Customer-Led Network Revolution

CLNR Trial Analysis

Capacitor Bank Autonomous and Single + GUS Voltage Control

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Executive Summary

The work detailed in this document is conducted using the IPSA2 models of Denwick network to evaluate the capability of Hedgeley Moor Mechanically Switched Capacitor Bank in accommodating LCT following the deployment of GUS. This has been achieved using validated network models and a combination of real load and generation data from the Customer Led Network Revolution (CLNR) Project.

Steady-state IPSA2 models have been previously developed and validated using SCADA data. The network model (Denwick_8Feeders_Model_v2.3.6b - all in.i2f) is used for this study. The operation of the GUS system has been previously validated using results from trials of the operation of GUS with HV/LV transformers. Due to the timing during the year of the CLNR trials the data from the closed loop GUS voltage control trial did not provide data that enables validation of the GUS model in collaboration with the capacitor bank. The GUS system interacts with the capacitor bank in CLNR in an identical manner, i.e. the GUS system issues a target voltage setpoint to the AVC (Automatic Voltage Control) relay and therefore operation of GUS system with the HV/LV transformers has broad applicability.

In addition, pre-trial simulation is conducted to determine the appropriate settings for the switched capacitor units in the field trials and is shown in the Appendix. This has been achieved using validated network models and a combination of real load and generation data from the Customer Led Network Revolution (CLNR) Project.

Steady-state IPSA2 models have been previously developed and validated using SCADA data. The network model (Denwick_8Feeders_Model_v2.3.6b - all in.i2f) is used for this study.

The load data for the post-trial analysis cases are derived from actual data from the SCADA system of this network. This is supplemented, in order to create realistic future scenarios, with LCT profiles derived from CLNR work in LO1 where possible.

This study focuses on the Autonomous and Single + GUS trials for the CLNR trial network at Denwick as per the trial design methodology [1, 2].Single + GUS implies the infrastructure under consideration, in this case the switched capacitor bank, is controlled by centralised control algorithm that has a global view of the network. In addition, the baseline trial that is required to evaluate the headroom uplift accruing to the network interventions can be evaluated.

In Table 1, the voltage control trials which have been expanded and augmented through trial analysis using the VEEEG methodology are given.

Table 1: List of Mechanically Switched Capacitor Bank voltage control field trials at Hedgeley Moor in Denwick

Trial No.	Trial Name
21. 50	Closed loop GUS voltage control system at Hedgeley Moor Capacitor Bank

Table 2 shows the extra voltage headroom and legroom from the mechanically switched capacitor bank at Hedgeley Moor.

Table 2 Extra Headroom and legroom from mechanically switched capacitor bank at Hedgeley Moor

Network Intervention	Size	Location	Extra Headroom (pu %)	Extra Legroom (pu %)
GUS+EAVC4	N/A	Hedgeley Moor	0	11.6

It can be seen that there is no extra headroom provided by the mechanically switched capacitor bank, which is because it can only boost the voltage.

Different critical busbars are considered in the post-trial analysis. The application of GUS controller can significantly increase the allowable ASHP and EV customer numbers if the College Goldscleugh busbar is considered. However, no extra LCT customer number can be connected with GUS controller if only the Akeld busbars are considered, because of the location of the capacitor bank and the capacitor bank stage position limits. If only the LV busbar, Akeld demand, is considered, more allowable ASHP and EV customers can be achieved.

Under voltage problems normally happen at HV voltage level first, while overvoltage problems normally happen at LV voltage level first. This is because of the HV/LV transformer boosts the voltage at the LV network.

By controlling the switched capacitor bank with the GUS controller, additional LCTs can be connected in the HV feeder cluster study. Additional amount of ASHP and EV customers, from 5% to 133%, can be connected, with GUS control. The analysis suggests that line drop compensation (LDC) algorithm could provide the same capability to accept extra LCT connections if uniformly distributed. However LDC techniques can fail as the system approaches its limit when non-uniform clustered distributions of LCT based load. These characteristics will be explored in the *DEI-CLNR-DC149- Analysis of collaborative voltage control on HV and LV networks*.

1 Introduction

The work detailed in this document is conducted using the IPSA2 models of Denwick network to evaluate the capability of Hedgeley Moor Mechanically Switched Capacitor Bank in accommodating LCT following the deployment of GUS. This has been achieved using validated network models and a combination of real load and generation data from the Customer Led Network Revolution (CLNR) Project.

Steady-state IPSA2 models have been previously developed and validated using SCADA data. The network model (Denwick_8Feeders_Model_v2.3.6b - all in.i2f) is used for this study

The load data for the post-trial analysis cases are derived from actual data from the SCADA system of this network. This is supplemented, in order to create realistic future scenarios, with LCT profiles derived through analysis of smart meter measurements detailed in previous CLNR reports, and previous work from industry studies. In the case of the PV and ASHP profiles the 95th percentile profile was assumed as this was felt to be a reasonable, conservative assumption for both load types.

This study focuses on the Autonomous and Single + GUS trials for the CLNR trial network at Denwick that are scheduled to be carried out towards the start of the trial period beginning in Oct 2012. In addition, the baseline trial that is required to evaluate the headroom uplift accruing to the network interventions can be evaluated.

In Table 3, the voltage control trials which have been expanded and augmented through trial analysis using the VEEEG methodology are given.

Table 3: List of Mechanically Switched Capacitor Bank voltage control field trials at Hedgeley Moor in Denwick

Trial No.	Trial Name
21. 50	Closed loop GUS voltage control system at Hedgeley Moor Capacitor Bank

2 Methodology and Assumptions

2.1 Overview

In order to ensure that the objectives of the CLNR project are met, a programme of systematic evaluation of the results from the network flexibility field trials has been developed at Durham University. This approach is derived from previous experience of trials at Durham University and from the outline approach referred to previously. It is required that the results from the trials are firstly used to validate the network and network component models [3]. The results from the trials should then be extended and augmented to ensure that the results are applicable to 80% of the GB distribution network.

The systematic approach proposed by Durham University consists of five steps: -

1. **V**alidation
2. **E**xtension
3. **E**xtrapolation
4. **E**nhancement
5. **G**eneralisation

This methodology is designated as VEEEG (Validation, Extension, Extrapolation, Enhancement, Generalisation) and is illustrated diagrammatically in Fig. 1

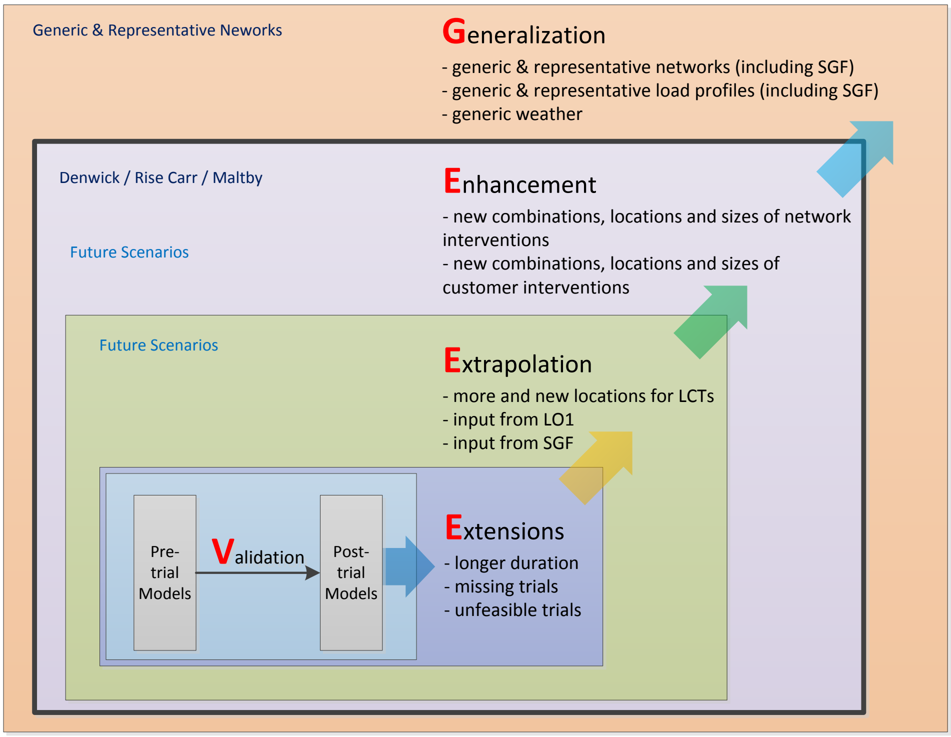

Fig. 1 Post-trial methodology VEEEG

For further details of the post-trial analysis methodology please refer to [4].

3 Trial Results and Validation

3.1 Validation of GUS voltage control of transformers

Due to the difficulty in getting results which illustrate the operation of the GUS system with the capacitor bank in the CLNR trial, results from the validation of the GUS operation with HV/LV transformers can be used. The identical algorithm operates across the systems included in the GUS trial so there is no loss in the applicability of the results.

Following analysis of the data from the relevant GUS voltage control trial of tapchanging HV/LV transformers the data from *23.11 Closed loop GUS voltage control system at Mortimer Road HV/LV* OLTC voltage control trial results from Mortimer Road is used in this work to illustrate how the trials have been used to inform the development and validate the operation of the GUS system and transformer models. As it was difficult to evaluate the operation of the GUS system, as the trial networks were robust, EES3 is operated manually to model additional load and generation LCTs as per *23.6 HV/LV OLTC Transformer at Mortimer Road with EES as PV generation*. The tapchanging HV/LV transformer is controlled by GUS to keep network voltages within the defined voltage limits. This trial is started from 3rd September 2014. Initially, there is no target voltage change due to wide voltage limits. Then tighter voltage limits are applied and target voltage changes have been observed. Trial results from the 17th September 2014 are adopted here for validation study.

For the trial on the GUS voltage control the following conclusions were found:

- A validated model of the closed loop GUS voltage control system in collaboration with a tapchanging HV/LV transformer has been developed. The control algorithm is developed with Python and IPSA2 to represent the DSSe and VVC used by SIEMENS in field trials. Voltage and load data from FDWH are utilized as input, together with the validated network model, to validate the developed control algorithm against results from field trials.
- The simulation results achieved demonstrate that the control algorithm developed in Python and IPSA2 can generally represent the control algorithm used in field trials for further study.
- There are some differences between target voltages from simulation and field trials, which are due to the following aspects:
  - The method used for converting tap position to target voltage is not exactly the same as that used in field trials, since the method used by SIEMENS is not known;
  - The difference between the network model used for validation and the network model used by GUS in field trials.
  - At the moment, all the loads on the same LV feeder are scaled with the same scaling factor, based on the load measured for the entire LV feeder.

The control algorithm can be further improved by replacing the current method with the exact method from SIEMENS for converting tap position to target voltage.

4 Post-trial analysis – Extension, Enhancement, Extrapolation and Generalization

4.1 Introduction

In the following sections, the results from an initial application of the VEEEG methodology, using a combination of a validated model of the GUS system and the Denwick HV network.

4.1.1 Summer and Winter Demand Profile

Winter Daily Demand Profile

Actual SCADA data from the network supplied by Denwick 66/20kV substation from Northern Powergrid is used in this study. The demand profile for the date 21st Jan, 2013 is used. This has been defined to be winter peak. The total demand on Denwick 66/20kV substation is shown in Fig. 2.

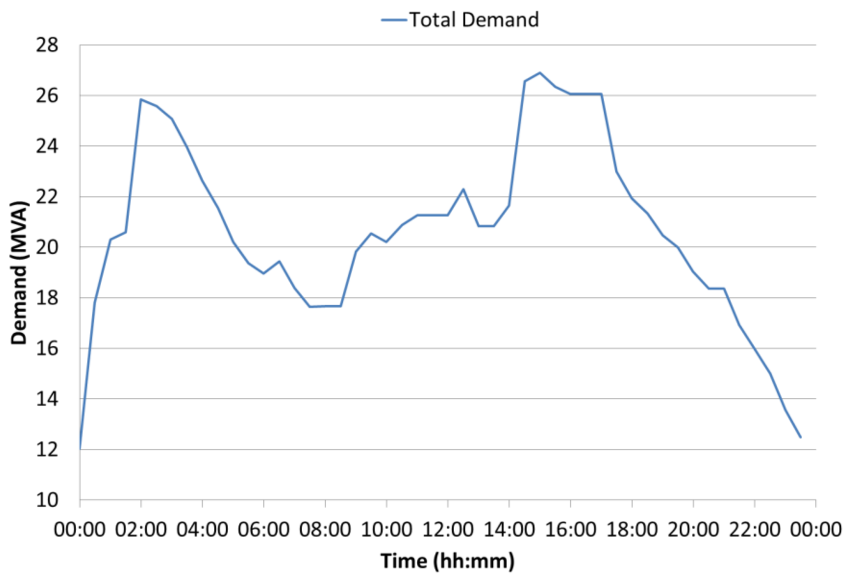

Fig. 2 Winter Daily Demand Profile – Total Demand

In this study, different scaling factors are utilized to scale the loads on different HV feeders, because there are significant variations between different HV feeder demand profiles, as shown in Fig. 3.

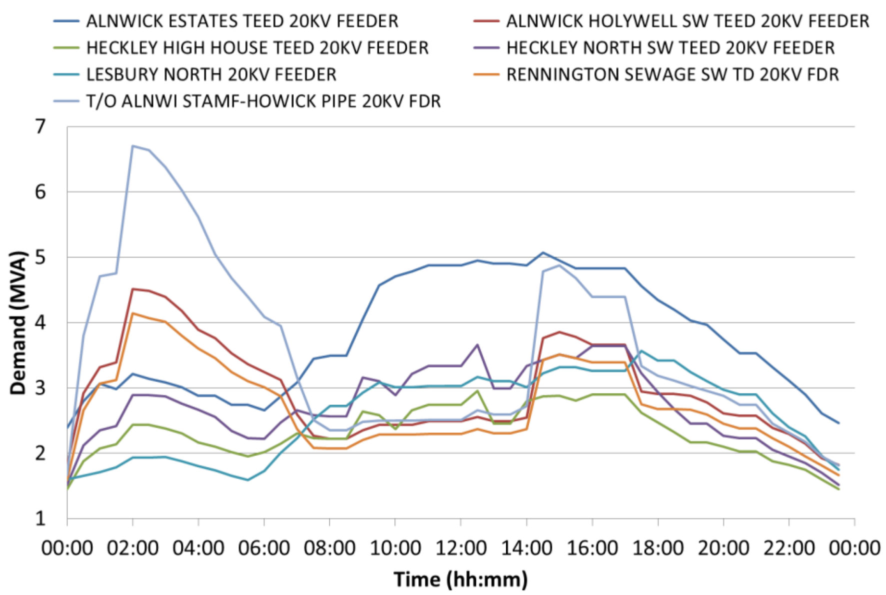

Fig. 3 Winter Daily Demand Profiles of 20kV Feeders

Summer Daily Demand Profile

The total demand on Denwick 66/20kV substation during a summer day (21st June, 2012) is shown in Fig. 4. This has been defined to be summer minimum.

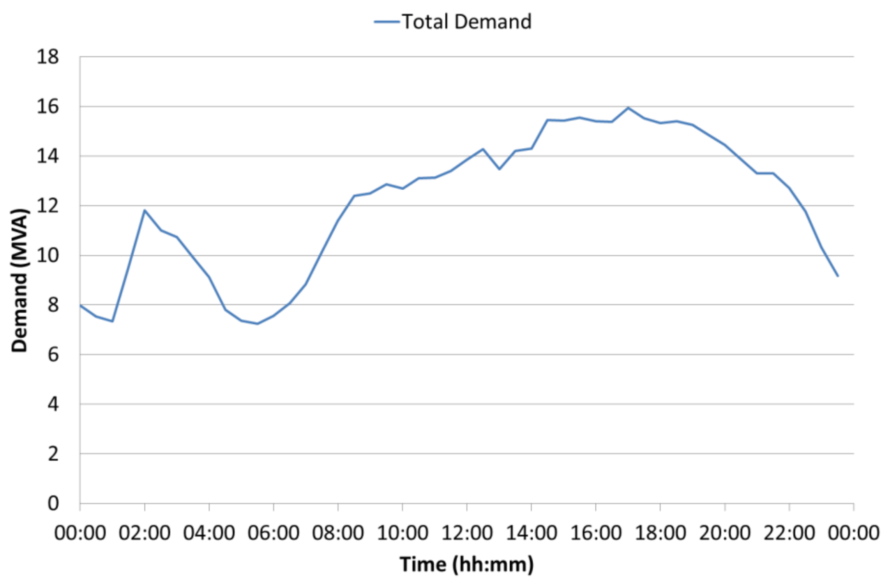

Fig. 4 Summer Daily Demand Profile – Total Demand

The demand profiles of multiple HV feeders are different from each other, as shown in Fig. 5.

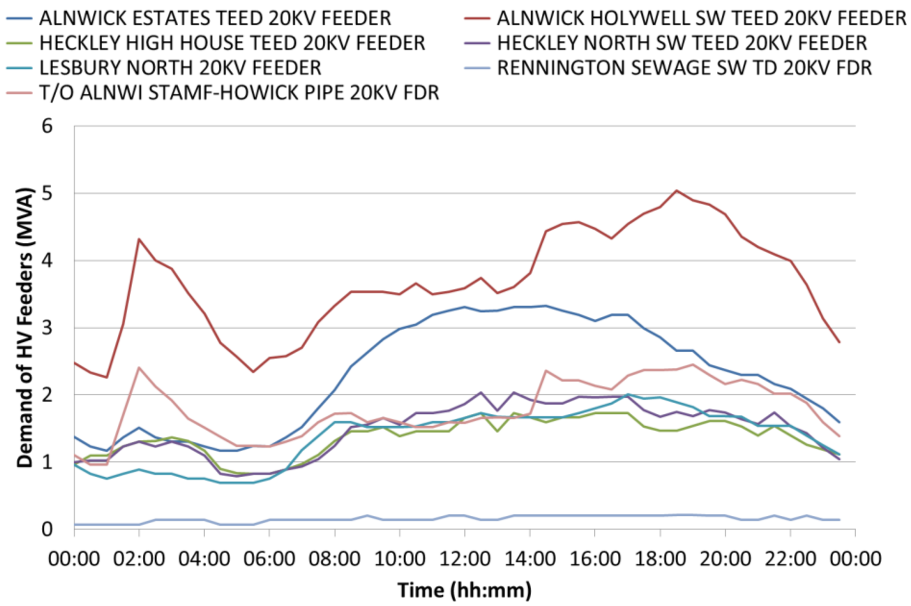

Fig. 5 Summer Daily Demand Profiles of 20kV Feeders

4.1.2 Air Source Heat Pump Model development

The air source heat pump profile is from *CLNR Learning Outcome 1: Initial Heat Pump Load Profiles from CLNR Low Carbon Technology Trials* [5]. The 95th percentile profile on 17th Jan 2013 is used in this post-trial analysis to represent the worst case scenario in terms of loading this network. This profile is shown in Fig. 6.

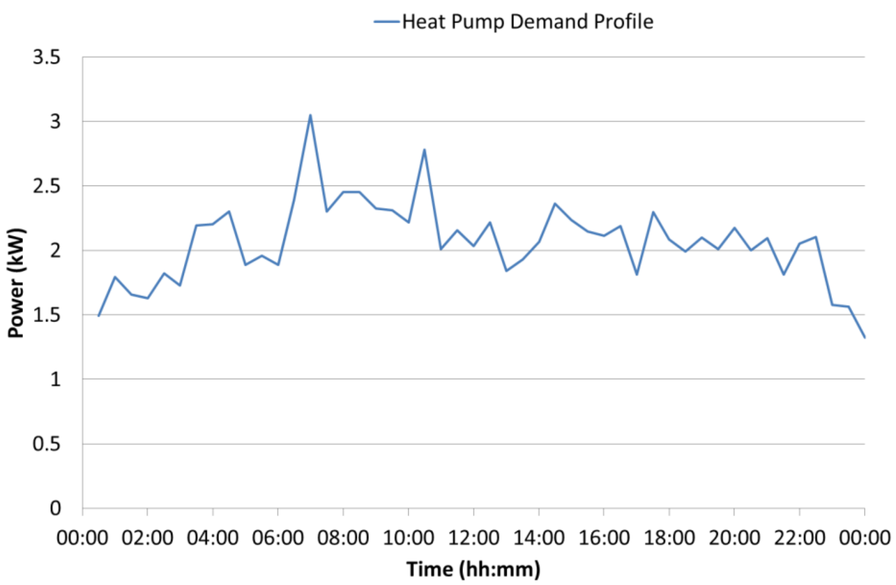

Fig. 6 Typical ASHP daily consumption profile (95th percentile)

4.1.3 Electric Vehicle Load Model Development

The EV consumer model used in this work was based on profiles developed previously in [6]. These profiles are based on real trial data from 19,872 charging events of 340 vehicles (electric, pure hybrid and fuel cell vehicles) from December 2009 to June 2011.

In order to create the profiles a number of assumptions were made. The average mileage covered per day was 12.5 miles [6] which is in line with the average trip commute distance for the case study area [7]. It was also assumed that every car drives the average daily distance and charges at home on a daily basis. The analysis considers the residual charge left in the battery, which will effectively reduce the charging time, but not the peak current drawn from the network. The typical EV profile is shown in Fig. 7.

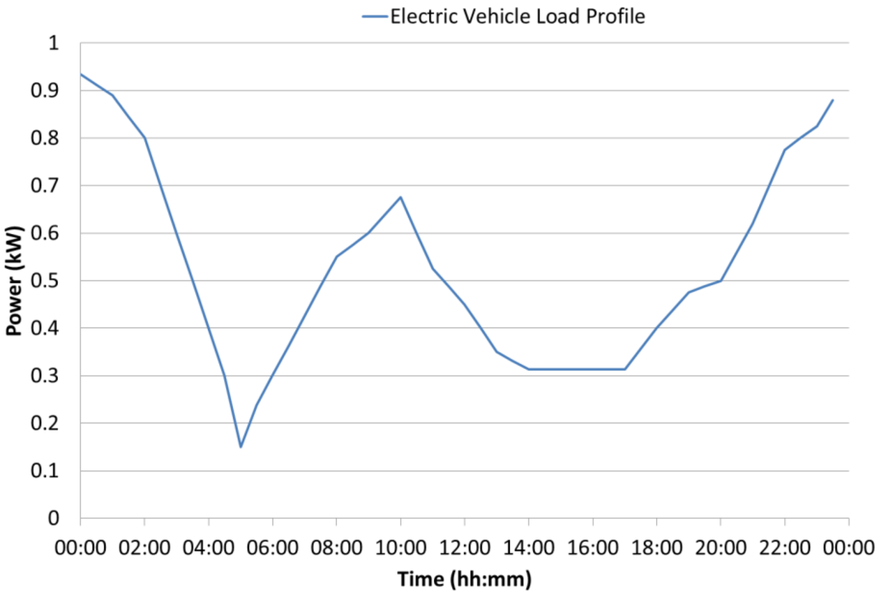

Fig. 7 Typical EV daily consumption profile

4.1.4 PV Generation Model Development

PV generation profile is from *Initial Load Profiles from CLNR Intervention Trials* [8]. The 95th export percentile of PV derived from the smart meter data is applied in this study to represent the worst case scenario. This PV generation profile is shown in Fig. 8.

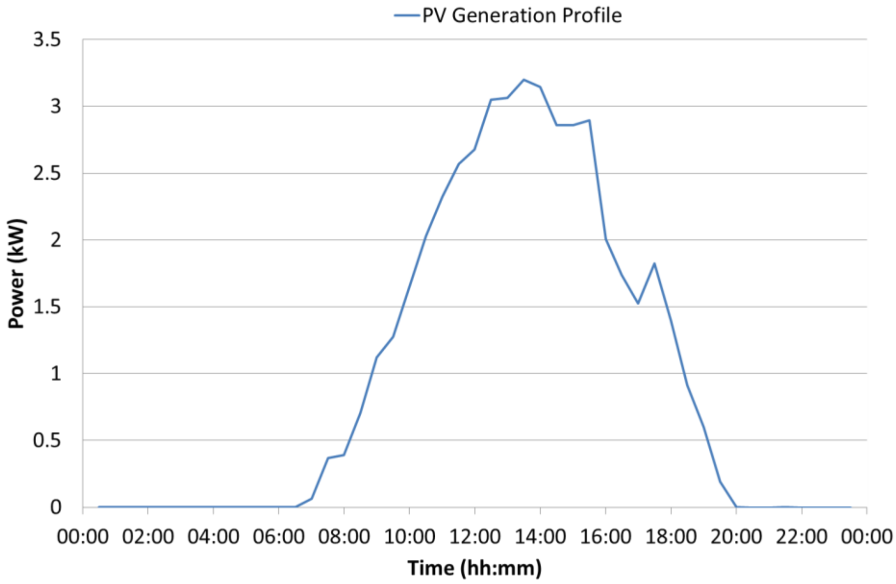

Fig. 8 Typical PV Daily Generation Profile (95th percentile)

4.1.5 Network Model

The initial trial analysis has been conducted on Denwick IPSA2 network model. The geographic overview of the network model is shown in Fig. 9.

Fig. 9 Geographical overview of Denwick network model in IPSA2

The mechanically switched capacitor bank, located at Hedgeley Moor, is shown in Fig. 9. There are two sections of capacitor banks, which are connected to the Heckley SW teed 20kV feeder (green section) and the Heckley High House teed 20kV feeder (red section) respectively. The monitoring HV/LV substations at the ends of these two 20kV HV feeders are also shown, which are Doddington Village and Akeld. It should be noted that there is a single phase feeder section after the Akeld HV/LV substation, which ends at College Goldscleugh.

This study is mainly based on the capacitor group connected to the Heckley High House feeder (red section), as for the Heckley SW feeder (green section), a HV regulator (Hepburn Bell Regulator) is located after the Hedgeley Moor Capacitor bank, which makes it difficult to evaluate the performance of the capacitor bank. This is illustrated by the schematic diagram of Denwick, as shown inFig. 10. These two sections are disconnected in this study.

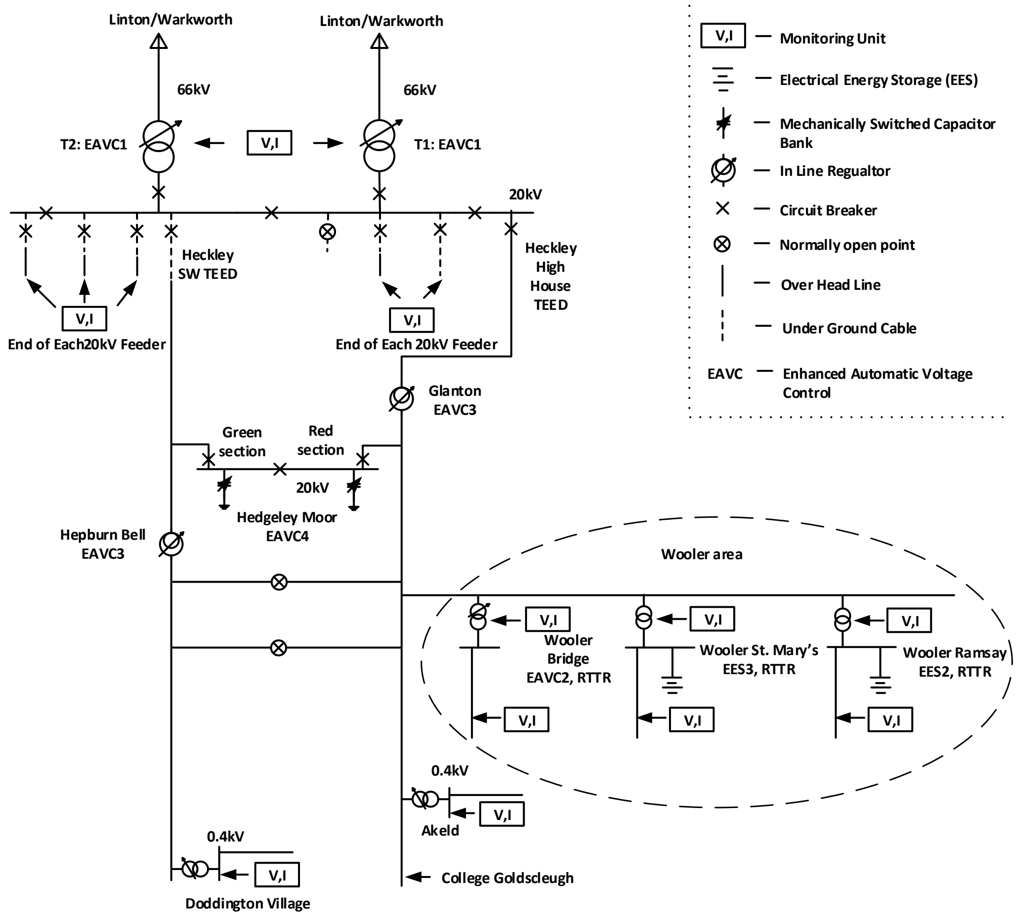

Fig. 10 Schematic diagram of Denwick

It is necessary to scale the loads on each HV feeder separately, instead of scaling all the loads with a same scaling factor. The loads in the Denwick IPSA2 network model have been renamed with a certain way, in which it is possible to distinguish the loads on different feeders and scale them with different scaling factors.

The parameters of Mechanically Switched Capacitor Bank (red section) are listed in Table 4. The original parameters are listed first and then the parameters used for enhancement study are also included.

Table 4 Parameters of Hedgeley Moor Capacitor Bank – Rd Section

Location	Range of Capacitor Stage Positions	Capacitor Step Size	
Hedgeley Moor (Red Section)	0-8	1MVAr/Stage	Original
Hedgeley Moor (Red Section)	0-8	0.5MVAr/Stage	Enhancement

In this study, the rest EAVCs in the Denwick network model are at their existing settings, as shown in Table 5.

Table 5 EAVC Settings

EAVC	Location	Target Voltage (pu)	Bandwidth (%)	Tap Position (%)
EAVC11	Denwick Primary T1	1.01	1.67	-
EVAC12	Denwick Primary T2	1.01	1.67	-
EAVC31	Glanton	-	-	-1.25(locked)
EAVC32	Hepburn Bell	1.00	1.5	-
EAVC42	Hedgeley Moor (Green section)	1.00	2	-

4.2 Extension

The annual SCADA data from Northern Powergrid and the Denwick IPSA2 model are used to evaluate the simple voltage headroom and voltage legroom at different locations of the Denwick network. A summary of the results from this analysis are shown in Table 6.

Table 6 Baseline Simple Voltage Headroom and Legroom from Extension

] Location	Voltage Headroom (pu %)	Voltage Legroom (pu %)
Hedgeley Moor Capacitor	4.06	5.00
Akeld 20/0.4kV Substation	4.68	1.82
Akeld 433V Bar	2.61	7.40
Akeld Demand	3.00	5.48

It can be seen from Table 6 that the voltage headroom in the Akeld LV network is much smaller than the voltage legroom. This is because the 20kV/0.433kV power transformer boosts the LV voltage and gives extra headroom of 0.0825pu (compared to the 20kV/0.4kV transformer).

Table 7 shows the extra voltage headroom and legroom from EAVC4.

Table 7 Extra Headroom and legroom from EAVC4

Network Intervention	Size	Location	Extra Headroom (pu %)	Extra Legroom (pu %)
GUS+EAVC4	N/A	Hedgeley Moor	0	11.6

It can be seen that there is no extra headroom provided by the mechanically switched capacitor bank, which is because it can only boost the voltage.

4.3 Extrapolation and Enhancement

The Heckley SW Teed 20kV feeder is used for the extrapolation study. The customer details of this HV feeder are listed in Table 8. The customer details are derived from the MPANs (Meter Point Administration Numbers) of customers in Denwick. Profile class 1 and 2 represent domestic customers, while profile class 3 to 8 represent non-domestic customers. Therefore 76.24% of the customers on the Heckley Sw Teed Feeder are domestic customers.

Table 8 Customer Details of Heckley Sw Teed Feeder

Profile Class	Customer Number	Percentage
1	174	57.43%
2	57	18.81%
3	50	16.50%
4	10	3.30%
5	5	1.65%
6	4	1.32%
7	3	0.99%
8	0	0.00%
Total	303	100%

4.3.1 Control Mode in Extrapolation Study

Two control modes are utilized in the extrapolation study: autonomous control and GUS control. In the autonomous control mode, the busbar at Hedgeley Moor is set as the target busbar. 1.00pu is set as target voltage and 1% is set as bandwidth. Only the voltage at Hedgeley Moor is being monitored.

The target voltage and bandwidth in the autonomous control mode are illustrated in Fig. 11. The capacitor bank is controlled to maintain the target busbar voltage within the voltage range: (voltage upper band, voltage lower band). It should be noted that sometimes the bandwidth is defined as the difference between the voltage upper band and the voltage lower band, which is twice of the one defined in Fig. 11. Here, the definition shown in Fig. 11 is used as it is adopted by Northern Powergrid.

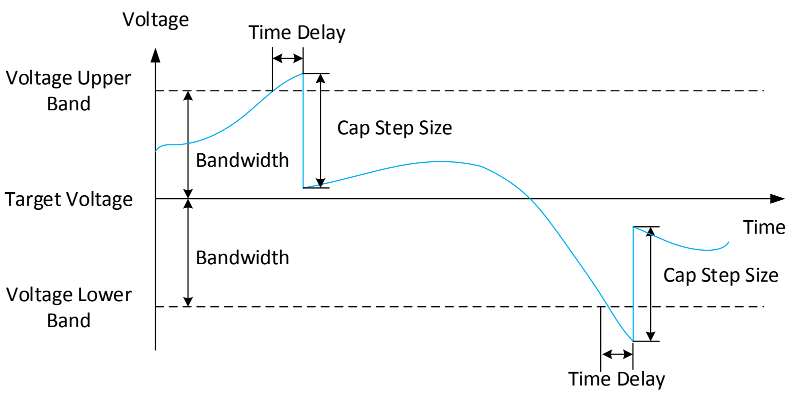

Fig. 11 The principle of autonomous control

In the GUS control mode, the capacitor bank is controlled to keep all the voltages along the Heckley High House feeder within statutory limits.

4.3.2 ASHP clustering on HV feeder

The ASHP power consumption profile from the SDRC report, described in 4.1.2 was used in this study. A HV Feeder Cluster is studied. The allowable ASHP customer numbers for HV feeder cluster are shown in Table 9. As shown in Table 9, different critical busbars are considered in the extrapolation study:

- Akeld busbars: The Akeld HV/LV substation is the most remote three-phase substation located on the Heckley High House feeder in the model. Akeld 20kV busbar, Akeld LV substation 0.4kV busbarand Akeld Demand (LV feeder remote end) are considered as critical busbars. College Goldscleugh is not considered;
- College Goldscleugh 20kV busbar: the remote feeder end of the Heckley High House 20kV feeder is also considered as critical busbar, in addition to the Akeld busbars;
- Akeld Demand: only the Akeld LV feeder end is considered as critical busbar, as there is no 20kV customers connected to the Heckley High House feeder.

Different busbars are considered due to the level of detail in the model. Also, two different sets of mechanically switched capacitor banks are applied in this study, as shown in Table 4.

It was found that the selection of critical busbar and the capacitor bank reactive power output limit have a significant impact on the results.

Table 9 Allowable Domestic ASHP Customer Number on Heckley High House 20kV Feeder

Scenario	ASHP Customer Number		Percentage Increase on BAU (%)	
	Capacitor bank maximum reactive power setting point - 7MVAr	Capacitor bank maximum reactive power setting point - 4MVAr	Capacitor bank maximum reactive power setting point - 7MVAr	Capacitor bank maximum reactive power setting point - 4MVAr
Autonomous Control Mode with Akeld Busbar (0.4kV)	1572	1228	0%	0%
GUS + EAVC4 with Akeld Busbar (0.4kV)	2251	1228	43%	0%
Autonomous Control Mode with College Goldscleugh (20kV)	892	590	0%	0%
GUS + EAVC4 with College Goldscleugh Considered (20kV)	2082	1109	133%	88%
Autonomous Control Mode only with Akeld Demand busbar (0.4kV)	2188	1449	0%	0%
GUS + EAVC4 Only with Akeld Demand busbar (0.4kV)	2400	1449	10%	0%

It can be seen that generally the application of GUS control can increase the allowable ASHP customer number, if the capacitor bank maximum reactive power setting point is 7MVAr. However, the application of GUS controller cannot increase the allowable ASHP customer number if Akeld 0.4kV busbars are considered as the critical busbar and the capacitor bank maximum reactive power setting point is 4MVAr. This is because the distance between the Hedgeley Moor Mechanically Switched Capacitor Bank and Akeld Busbars is short, and the capacitor bank has limited reactive power output. If the College Goldscleugh busbar is instead considered, less ASHP customer numbers can be connected. The application of GUS controller can significantly increase the allowable ASHP customer number in this case. If only the voltage at the Akeld demand busbar is considered as a critical busbar, the allowable ASHP customer number can be further increased however the application of the GUS controller does not increase the penetration of ASHPs that could be connected.

This results indicate, as expected; that GUS could have an impact on increasing the capability to connect ASHP customers when the remote end is further away from the capacitor bank, and the capacitor bank has sufficient reactive power capacity.

The simulation results of Hedgeley Moor Capacitor Bank (maximum reactive power setting point as 4MVAr) under autonomous control mode are shown in Fig. 12 and Fig. 13. 1228 ASHP customers are connected. It can be seen that the capacitor stage position of the capacitor bank is controlled to maintain the voltage at Hedgeley Moor between 0.99pu and 1.01pu. The voltage of the Akeld 20kV busbar dropped below the statutory voltage lower limit at 10:30.

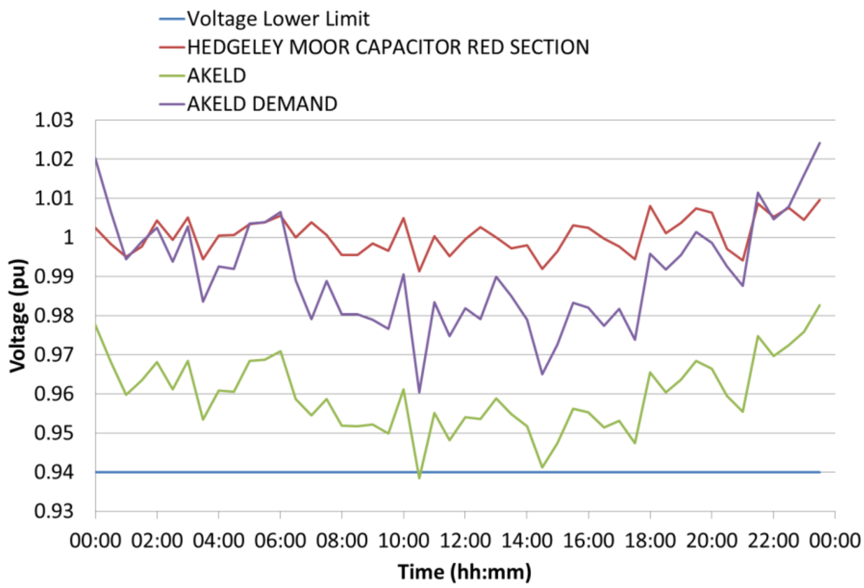

Fig. 12 Voltage Profiles – Capacitor Bank (maximum reactive power setting point as 4MVAr) under Autonomous Control Mode, ASHP HV Feeder Cluster

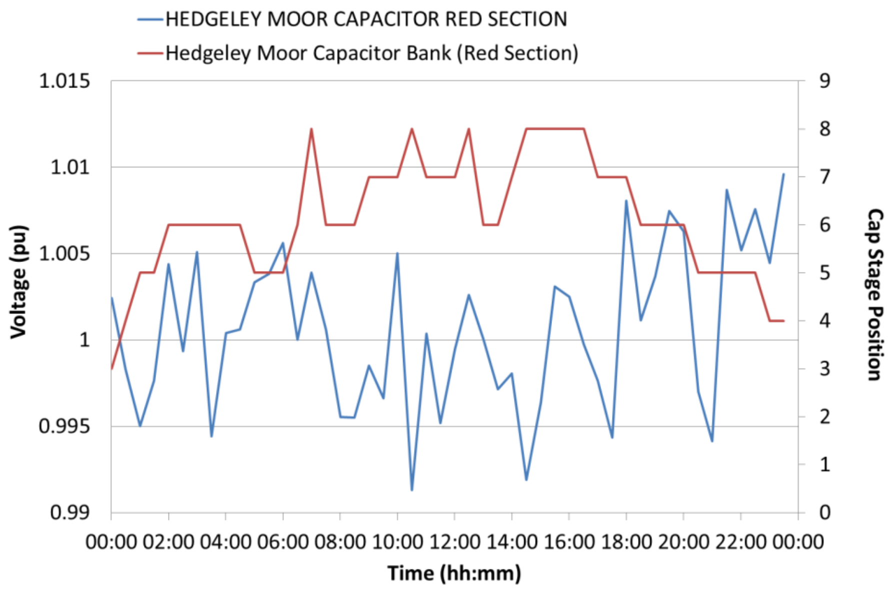

Fig. 13 Voltage Profile and Stage Position – Capacitor Bank (maximum reactive power setting point as 4MVAr) under Autonomous Control Mode, ASHP HV Feeder Cluster

The simulation results for Hedgeley Moor Capacitor Bank (maximum reactive power setting point as 4MVAr) under GUS control mode are shown in Fig. 14 and Fig. 15. 1228 ASHP customers are connected. It can be seen that the mechanically switched capacitor bank operates to maintain the voltages within the statutory limits, but at 10:30, the mechanically switched capacitor bank cannot keep the voltage of the Akeld 20kV busbar above the voltage lower limit, as it reaches its stage position limits.

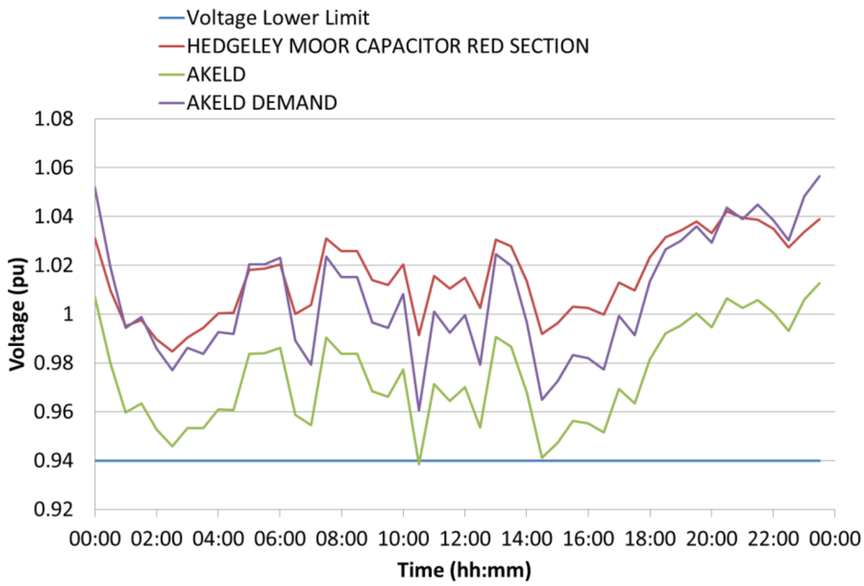

Fig. 14 Voltage Profiles – Capacitor Bank (maximum reactive power setting point as 4MVAr) under GUS Control Mode, ASHP HV Feeder Cluster

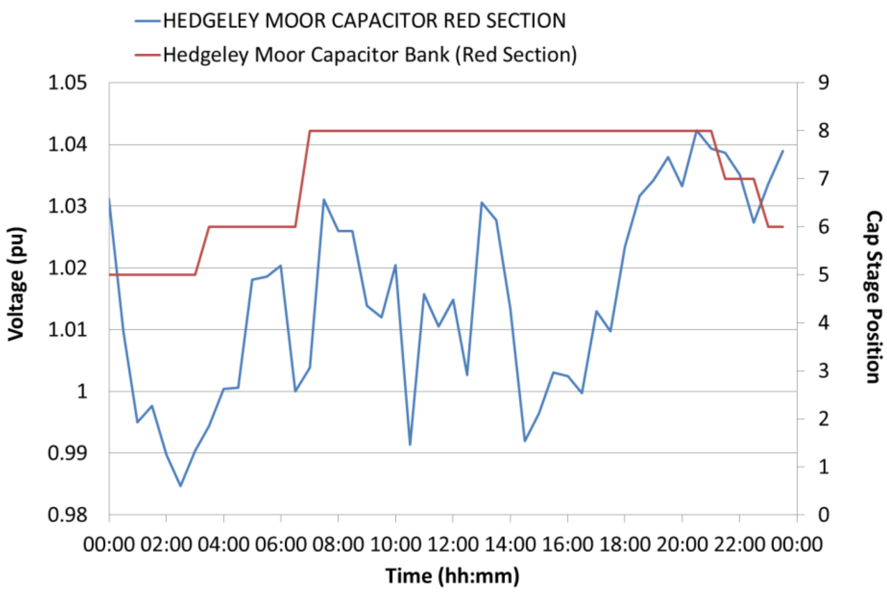

Fig. 15 Voltage Profile and Stage Position – Capacitor Bank (maximum reactive power setting point as 4MVAr) under GUS Control Mode, ASHP HV Feeder Cluster

4.3.3 EV clustering on HV Feeder

The typical EV consumption profile described in 4.1.3 was used in this study. In this analysis, the winter scenario is considered only as this represents the worst case. In the following, a HV feeder cluster is considered for extrapolation.

Allowable EV customer numbers for HV feeder cluster are shown in Table 10. It can be seen that generally the application of GUS control can increase the allowable ASHP customer number, if the capacitor bank maximum reactive power setting point is 7MVAr. However, the application of GUS controller cannot increase the allowable EV customer number if Akeld Busbars are considered, and the capacitor bank maximum reactive power setting point is 4MVAr.

If the College Goldscleugh busbar is instead considered, less EV customer number can be connected. The application of GUS controller can significantly increase the allowable EV customer number in this case. If only the voltage at the Akeld demand busbar is considered as critical busbar, the allowable EV customer number can be further increased however the application of the GUS controller does not increase the penetration of EVs that could be connected, when the capacitor bank maximum reactive power setting point is 4MVAr.

This results indicate, as expected, that GUS could have an impact on increasing the capability to connect EV customers when the remote end is further away from the capacitor bank, and the capacitor bank has sufficient reactive power capacity.

Table 10 Allowable Domestic EV Customer Number on Heckley High House 20kV Feeder

Scenario	**Allowable Domestic EV Customer Number**		**Percentage Increase on BAU (%)**	
Autonomous Control Mode with Akeld Busbar (0.4kV)	5522	4636	0%	0%
GUS + EAVC4 with Akeld Busbar (0.4kV)	6818	4636	23%	0%
Autonomous Control Mode with College Goldscleugh (20kV)	3186	2591	0%	0%
GUS + EAVC4 with College Goldscleugh Considered (20kV)	6245	4141	96%	60%

Autonomous Control Mode only with Akeld Demand busbar (0.4kV)	6776	5246	0%	0%
GUS + EAVC4 Only with Akeld Demand busbar (0.4kV)	7137	5204	5%	-1%

The simulation results for Hedgeley Moor Capacitor Bank (maximum reactive power setting point as 4MVAr) under autonomous control mode are shown in Fig. 16 and Fig. 17. 4636 EV customers are connected.

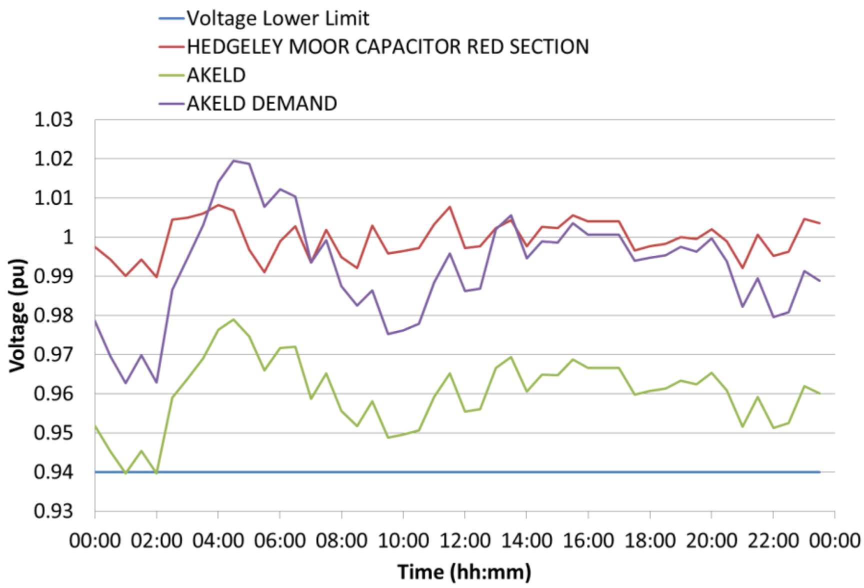

Fig. 16 Voltage Profiles – Capacitor (maximum reactive power setting point as 4MVAr) Bank under Autonomous Control Mode, EV HV Feeder Cluster

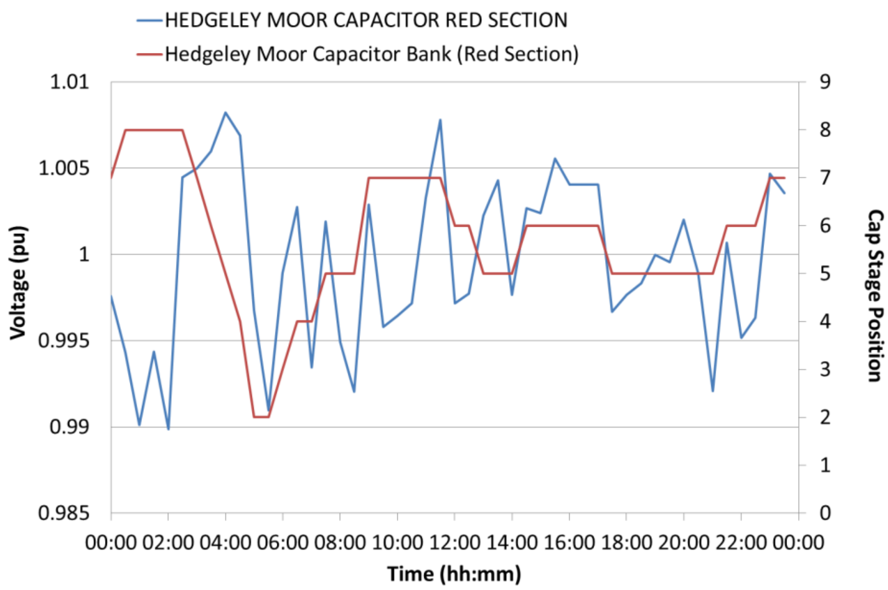

Fig. 17 Voltage Profile and Stage Position – Capacitor Bank (maximum reactive power setting point as 4MVAr) under Autonomous Control Mode, EV HV Feeder Cluster

The simulation results for Hedgeley Moor Capacitor Bank (maximum reactive power setting point as 4MVAr) under GUS control mode are shown in Fig. 18 and Fig. 19. 4636 EV customers are connected.

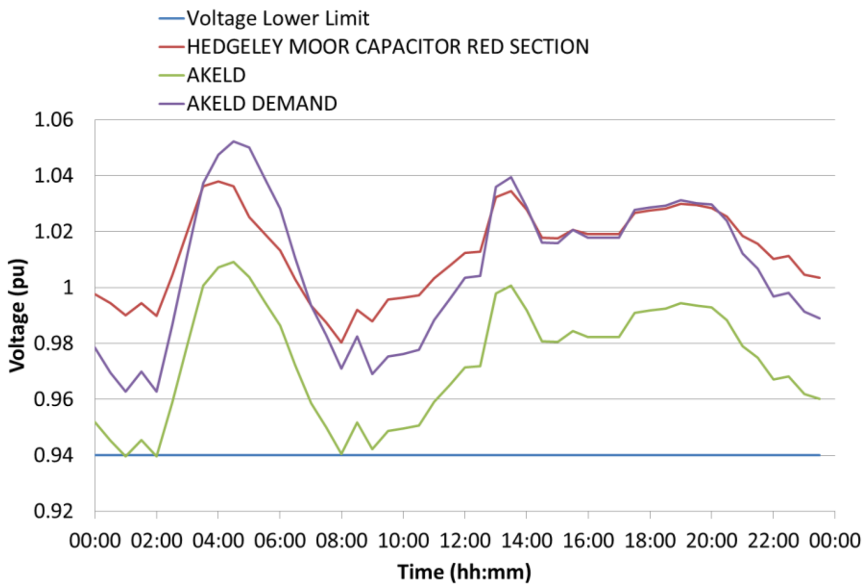

Fig. 18 Voltage Profiles – Capacitor Bank (maximum reactive power setting point as 4MVAr) under GUS Control Mode, EV HV Feeder Cluster

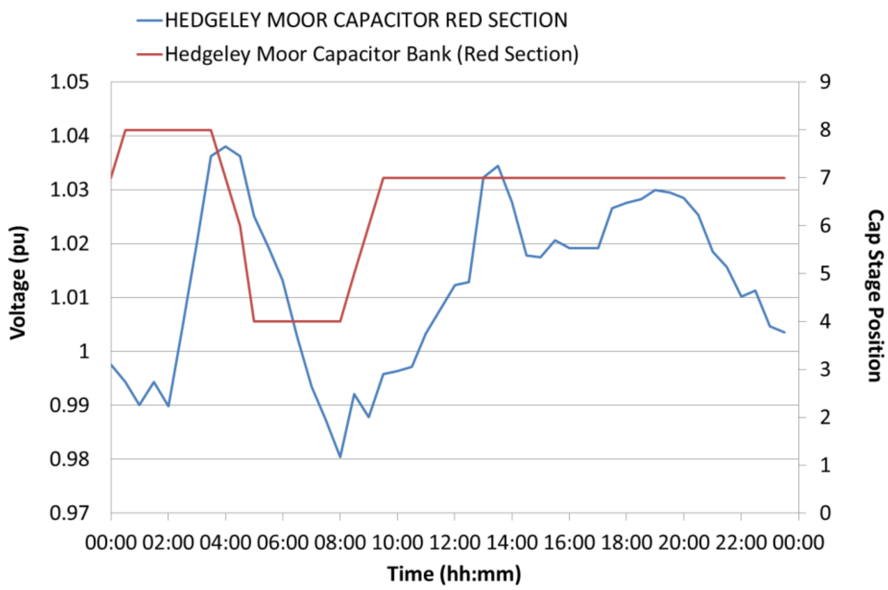

Fig. 19 Voltage Profile and Stage Position – Capacitor Bank (maximum reactive power setting point as 4MVAr) under GUS Control Mode, EV HV Feeder Cluster

Another thing that should be noted is that the application of GUS control doesn't enhance the allowable EV customer number, if only the Akeld Demand busbar is considered, and the capacitor bank maximum reactive power output is set as 4MVAr. On the contrary, the allowable EV customer number is reduced, when the GUS control is implemented. The reason is explained in the following. 5204 EV customers are connected.

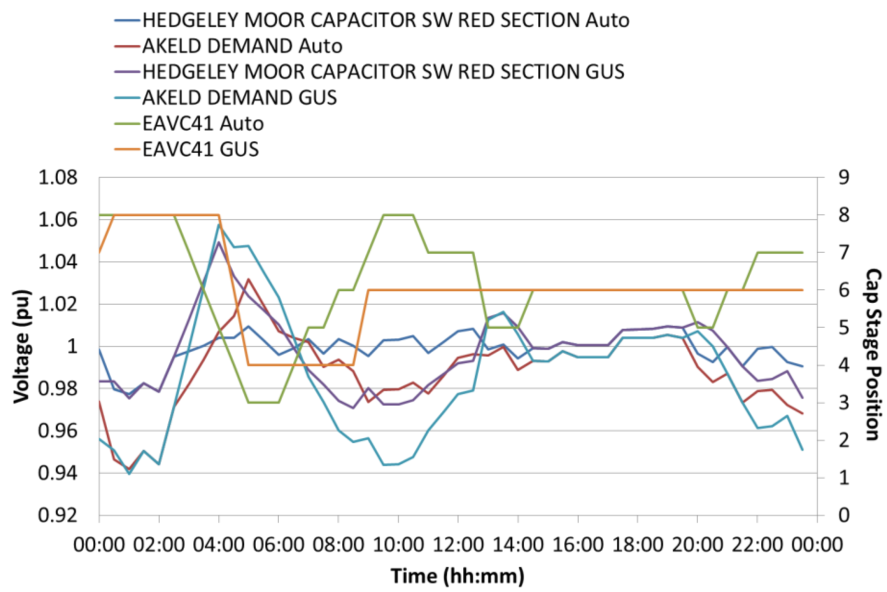

Fig. 20 Voltage and EAVC4 Cap Position (maximum reactive power setting point as 4MVAr) under autonomous control and GUS control

It can be seen from Fig. 20 that at time t=01:00, the voltage of Akeld Demand dropped below 0.94pu, when the Hedgeley Moor Capacitor Bank (Red Section, named as EAVC41) is under GUS control mode, while the voltage was still above 0.94pu, when the capacitor bank is under autonomous control mode. The capacitor bank was at the same stage at t = 01:00 for both control modes. The reason for the voltage difference is due to the position of other EAVCs across the network, as shown in Fig. 21 and Fig. 22. The EAVCs' details can be found in Table 5.

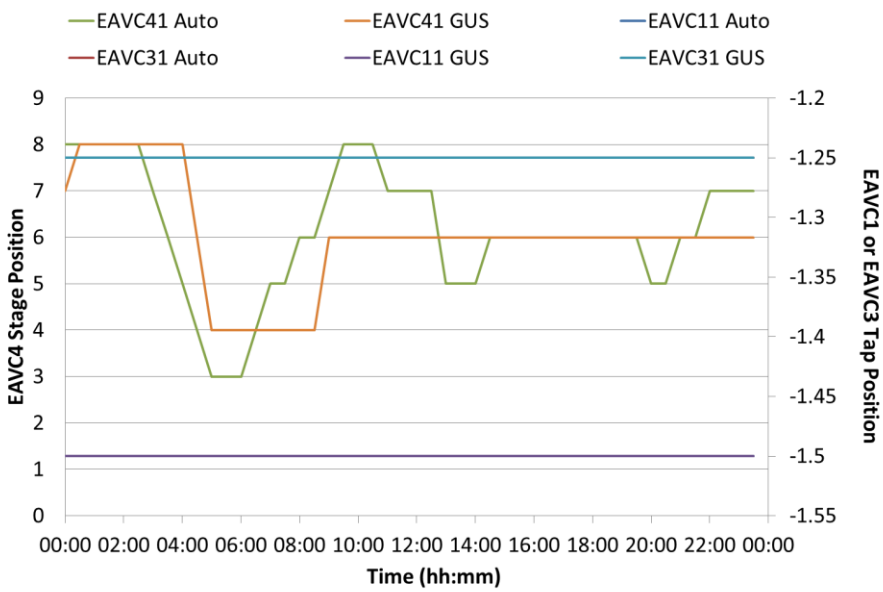

Fig. 21 EAVCs upstream and downstream of capacitor bank

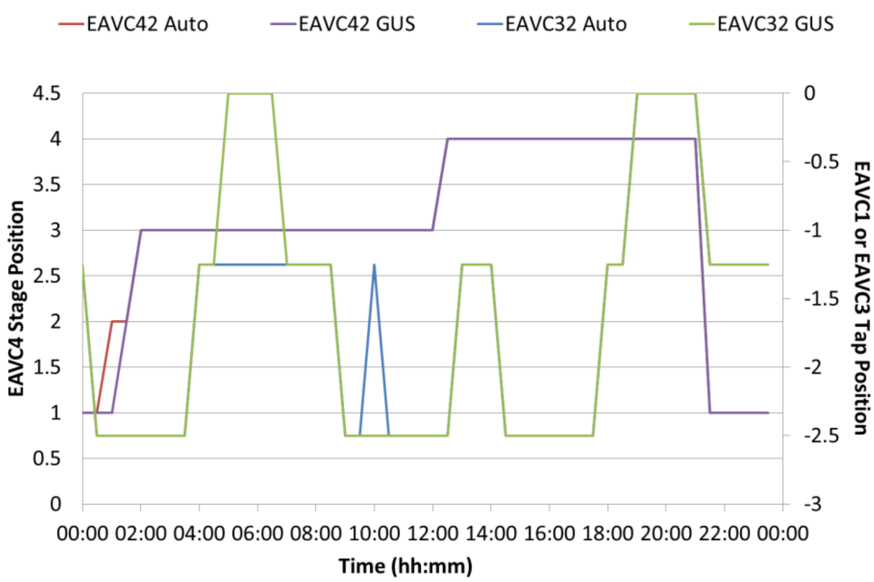

Fig. 22 EAVCs at adjacent 20kV feeder

It can be seen from Fig. 22 that at t=01:00, EAVC42 is at stage 2 when EAVC41 is under autonomous control mode, while EAVC42 is at stage 1 when EAVC41 is under GUS control mode. The EAVC42 with a higher stage position provides a larger reactive power support across the network.

4.3.4 PV clustering HV Feeder

The PV power generation profile described in 4.1.4 was used in this study. In contrast with the analyses of HP and EV load, the VEEEG analysis of the PV cluster uses daily demand profiles of a summer day 21st June, 2012.

The allowable domestic PV customer numbers are shown in Table 11. As mechanically switched capacitor bank can only boost the voltage, here only one set of mechanically switched capacitor bank is tested. It can be found that the application of GUS reduces the allowable domestic PV customer number. This is because the operations of other EAVCs in autonomous control mode and in GUS control mode.

Table 11 Allowable Domestic PV Customer Number on Heckley High House 20kV Feeder

Scenario	Allowable Domestic PV Customer Number	Percentage Increase on BAU (%)
Autonomous Control Mode with Akeld Busbar (0.4kV)	1341	0%
GUS + EAVC4 with Akeld Busbar (0.4kV)	1252	-7%
Autonomous Control Mode with College Goldscleugh (20kV)	1341	0%
GUS + EAVC4 with College Goldscleugh Considered (20kV)	1252	-7%
Autonomous Control Mode only with Akeld Demand busbar (0.4kV)	1341	0%
GUS + EAVC4 Only with Akeld Demand busbar (0.4kV)	1252	-7%

The reason why considering the voltage of the College Goldscleugh 20kV busbar did not change the allowable domestic PV customer number is the voltage violation happened at the LV side of Akeld.

The simulation results for Hedgeley Moor Capacitor Bank under autonomous control mode are shown in Fig. 23 and Fig. 24. 1341 PV customers connected.

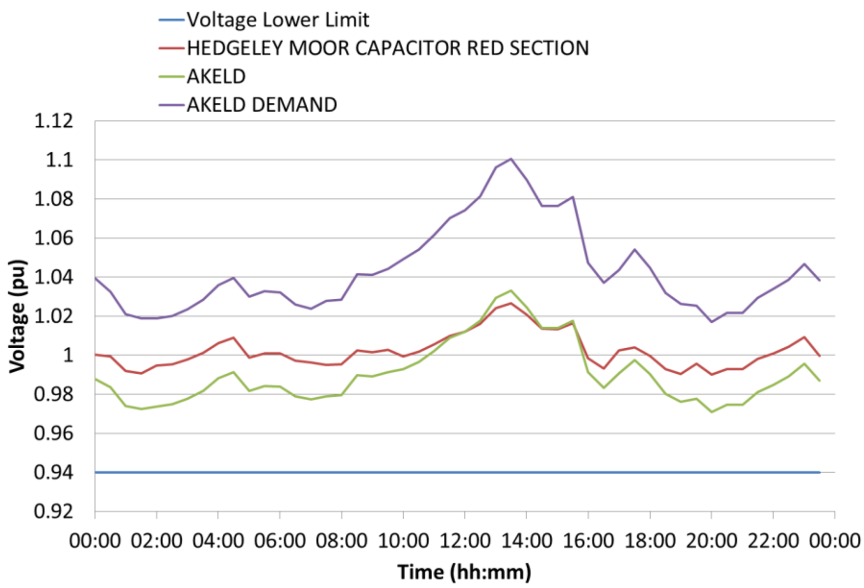

Fig. 23 Voltage Profiles – Capacitor Bank under Autonomous Control Mode, PV HV Feeder Cluster

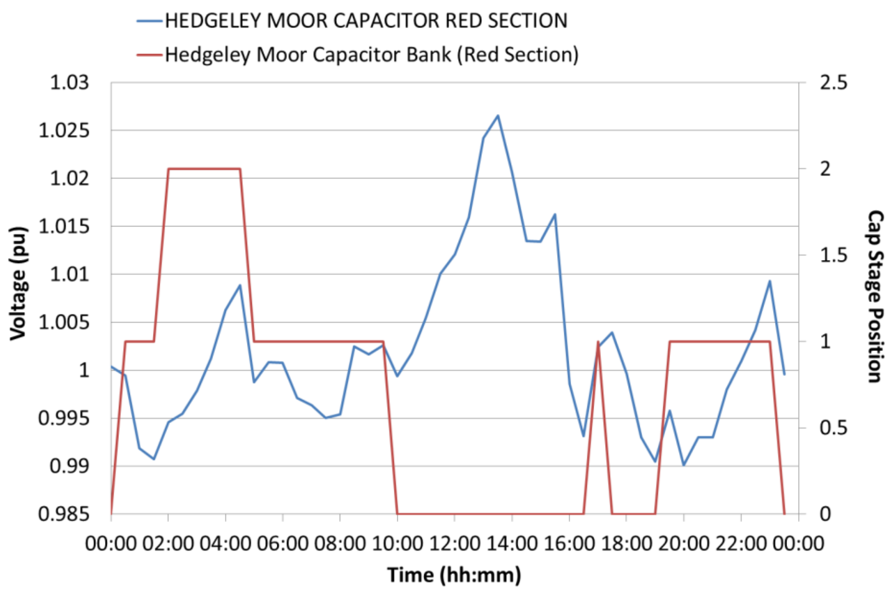

Fig. 24 Voltage Profile and Stage Position – Capacitor Bank under Autonomous Control Mode, PV HV Feeder Cluster

The simulation results for Hedgeley Moor Capacitor Bank under GUS control mode are shown in Fig. 25 and Fig. 26. 1252 PV customers connected.

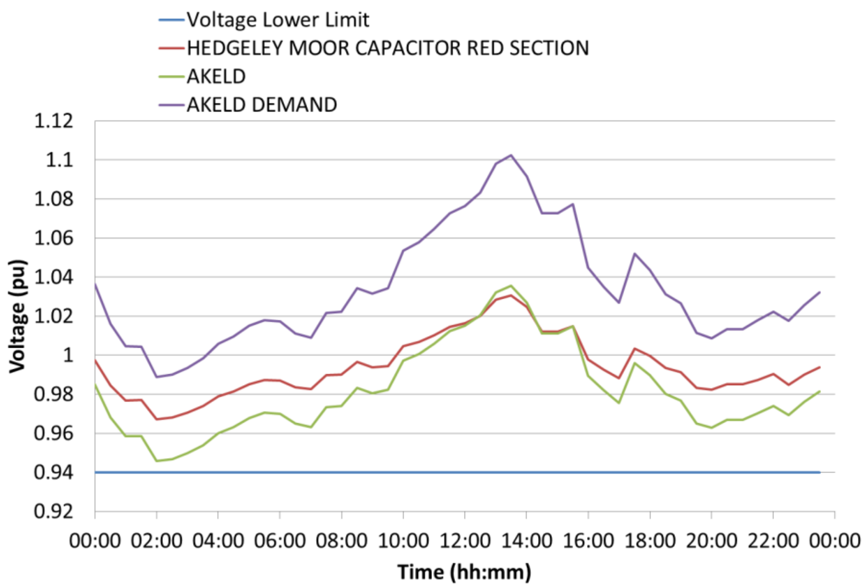

Fig. 25 Voltage Profiles – Capacitor Bank under GUS Control Mode, PV HV Feeder Cluster

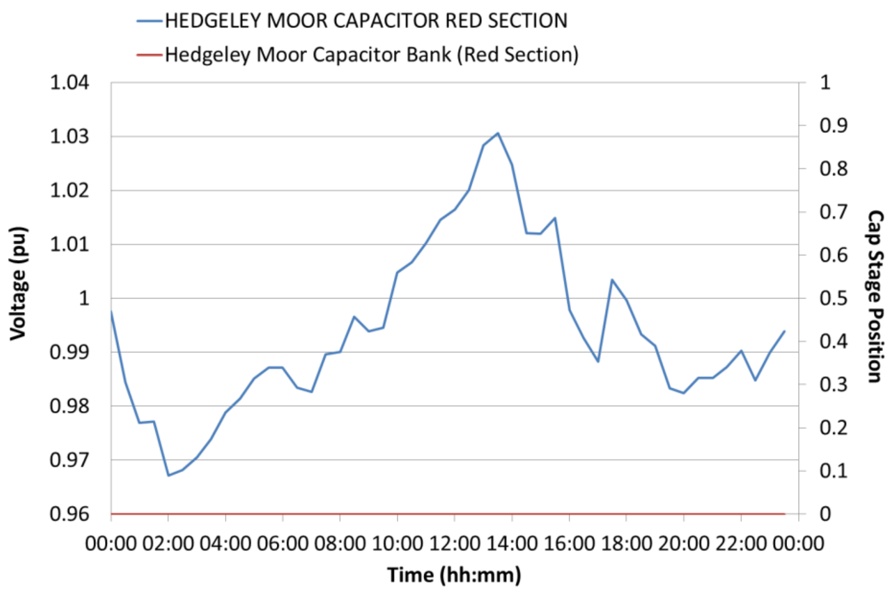

Fig. 26 Voltage Profiles and Stage Position – Capacitor Bank under GUS Control Mode, PV HV Feeder Cluster

4.4 Generalisation

Previously the voltage sensitivity factor has been defined to describe the sensitivities of network voltages to the real power P and reactive power Q injections, which can be analyzed through the use of the Jacobian Matrix [9], as shown in (1):

$$\begin{bmatrix}\Delta\boldsymbol{\theta}\\ \Delta\mathbf{V}\end{bmatrix} = J^{-1}\begin{bmatrix}\Delta\mathbf{P}\\ \Delta\mathbf{Q}\end{bmatrix} = \begin{bmatrix}\frac{\partial\boldsymbol{\theta}}{\partial\mathbf{P}} & \frac{\partial\boldsymbol{\theta}}{\partial\mathbf{Q}}\\ \frac{\partial\mathbf{V}}{\partial\mathbf{P}} & \frac{\partial\mathbf{V}}{\partial\mathbf{Q}}\end{bmatrix} \times \begin{bmatrix}\Delta\mathbf{P}\\ \Delta\mathbf{Q}\end{bmatrix} \tag{1}$$

Voltage sensitivity factors relate the change in voltage at a network node due to the import or export of real or reactive power at a particular load or generation node elsewhere in the network (in this study at the remote end). In this section, all the voltage sensitive factors (VSF) of the trialled network capacitor bank locations are listed in Table 12Table 12. To illustrate the meaning of these metrics for if the VSF Q (V/MVAr) is 12.1 for each MVAr injected at Hedgeley Moor Capacitor Bank (Heckley High House Feeder) the voltage at Akeld LV substation busbar, and the downstream LV network, will increase by 12.1V.

Table 12 VSFs for capacitor bank locations with the Denwick HV system

Import/Export Node	Remote Busbar Name	VSF Q (%/MVAr)	VSF Q (V/MVAr)
Hedgeley Moor Capacitor Bank (Heckley High House Feeder)	Akeld Demand	3.04%	12.1
Hedgeley Moor Capacitor Bank (Heckley North SW Feeder)	Doddington Village Demand	2.11%	8.4
Windylaw Capacitor Bank (Rennington Sewage SW TEED Feeder)	Waren Mill Demand	1.67%	6.7
Windylaw Capacitor Bank (Alnwick Holywell SW TEED Feeder)	Belford West Demand	1.43%	5.8

It can be seen therefore that the additional headroom created by a reactive power source can be easily estimated if these metrics are available.

Similarly, the validated networks from the CLNR project it is possible to define some metrics which characterise the impact of distributed new load or generation on the networks. This is similar to previous work which uses the concept of “apparent impedance” to evaluate the capability of networks to accept distributed small-scale embedded generation.

In this work the VSFs described earlier have been extended and are defined as distributed voltage sensitivity factors (DVSF). A DVSF describes the change in voltage at a node (usually at the remote end where the greatest voltage variation is observed) due to a defined change in real or reactive power at a number of related nodes (e.g. all the customers downstream of an LV substation).

Table 13 DVSFs and % voltage increase at remote end due to evenly distributed penetrations of PV on CLNR rural networks

HV Cluster	DVSF (%/kW)	DVSF (Normalised)	10% 3kW PV	30% 3kW PV	50% 3kW PV
PV					
Hedgeley Moor Capacitor (Heckley North SW Feeder)	0.63	1.09	0.2%	0.6%	0.9%
Hepburn Bell Regulator	0.58	1.00	0.2%	0.5%	0.9%
Glanton Regulator	5.80	10.02	1.7%	5.2%	8.7%
Hedgeley Moor Capacitor (Heckley High House Feeder)	5.12	8.84	1.5%	4.6%	7.7%
EV/ASHP					
Hedgeley Moor Capacitor (Heckley North SW Feeder)	0.64	1.11	0.2%	0.6%	1.0%
Hepburn Bell Regulator	0.59	1.01	0.2%	0.5%	0.9%
Glanton Regulator	6.93	11.95	2.1%	6.2%	10.4%
Hedgeley Moor Capacitor (Heckley High House Feeder)	5.96	10.29	1.8%	5.4%	8.9%

The DVSF therefore can be used to roughly evaluate impact on remote end voltage on additional distributed generation or load. For example the DVSF would predict that assuming a voltage headroom of 1%, it would be possible to connect a 50% penetration of PV generation assuming 3kW peak installations per customer.

However, it can be seen from the results above that there is a large variation in the capability of a capacitor bank to increase the penetration of LCT in a downstream HV cluster.

5 Discussion and conclusions

In Table 14, the voltage control trials which have been expanded and augmented through trial analysis using the VEEEG methodology are given.

Table 14: List of Mechanically Switched Capacitor Bank voltage control field trials at Hedgeley Moor in Denwick

Trial No.	Trial Name
21. 50	Closed loop GUS voltage control system at Hedgeley Moor Capacitor Bank

However, due to the timing of the CLNR trials the data from the closed loop GUS voltage control trial did not provide data that enables validation of the GUS model. In place of this, the results of the validation of the analysis of GUS with the HV/LV tapchanger are presented, which described the capacitor bank in an identical manner. This GUS model is used for analysis in this work.

Table 15 shows the extra voltage headroom and legroom from the mechanically switched capacitor bank at Hedgeley Moor.

Table 15 Extra Headroom and legroom from mechanically switched capacitor bank at Hedgeley Moor

Network Intervention	Size	Location	Extra Headroom (pu %)	Extra Legroom (pu %)
GUS + EAVC4	N/A	Hedgeley Moor	0	11.6

It can be seen that there is no extra headroom provided by the mechanically switched capacitor bank, which is because it can only boost the voltage.

The following findings have been derived from the pre-trial simulation post-trial analysis.

1. Different critical busbars are considered in the study. The application of GUS controller can significantly increase the allowable ASHP and EV customer numbers if the College Goldscleugh busbar is considered. However, no extra LCT customer number can be connected with GUS controller if only the Akeld busbars are considered, because of the location of the capacitor bank and the capacitor bank stage position limits. If only the LV busbar, Akeld demand, is considered, more allowable ASHP and EV customers can be achieved;
2. Under voltage problems normally happen at HV voltage level first, while overvoltage problems normally happen at LV voltage level first. This is because of the HV/LV transformer boosts the voltage at the LV network.

The allowable LCT customer numbers also depend on the operation of other EAVCs. As shown in section 4.3.3, if only the Akeld Demand busbar is considered as critical busbar, applying GUS controller reduces the allowable EV customer number.

6 Appendix A - Pre-trial simulation

Pre-trial simulation has been conducted to build the confidence for field trials. Simulation has been conducted with different target voltages and bandwidths. The parameters of Mechanically Switched Capacitor Bank (red section) are listed in Table 16.

Table 16 Parameters of Hedgeley Moor Capacitor Bank – Red Section

Location	Range of Capacitor Stage Positions	Capacitor Step Size
Hedgeley Moor (Red Section)	0-8	0.5MVAr/Stage

As mentioned above, the capacitor bank section connected to the Heckley High House feeder is selected for this post-trial analysis. In this study, the rest EAVCs are at their existing settings, as shown in Table 17.

Table 17 EAVC Settings

EAVC	Location	Target Voltage (pu)	Bandwidth (%)	Tap Position (%)
EAVC11	Denwick Primary T1	1.01	1.67	-
EVAC12	Denwick Primary T2	1.01	1.67	-
EAVC31	Glanton	-	-	-1.25(locked)
EAVC32	Hepburn Bell	1.00	1.5	-
EAVC42	Hedgeley Moor (Green section)	1.00	2	-

A winter daily demand profile (21st Jan, 2013, shown in section 4.1.1) is used for the pre-trial simulation. The initial position of the Hedgeley Moor capacitor bank is set as 0.

The Akeld 20kV busbar and the Percy Cross South 20kV busbar are controlled by GUS within upper and lower voltage limits. The Akeld 20kV busbar is at the end of the three-phase feeder of the Heckley High House teed 20kV feeder, while the Percy Cross South 20kV busbar is the HV/LV substation which is close to the red section of the Hedgeley Moor capacitor bank. The upper voltage limit is set as 1.016pu, to avoid overvoltage on the LV network immediately downstream of the Percy Cross South HV/LV substation. This upper voltage limit is based on the following assumptions:

- A 20kV/0.433kV transformer is used at the Percy Cross South HV/LV substation;
- The tap position of this transformer is set at 0%;
- The voltage drop across the transformer is neglected.

Multiple lower voltage limits are adopted. Simulation results for various lower voltage limits are shown in the following.

a) Lower voltage limit as 0.94pu

The lower voltage limit is set as 0.94pu for the 20kV busbar of Akeld. Busbar voltages and the Hedgeley Moor capacitor stage position are shown in Fig. 27.

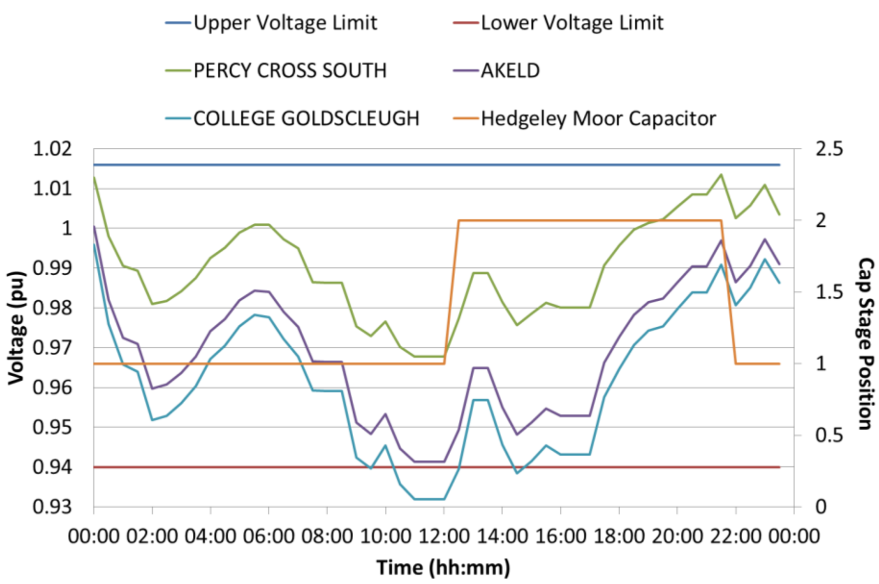

Fig. 27 Simulation Results with Lower voltage limit as 0.94pu

As shown in Fig. 27, the voltage at Akeld and Percy Cross South were controlled within limits. However, the voltage at College Goldscleugh will drop below the statutory voltage lower limit (0.94pu).

b) Lower voltage limit as 0.95pu

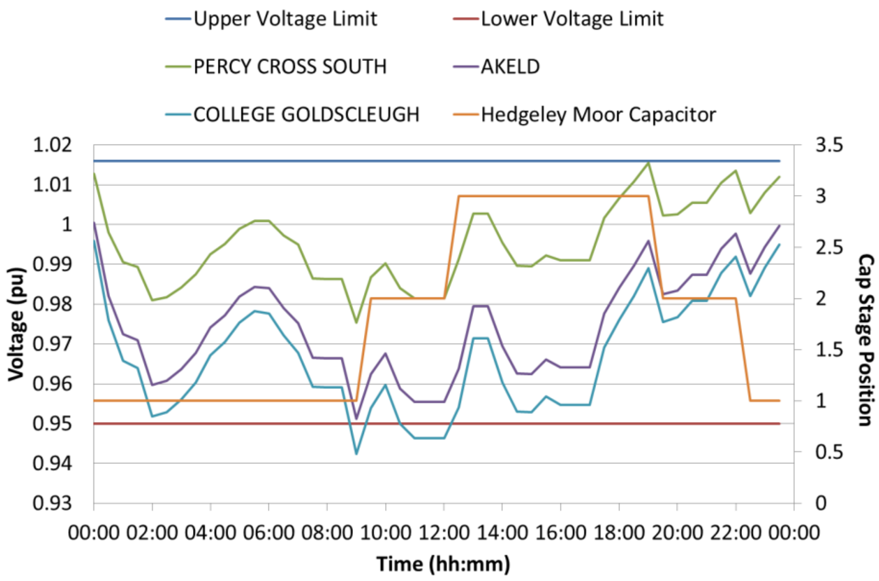

Fig. 28 Simulation Results with Lower voltage limit as 0.95pu

c) Lower voltage limit as 0.96pu

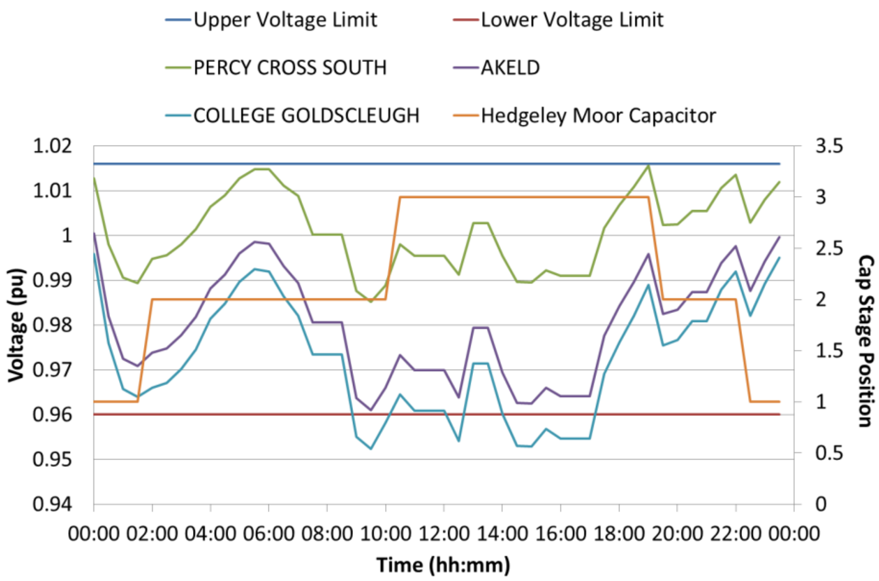

Fig. 29 Simulation Results with Lower voltage limit as 0.96pu

d) Lower voltage limit as 0.97pu

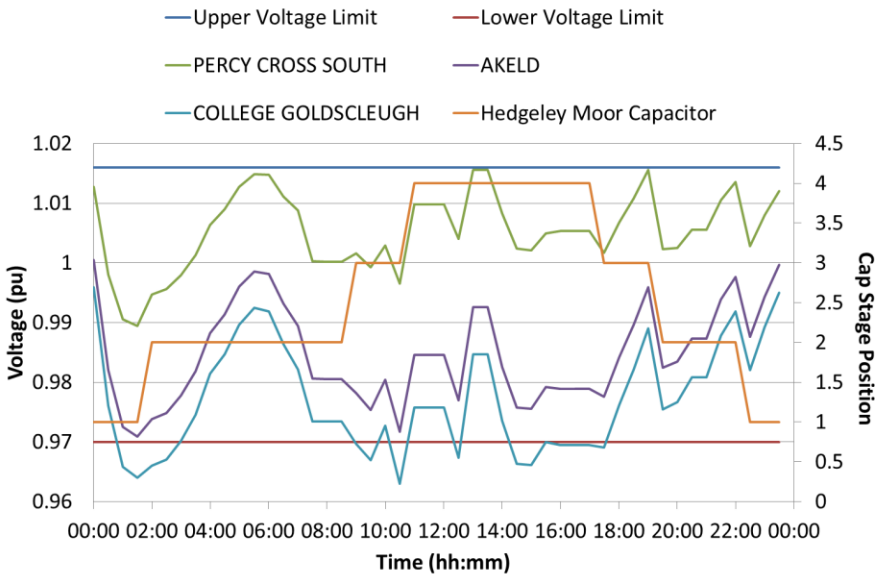

Fig. 30 Simulation Results with Lower voltage limit as 0.97pu

e) Lower voltage limit as 0.98pu

With the lower voltage limit set as 0.98pu, it is not possible to always keep the voltage at Akeld and the voltage at Percy Cross South within the voltage limits simultaneously. This is shown with the simulation results in Fig. 31 and Fig. 32.

As shown in Fig. 31, the voltage at Percy Cross South is above the upper voltage limit between 12:30 and 13:00, and between 14:30 and 17:30. The position of the Hedgeley Moor capacitor bank is at 5. If the Hedgeley Moor capacitor bank tapped from 5 to 4, to reduce the voltage at Percy Cross South, the voltage at Akeld will drop under the lower voltage limit, as shown in Fig. 32.

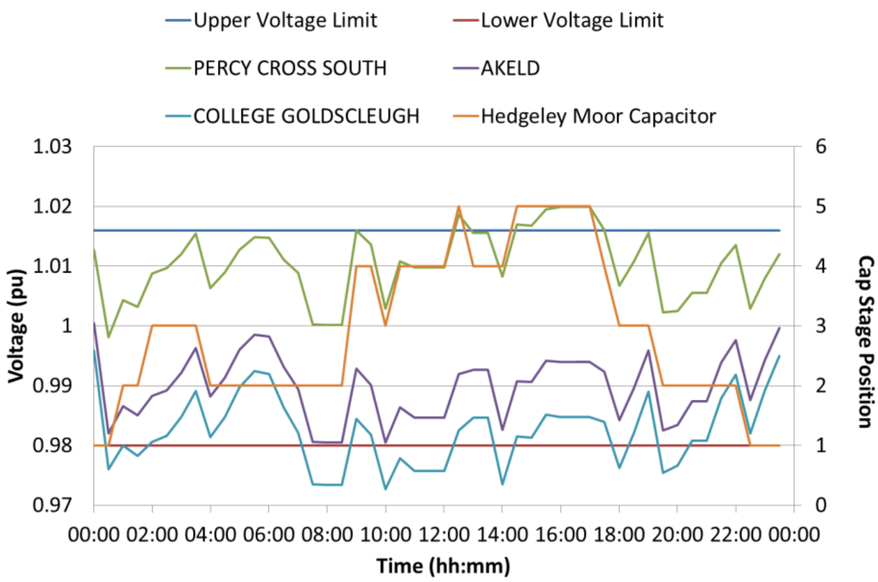

Fig. 31 Simulation Results with Lower voltage limit as 0.98pu – Upper Voltage Limit Violation

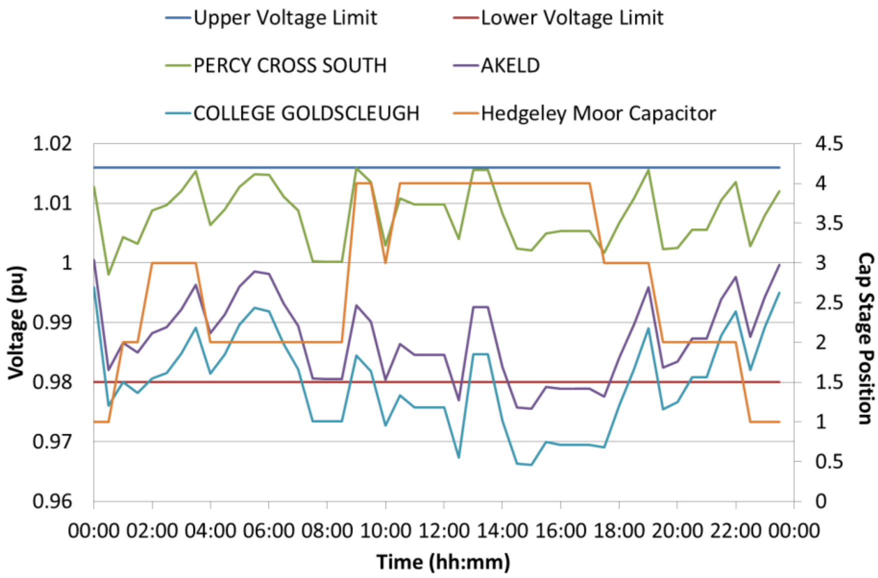

Fig. 32 Simulation Results with Lower voltage limit as 0.98pu – Lower Voltage Limit Violation

It is recommended, based on the simulation results shown above, to set the upper voltage limit as 1.016pu, and set the lower voltage limit between 0.95pu to 0.97pu in the GUS + Hedgeley Moor capacitor bank field trial. However, this is based on winter peak loading and therefore depending on the dates of the actual trial this will need to be revised.

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