THE APPLICATION OF CONSERVATION VOLTAGE REDUCTION (CVR) TO DISTRIBUTION NETWORKS WITH HIGH UPTAKE OF HEAT PUMPS AND ELECTRIC VEHICLES

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ABSTRACT

Demand on future distribution networks is forecast to increase due to the electrification of heat and transport. Conservation Voltage Reduction (CVR) will be a powerful technique in the network planner's toolbox that can be applied to release capacity and defer reinforcement. The potential benefits of CVR were assessed for a representative UK LV distribution network in 2020 and 2030. The voltage dependency of domestic loads, heat pumps and electric vehicles was explicitly modelled. Results from network modelling of domestic load voltage dependency were validated against recent network trials.

Our findings indicate that material reductions in peak demand are achievable through the application of CVR for future distribution networks with a high uptake of heat pumps and electric vehicles. This will enable capacity release and defer network reinforcement investment.

INTRODUCTION

Conservation voltage reduction (CVR) has been used with success particularly in the US to reduce peak demand load and energy costs to the consumer. CVR can be implemented via a number of technologies and techniques to reduce the voltage on feeders in the HV and LV networks. The magnitude of voltage reduction is such that the end-user should not notice any change in quality of supply.

Wang and Wang recently carried out a comprehensive review on implementing and assessing CVR [1]. This summarised the results of a number of network trials indicating the benefits of CVR as well as some of the technical challenges. ESB also found that early stage results were positive for the application of CVR at several Irish distribution network trial sites [2].

The reduction in demand load and energy is dependent on the types of loads connected. CVR is effective on constant impedance or constant current loads where a reduction in voltage leads to a reduction in power. In addition, losses will be reduced for constant impedance loads due to reduced current. However, CVR on voltage dependent (constant power) loads will lead to increased losses and thus higher load. Also, for constant impedance resistive loads such as space heaters, reduced voltage may reduce the current however the same amount of energy is required so there are no energy efficiency savings for the consumer.

CVR can be implemented on the LV network through various means such as tap change of the HV/LV transformer, or capacitors or STATCOMs located along LV feeders. The benefits of CVR specifically for peak load reduction are represented by a ratio that is the percentage reduction in demand per percentage reduction in voltage.

$$CVR = \%\Delta D / \%\Delta V$$

Where D can be defined as active or apparent power.

UK distribution networks will need to adapt in order to integrate the future forecast high uptake of heat pumps and EVs as heat and transport are decarbonised. Uptake of low carbon technologies (LCTs) across the UK including embedded Photo-Voltaics (PV), Electric Vehicles (EVs) and Heat Pumps (HPs), has been forecast through work commissioned by the UK electricity and gas regulator Ofgem and the Department for Energy and Climate Change (DECC). These uptake figures have been utilised by UK Distribution Network Operators (DNOs) to forecast expected load (demand and generation) related network reinforcement investment requirements for the next regulatory period [3]. Investment requirements for distribution networks will be material in order to avoid constraining uptake of LCTs. CVR could be a powerful technique in the distribution network planner's 'toolbox' to release capacity of constrained networks and to enable reinforcement investment to be deferred. However, the success of CVR will be influenced by the voltage dependency of the LCT demand loads connecting to the network in increasing numbers.

Electricity North West are a leader in the development and trial of innovative technologies, commercial arrangements and operational techniques to respond efficiently to future uptake of LCTs. This is demonstrated through Electricity North West's success in obtaining competitive funding under the Low Carbon Networks (LCN) Fund administered by Ofgem and successful delivery of these projects.

Electricity North West's Second Tier LCN Fund CLASS (Customer Load Active System Services) project aims to demonstrate a low cost, rapidly deployable solution that applies innovative and active voltage management using automated substation controllers on primary transformers. This should provide a range of demand response capabilities and network voltage regulation services, releasing capacity.

Electricity North West's Second Tier LCN Fund Smart Street (formerly *eta*) project will apply voltage regulation equipment (i.e. on-load tap changing transformers and capacitors) to HV and LV networks to manage the voltage profile along the circuits and operate these networks in differing configurations (i.e. radial and meshed); and through the application of real-time network configurations and voltage optimisation deliver a reduction in network losses and customers' energy consumption. This will release capacity headroom on the network and enable deferment of reinforcement investment.

In this study, we aim to demonstrate and quantify the potential benefits of CVR to reduce peak demand (and losses) for both current network load characteristics as well as for future distribution networks with an increased uptake of HPs and EVs. This will contribute to the learning from CLASS and Smart Street. As monitored network data becomes available from voltage reduction trials associated with these projects, further model development and validation will be possible.

CVR is realised through a reduction in voltage at the HV/LV substation transformer for the purposes of this study. This would be achieved through a change to the tap settings of the HV/LV transformer. In the Smart Street project the voltage will be altered both at the secondary substation and along the feeder.

NETWORK MODEL

A power systems model of the Dunton Green LV network located in the Electricity North West licence area was built in IPSA power systems modelling software [4].

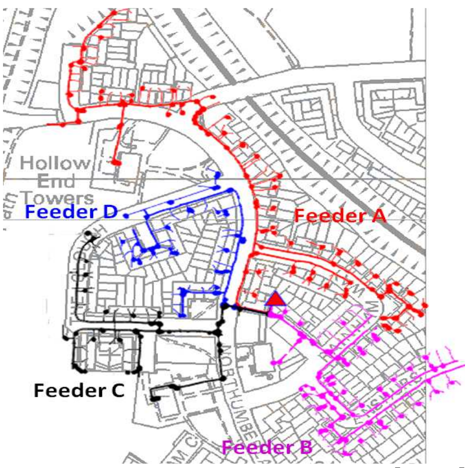

Figure 1 – Dunton Green LV network model

This area contains 180 customers and primarily comprises of quasi-semi-detached social housing supplied by four LV feeders. Based on studies which formed part of Electricity North West's Second Tier LCN Fund Smart Street bid, this network is representative of suburban networks in the UK, which are expected to have a relatively high uptake of HPs and EVs.

Domestic Load

An After Diversity Maximum Demand (ADMD) load of 1.25kW based on 245V at the secondary substation LV terminals was applied to all domestic properties. This is based on Electricity North West's experience of similar LV feeders. The makeup of domestic loads was based on the Household Electricity Survey findings [5]. Underlying load growth was assumed to be negligible thus the ADMD represents the proportions of the base load for 2020 and 2030. The addition of HPs and EVs represents load growth.

The Household Electricity Survey results are for domestic properties with gas heating so uptake of HPs representing additional load on the LV network is a reasonable assumption.

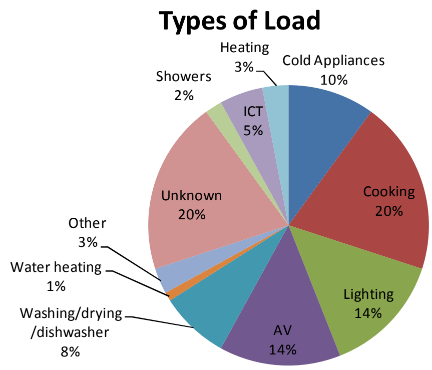

Figure 2 – Breakdown of domestic loads at peak demand (6-7pm) reproduced from [5]

Voltage Dependency Models

Domestic Loads

The voltage dependency of some of the different domestic loads shown in Figure 2 is provided in Table 1. These were aligned with the type and proportion of domestic load at peak demand to develop a domestic load voltage dependency ZIP model for each category in Figure 2. A ZIP load model is a polynomial model for real and reactive power which is voltage dependent. It models a load as a combination of constant impedance, constant current and constant power. Categories with similar load properties were lumped into one ZIP model. For unknown loads and /or small loads of unknown characteristics, constant power loads were assumed. This represents 31% of the domestic load and mostly comprised of the 20% 'unknown' loads shown in Figure 2.

Table 1 – Voltage dependency of some typical domestic loads [6]

Appliance	*Apparent Power at 230V (VA)*	*Apparent Power at 220V (VA)*	*Apparent Power at 210V (VA)*
Dell LCD	49.71	49.33	48.95
Dell CRT	80.09	79.38	78.67
Acer Laptop	92.23	92.28	91.34
Microwave Oven	1285	1227	1162
CFL Bulb 7W	5.81	5.48	5.16
Incandescent Bulb 60W	52.77	49.43	45.94
Halogen 42W	39.51	36.97	34.42
Kettle	1953	1791	1636
Vacuum Cleaner	713.6	653.6	598.4
Fridge	146.4	133.8	121.4

The domestic load applied in the network model consists of a constant load component of 31% of load (no voltage dependency) and ZIP models for the loads which have constant impedance or constant current components.

Heat Pumps
Heat pumps were assumed to be constant power loads of 1.6kW based on Electricity North West's RIIO - ED1 WJBP submission with a 0.95 power factor [7].

Electric Vehicles
EV chargers were assumed to be voltage dependent loads and were represented in the network model with a ZIP model. Based on the analysis of four types of EV, a generic EV charger model cannot be easily made [8]. Three of the four EV types investigated had a linear relationship between power and voltage. Therefore, based on the findings of independent studies, the characteristics of EV charger model type 3 was used to represent the range of EV chargers in the CVR studies. The EV charger model has a linear relationship between voltage and power and has a slightly inductive power factor. The power consumption was scaled to 1.2kW and 0.95kW (from 1.528kW) to represent the peak demand for fast and slow EV chargers. The same characteristic was assumed for both charging types for the purposes of this study.

Future HP and EV Uptake
Future HP and EV uptake is based on Electricity North West's 'best view' LCT scenario from Electricity North West's business plans to be presented to Ofgem for the upcoming regulatory period. The percentage increase in HPs and EVs between 2014 to 2020 and 2020 to 2030 was calculated for the ENW licence area and then applied to the Dunton Green LV network. Based on the percentage increase of uptake, an integer number of HP and EV installations was applied to the network. The percentage uptake was based on a an estimate of 50% penetration (90 households) of HPs, 50% penetration (90 households) of fast charging EVs in 2030 and approximately 25% penetration (43 households) of slow charging EVs in 2020. The uptake of HPs and EV was evenly distributed throughout the Dunton Green network.

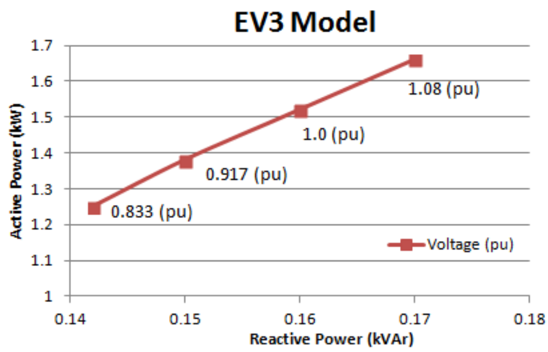

Figure 3 – Voltage dependency of EV model type 3 [8]

Sensitivity
The sensitivity of CVR to HPs and EVs was analysed separately by modelling the network for HP and EV uptake in 2030.

Clustering
Clustering of HPs was investigated by observing the CVR in 2030 when there is 100% uptake of HPs on a single feeder and distributed uptake on the remaining three feeders. This could be the result of a social housing initiative. This represented a 65% penetration (117 households) of HPs at Dunton Green.

Phase unbalance has not been assessed in this study although it is recognised that this would influence the aggregated benefits of CVR at the HV/LV transformer.

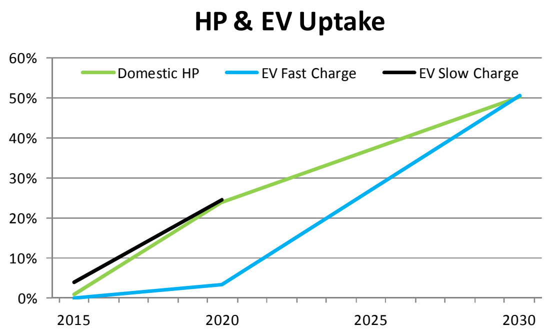

Figure 4 – Future percentage uptake of HP and EV on Dunton Green LV network
(Note that by 2030 slow charge EVs have been replaced by fast charge only EVs)

RESULTS

Base Model
The base model considers the potential CVR benefits of domestic loads prior to uptake of HPs and EVs. Results for the base model CVR were compared with recent network trial data for the purposes of validating the model. For direct comparison to ESB trials the results for our study assess the CVR associated with the active

power, CVRp.

The single phase voltage on the LV side of the MV/LV transformer was assumed to be 245V based on typical Electricity North West running arrangements and network characteristics. This was reduced to explore CVR benefits.

Table 2 – Comparison of CVR for base model with domestic load voltage dependency

Voltage Reduction at MV/LV Tx	CVRp
250V to 245V	0.764
245V to 230V	0.740
230V to 220V	0.740

This gives an average CVR ratio (based on active power) of 0.75 due to decreased power consumption of some domestic loads as voltage decreases. This is comparable to CVR ratios observed in other independent studies such as the ESB field trials for urban and rural networks. CVR ratios observed in these studies are shown in Table 3. This is based on a 2.5% to 3% voltage reduction (230V to 223V) at the sending voltage from the substation.

Table 3 – ESBN Field Trial Results [2]

Network	CVRp
Waterville (rural)	0.58
Sneem (rural)	0.83
Sallynoggin (urban)	0.98

Feeder Voltage

From the studies undertaken, the minimum voltage at the transformer was determined before the voltage drops below statutory limits at the end of the LV feeders (statutory lower limit = 216V or 0.94pu). Figure 5 compares the voltage on feeder A (most heavily loaded) for the base case at different supply voltages. It can be seen that at 220V, the voltage falls below statutory limits relatively close to the supply point.

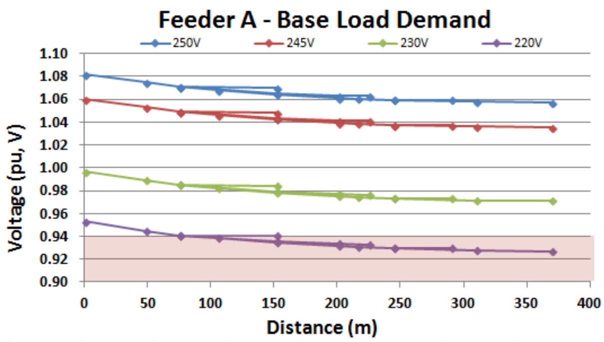

Figure 5 – Voltage along Feeder A (Base Case)

2020/2030 Models

The future models included both domestic loads as well as loads due to the uptake of HPs and EVs. The effect of uptake of HPs and EVs on CVR benefits was decoupled to explore the sensitivity of individuals LCT types. The combined effect of HPs and EVs was also analysed. The results are tabulated below for a voltage reduction from 245V to 230V.

Table 4 – Estimated benefits of CVR for future HP and EV uptake (245V to 230V)

Scenario	CVR
Base Load	0.745
2030 Model (HP Only)	0.415
2030 Model (HP Only with clustering)	0.358
2030 Model (EV Only)	0.834
2020 Model (EV + HP)	0.614
2030 Model (EV + HP)	0.536

Results indicate that whilst there is a reduction in CVR with the uptake of HPs, which are modelled as a constant power load with no voltage dependency, there are still benefits to be gained from application of CVR. Due to the linear voltage dependency of the EV type modelled, EVs contribute to the load reduction with application of CVR.

The two LCTs produce opposite trends for the CVR ratio, with CVR for uptake of both HPs and EVs slightly lower than with baseload. A material reduction in load is still achieved (3.2%) on the Dunton Green network by reducing the voltage from 245V to 230V at the substation.

Figure 6 demonstrates the potential benefits of CVR under a range of future LCT uptake scenarios for varying voltage reductions at the supply point.

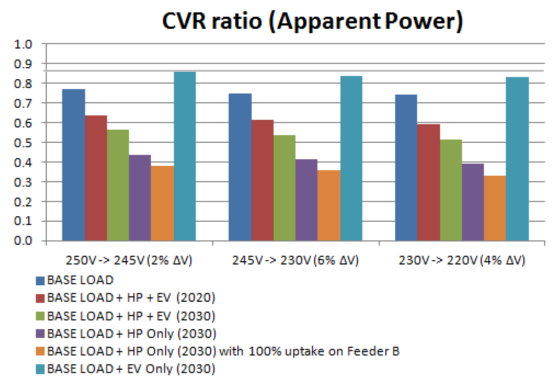

Figure 6 – CVR ratio for a range of LCT scenarios

Feeder Voltage

Compared to the base case, once HP and EV uptake is considered, the voltage at the secondary substation can only be reduced to 230V before voltage drop below statutory limits is observed in 2030. This is shown in Figure 6.

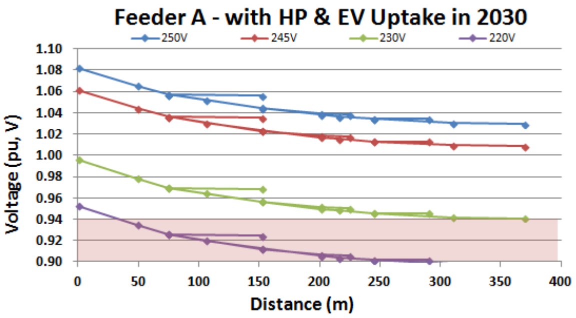

Figure 7 – Voltage along Feeder A (2030)

CONCLUSIONS

Early research and field trials undertaken in the US and Ireland have indicated CVR techniques have successfully resulted in energy savings. In the future load will increase due to LCTs such as HPs and EVs which are voltage dependent loads. This paper investigates the effect this voltage dependent load growth may have on CVR benefits in the future and implications for peak demand.

By 2030 with an uptake of 50% of both EVs and HPs in the network under study, a reduction of load of 3.2% was seen for a 6% voltage reduction. This is a material reduction of power during peak times and can be used as a tool by network operators. It can help reduce the strain on the network during peak load periods by managing load profiles and therefore defer network reinforcement.

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