.6kV). The topological diagram of the Landgate LV network is presented in Fig. 3. It has six radial feeders and supplies power to 351 residential loads. The corresponding off-load tap changer transformer (blue dot in Fig. 3) is set to have a 5.75% boost (i.e., 6.6kV/423V).

The minute by minute profiles for the commercial and industrial customers are produced using the historical aggregated Elexon half-hourly profiles [7] combined with recorded maximum values. Fig. 4 shows the estimated profiles

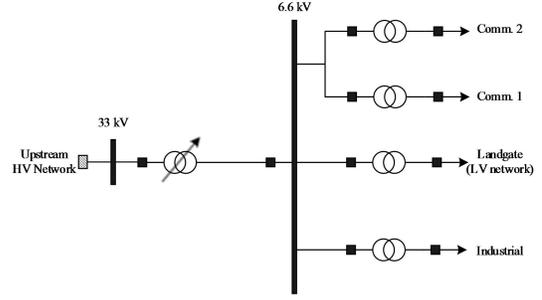


Figure 2. Diagram of the HV network.

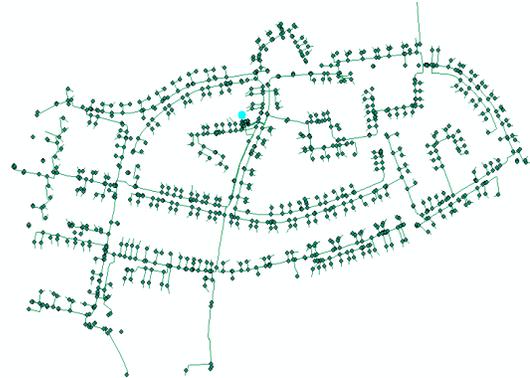


Figure 3. Diagram of Landgate LV network.

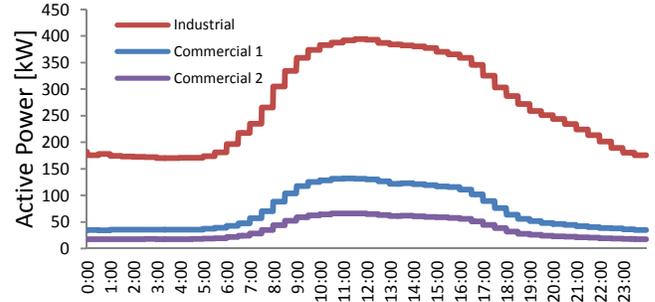


Figure 4. Commercial and Industrial Profiles (19 December 2011).

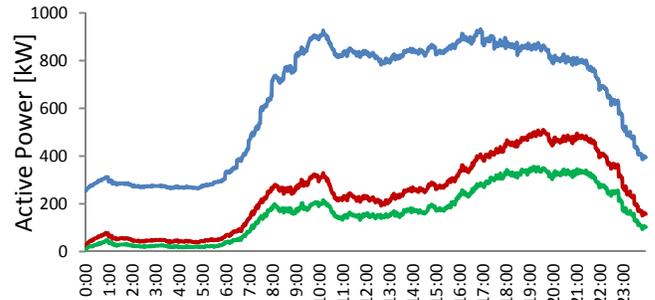


Figure 5. Aggregated active power of the network (blue), aggregated residential demand (red), and aggregated residential demand modeled with ZIP parameters (green).

for 19 December 2011 (with a peak demand of 394 kW for the industrial load and respectively 132 kW and 66 kW for the commercial loads and a power factor of 0.96). On this same day, the peak demand of the residential loads is approximately 500 kW. This particular day will be used in the simulations. OpenDSS [13] and Matlab were used in this study to

implement the time-varying ZIP parameters and assess the corresponding impacts when changes in voltages are made.

Based on the ZIP parameters available in the literature (see Table 1), it was possible to model approximately 70% of the residential (active power) peak demand. This represents to around 40% of the whole peak demand (as shown in Fig. 5) and will be the only part of the load that will respond to changes in voltages.

B. Boundaries for Voltage Changes at the Primary Sub

The voltage target for the secondary of the primary substation was changed (0.01 p.u. steps) in order to assess how the ZIP-modeled load responds and to quantify the final voltages for residential customers. The standard BS EN50160 [5] was adopted to determine whether voltage excursions happened. This standard (adapted for UK LV networks) states that the 10 minute rms phase to neutral voltages should not exceed 10% of nominal (230V). In addition, 95% of measurements should not be below 6% of nominal and never below 15% of nominal. Although the standard considers a week, here it will be used for a day.

The results from the simulations showed that the minimum and maximum feasible voltage targets at the primary substation are 0.97 and 1.02 p.u., respectively. Values outside these limits could result in voltage issues to customers and non-compliance with BS EN50160. The corresponding results for three voltage targets (1.02, 1.00 and 0.97 p.u.) are presented in Fig. 6. It is important to highlight that although voltage targets of 1.03 and 0.96 p.u. did result in a limited number of excursions (around the 2% of the daily), a more conservative range was adopted given that the simulations were limited to a day only.

C. Load Response to Voltage Changes

In Fig. 7 it is shown the period during the studied day with the largest load responses (in kW) to voltage changes. This period corresponds to 6pm to 7pm (peak load). In this case, the almost equal power differences between consecutive voltage targets suggest a (close to) linear relationship between load response and voltage change. Indeed, after calculating the coefficient of determination (R^2) for different instants, around 99% showed a linear behavior. This, of course, is related to the mix of loads present in the corresponding instant. Consequently, although this relationship is predominant, this cannot be generalized.

The period with the smallest load responses to voltage target changes at the primary substation is presented in Fig. 8. This period corresponds to 4am to 5am (minimum load). Also in this case, the results suggest a relationship of load response and voltage changes close to linear.

Considering that typically primary substations in the UK have target voltages above nominal, it can be said that the maximum feasible change in the target voltage for this network is 5%, i.e., from 1.02 to 0.97 p.u. The total load response (both active and complex power) throughout the day

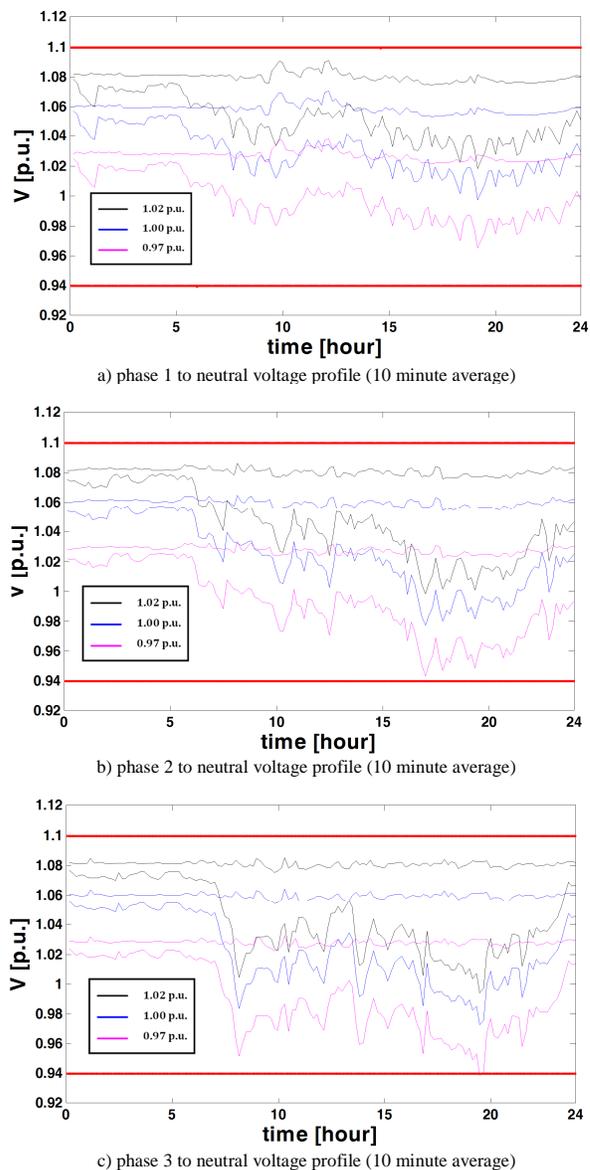


Figure 6. Maximum and minimum voltages found in the LV network for different voltage targets at the primary substation.

or such a change in the voltage target at the primary substation is shown in Fig. 9.

The average (active power) load response throughout the day compared to the total load of the network is 1.75% with a maximum of 3.24%, as summarized in Table 2. However, if the average response is compared to the total residential load, this figure goes up to 4.65%. More interesting is the percentage compared to the part of the residential load modeled with the ZIP parameters, with an average of 8.01%. This highlights the importance in adequately modeling most of the load with ZIP parameters to truly quantify the potential effects. During the peak load alone (at 4.56pm), the corresponding figures were 2.22, 4.78 and 7.30%, respectively. The complex power showed a similar trend.

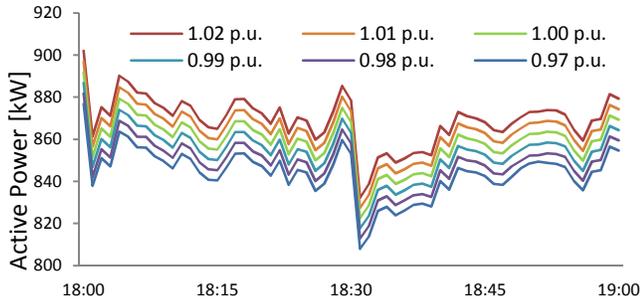


Figure 7. Period with largest load responses to voltage changes.

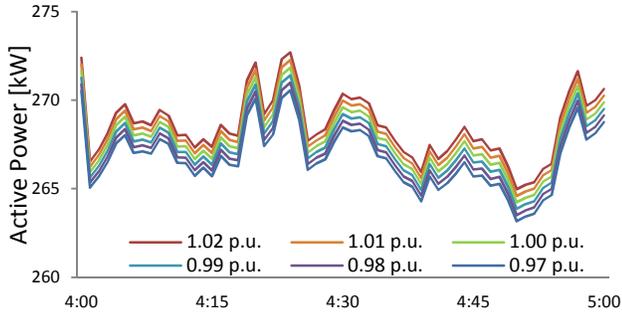


Figure 8. Period with smallest load responses to voltage changes.

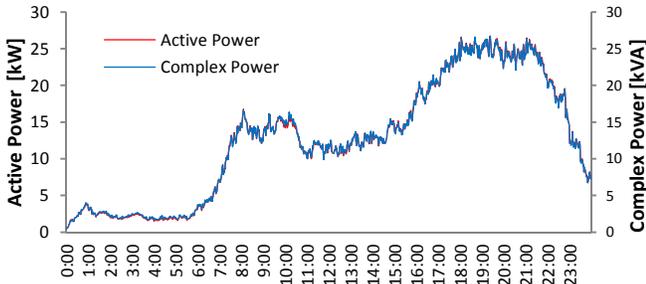


Figure 9. Total load response (active and complex power) for a voltage target change from 1.02 to 0.97 p.u.

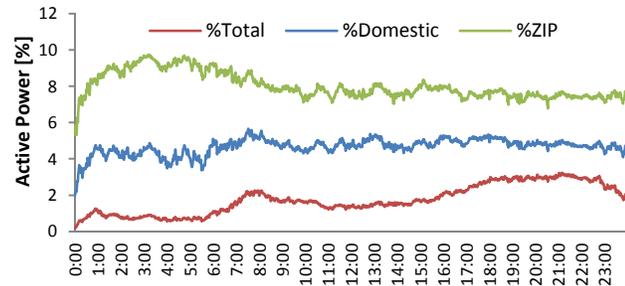


Figure 10. Percentage of active power response during the day compared to different aggregated loads.

TABLE 2. LOAD RESPONSE SUMMARY

Values	%Total	%Residential	%ZIP
Minimum (daily)	0.17	1.96	5.31
Maximum (daily)	3.24	5.66	9.73
Average (daily)	1.75	4.65	8.01
Average (6-7pm)	2.88	5.06	7.62
Average (4-5am)	0.67	4.07	9.37

IV. CONCLUSIONS

The quantification of load response to voltage changes in distribution networks is important in the context of

Conservation Voltage Reduction but also due to the potential usages of such a controllable resource if aggregated (e.g., congestion management or provision of reserves).

Here, a methodology was presented by which around 70% of the peak residential load in a small UK HV-LV network (peak of 932kW) was modelled with time-varying ZIP parameters based on the corresponding appliances used by ‘synthetic’ households (351, peak of 500kW). This detailed modelling first allowed determining the feasible ranges of voltage targets (considering BS EN50160) that could be applied to the corresponding OLTC-enabled primary substation (33kV/6.6kV). Then, it was possible to quantify the load responses to voltage changes.

The results suggest that –even considering voltage constraints– there is considerable load response that can be unlocked from residential loads. However, this is highly dependent on the time of the day. For this particular case study, the active power reductions also presented a linear behavior respect to voltage change. This is likely to be the influence of modeled appliances and their ZIP models.

V. ACKNOWLEDGMENT

The authors would like to thank the support of Electricity of North West Limited (ENWL) for the funding and making available the network data. Also to the Centre for Renewable Energy Systems Technology at Loughborough University, UK, for making available the CREST tool.

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