Customer-Led Network Revolution

Tapchanging Secondary Transformer Autonomous and GUS Voltage Control

CLNR Trial Analysis

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Executive Summary

As part of the Customer Led Network Revolution (CLNR) project, tapchanging HV/LV transformers have been installed at 3 locations in the NE of England and Yorkshire, at Wooler Bridge, Darlington Melrose and Mortimer Road secondary substations. In addition, these tapchanging transformers are also integrated with the GUS distribution network control system which has been developed and deployed as part of the CLNR project programme.

Trials of these tapchanging HV/LV transformers under autonomous control were carried out between March and June 2014. Further trials of the tapchanging HV/LV transformers under the control of the GUS were carried out between July and September 2014. This report details the validation, extension, extrapolation, enhancement and generalization (VEEEG) of these trials.

A validated model of the closed loop GUS voltage control system operating 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 [1].

The installation of the tapchanging HV/LV transformer has been shown to increase the voltage headroom and legroom on the network as per Table 11.

Table 1 Additional Simple Headroom and Legroom due to network interventions

Network Intervention	Size	Location	Extra Headroom (pu %)	Extra Legroom (pu %)
Tapchanging transformer	N/A	HV/LV Substation	8.70	7.40

The impact of changing the bandwidth on HV/LV transformers, using the validated models developed as part of this work and the 1-minute time resolution data from the trial sites, was evaluated. It was found that decreasing the bandwidth from 4% to 3% increases the number of tapchanger operations by a factor of 3.7. However, it should be noted that the decreasing the bandwidth from 4% to 3% has the impact of increasing the effective legroom of the transformer by 0.5%.

The installation of the tapchanging HV/LV transformer has been shown to substantially increase the allowable penetration rates of LCT installations above BAU. The incremental change in the LCT penetration rates depend on the profile of LCTs and their location.

The capability of the tapchanging HV/LV transformer was improved further when integrated with the GUS system particularly when comparing PV installations with autonomous voltage control and single + GUS voltage control. Line drop compensation (LDC) techniques could be used to provide some of the benefits of voltage control using the GUS system however, LDC would not be able to provide the same level of capability to connect LCT as it relies on a simple static model of the downstream LV network which has limitations considering the: -

a. the anticipated non-uniform, unplanned growth in PV, ASHP and EV in LV networks;
b. dynamic distributions of loads due to possible changes in the geographical distribution of EV load;
c. variations in EV charging load due to customer behaviour changes.

The concept of the distributed voltage sensitivity factor (DVSF) is introduced in this work. This metric represents and relate the voltage change at the remote end of distribution network due to the real power import/export of all customers in the network. This enables us to evaluate the impact of increasing penetrations of LCT on different LV networks. DVSFs for the trial LV networks in CLNR and the UK generic networks given to illustrate the impact the distribution and number of customers and network topology have on remote end voltage in UK LV networks.

1 Introduction

As part of the Customer Led Network Revolution (CLNR) project, tapchanging HV/LV transformers have been installed at 3 locations in the NE of England and Yorkshire, at Wooler Bridge, Darlington Melrose and Mortimer Road secondary substations. In addition, these tapchanging transformers are also integrated with the GUS distribution network control system which has been developed and deployed as part of the CLNR project programme.

Trials of these tapchanging HV/LV transformers under autonomous control were carried out between January and June 2014. Further trials of the tapchanging HV/LV transformers under the control of the GUS were carried out between July and September 2014. This report details the validation, extension, extrapolation, enhancement and generalization (VEEEG) of these trials.

The work detailed in this report has been conducted using the models of Mortimer Road, Denwick HV network and Wooler Bridge LV network to evaluate the capability of these networks to accommodate LCT following deployment of tapchanging HV/LV transformers. This has been achieved using validated network models and a combination of real and synthesised load and generation data.

Steady-state IPSA2 models have been previously developed and validated using SCADA data. This model has been extended by the addition of a detailed LV network model using Northern Powergrid supplied data.

The load data for the VEEEG study cases are derived from actual data from the SCADA system of this network. This is supplemented, in order to create realistic future scenarios, with load profiles derived through analysis of CLNR smart meter measurements, of 9000 customers, and LCT profiles derived from salient literature and real data from CLNR trials. A list of the LV voltage control trials which have been expanded and augmented through trial analysis using the VEEEG methodology is given in Table 2. Baseline trials of the entire Denwick and Rise Carr networks are included as they provide the baseline data for all the further trials on the LV networks.

Table 2: List of LV voltage control network flexibility field trials at Wooler Bridge (from Denwick), Darlington Melrose (from Rise Carr) and Mortimer Road

Trial No.	Trial Name
21.11	Baseline system at Denwick
21.13	HV/LV OLTC Transformer at Wooler Bridge
21.28	Closed loop GUS voltage control system at Wooler Bridge HV/LV OLTC
22.8	Baseline system at Rise Carr
21.27	HV/LV OLTC Transformer at Wooler Bridge with EES as PV generation

22.10	HV/LV OLTC Transformer at Darlington Melrose
22.29	Closed loop GUS voltage control system at Darlington Melrose HV/LV OLTC
23.2	Baseline system at Mortimer Road
23.3	HV/LV OLTC Transformer at Mortimer Road (Autonomous)
23.11	Closed loop GUS voltage control system at Mortimer Road HV/LV OLTC
23.6	HV/LV OLTC Transformer at Mortimer Road with EES as PV generation

2 Methodology and assumptions

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 Newcastle University. This approach is derived from previous experience of trials at Newcastle 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 [1]. 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 Newcastle University consists of five steps:

1. Validation
2. Extension
3. Extrapolation
4. Enhancement
5. Generalisation

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

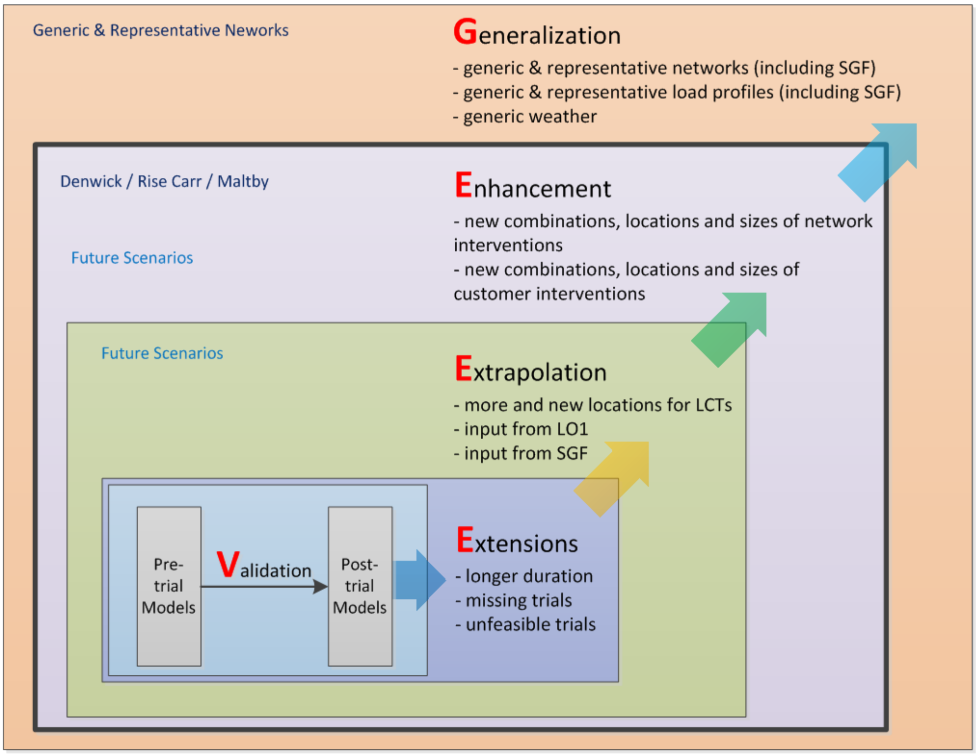

Fig. 1 Post-trial methodology VEEEG

3 Trial Results and Validation

3.1 Tapchanging HV/LV transformer

Following analysis of the data from the relevant autonomous tapchanging HV/LV transformer trials, the data from CLNR Field Trial *23.3 HV/LV OLTC Transformer at Mortimer Road (Autonomous)*, carried out from 8th January 2014 until the 26th February 2014, is used in this work to illustrate how the trials have been used to inform the development and validate tapchanging HV/LV transformer models.

In order to improve the quality of the data from the trial for validation purposes and also to evaluate changes in control settings, the deadband of the OLTC installed on Mortimer Road 11/0.4 kV transformer was changed from 3% to 1.5% on 5th February 2014. The AVC relay time delay time is set to 2 minutes for the duration of the trial. The tap step is from -4 to 4 and each step results in a change of 0.02 pu on the transformer secondary voltage under no-load conditions. The target voltage is for the trial period is 0.415kV (1.0375 pu).

3.1.1 Validation approach

The tapchanging HV/LV transformer models developed from the trials detailed earlier, are validated with the following steps:

1. Extract the total consumed real and reactive powerflows (P, Q) on Mortimer Road and secondary voltage of 11/0.4 kV transformer data (from iHost). Tap position data was extracted from the flexible data warehouse (FDWH).
   In this study, the iHost data was used as the sampling of the data is at a higher and more consistent rate than the data from the FDWH. The sampling rate of the data from the FDWH is inconsistent as the data point update is triggered by changes in the magnitude of the measurement. This approach minimises data transfer across the real system but presents considerable difficulties in the analysis of field trial data.
2. Model the primary side voltage using the data from the FDWH and iHost.
3. Simulate the transformer tapchanger behaviour using the simulated primary voltage, real and reactive power developed in IPSA/Python. Update model if the behaviour demonstrated by the field trial results is substantially different from the simulated results.
4. Compare the simulation and field trial results and analyse the difference between the two results

3.1.2 Baseline Data

In this initial validation study, data from the 14th February 2014 was used. Fig. 2 illustrates the real and reactive power flowing through the Mortimer Road 11/0.4kV transformer on 14th February 2014.

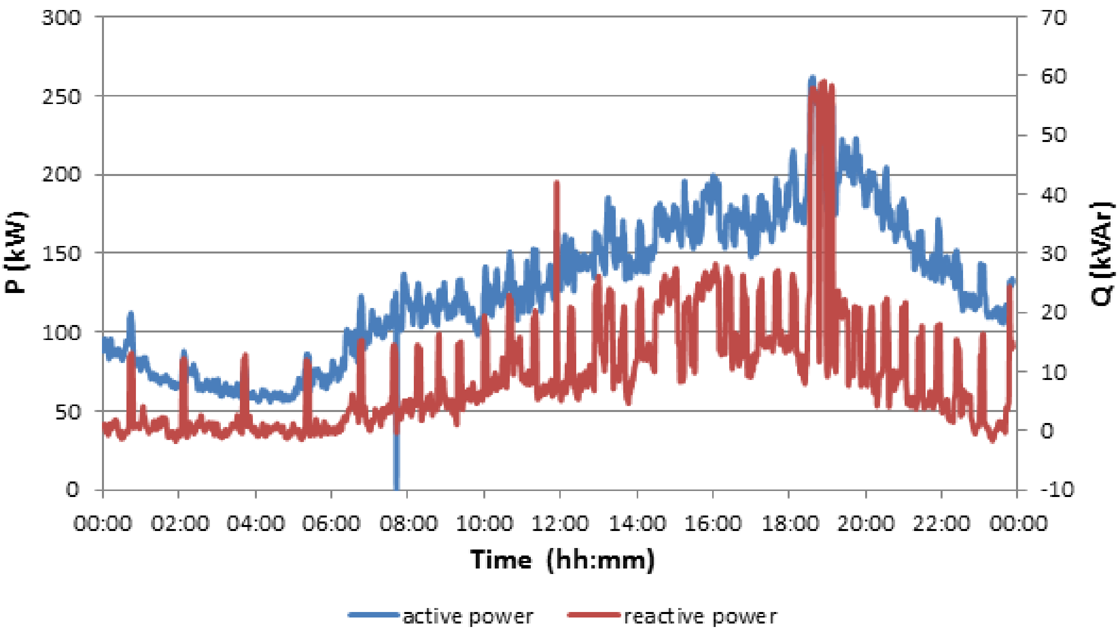

Fig. 2 Active and reactive power consumption of Mortimer Road on 14/02/2014

Fig. 3 illustrates the iHost and FDWH transformer secondary voltage profiles and the tap position data from the FDWH.

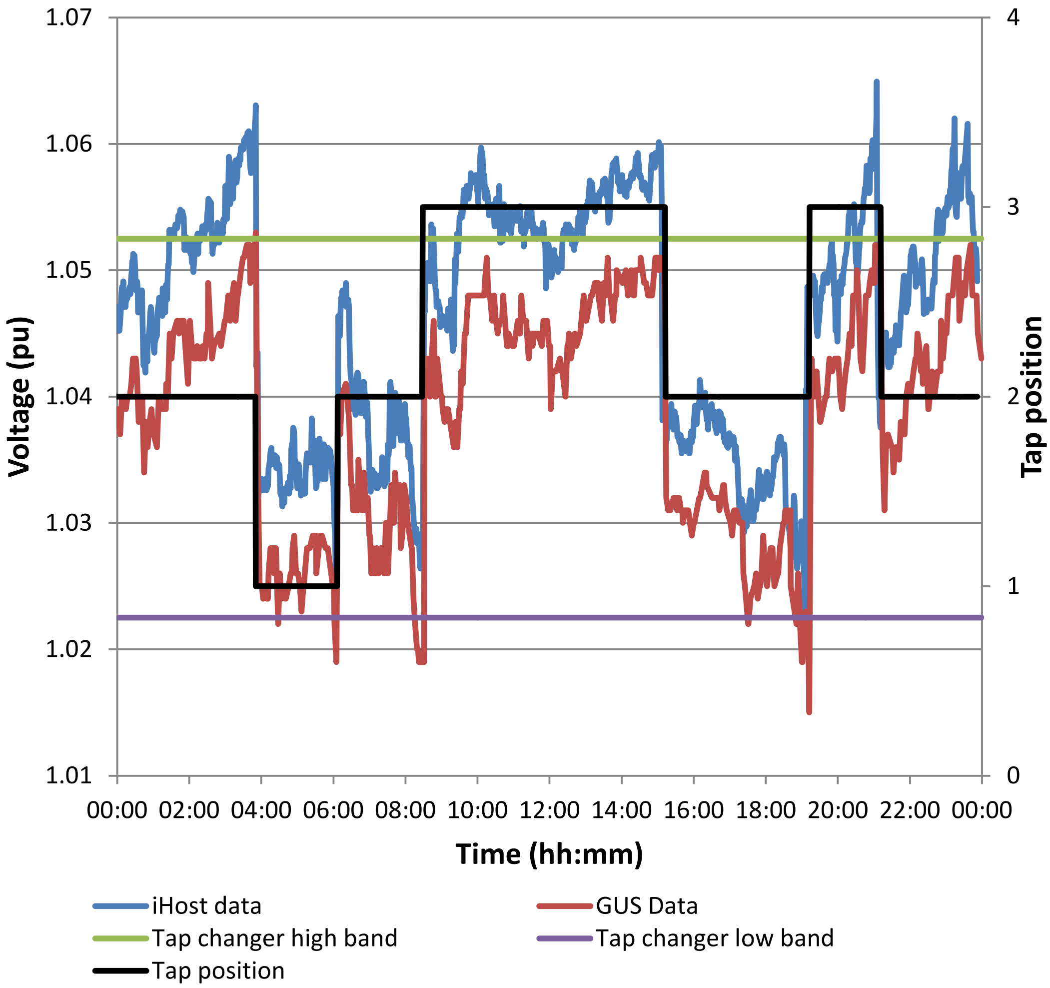

Fig. 3 Secondary voltage profiles and tap position of Mortimer Road on 14/02/2014 from iHost and FDWH

It can be seen from Fig. 3 that the voltage magnitudes from iHost is approximately 0.5% greater than those from the FDWH. In addition, the iHost voltage profile indicates that the AVR (Automatic Voltage Relay) is controlling the voltage to a target voltage of 1.045pu. In contrast, the voltage profile from the FDWH is controlling the voltage to the target voltage setting (1.0375pu).

Following consultation with Northern Powergrid and Siemens, it was found that the FDWH voltage data is from the AVR rather than iHost which provides the remainder of the data. Therefore, the FDWH voltage data should be used to validate OLTC models. However, the inconsistent sampling rate of the data stored on the FDWH (cannot be used for simulation work directly) poses a number of practical difficulties for modelling of the system. Therefore, recalibrated iHost voltage data is used as an input into the OLTC models. The recalibration of the iHost is within 0.5%. This is well within the tolerance limits for metering systems conventionally deployed on power systems. NPG have confirmed that the systems will be recalibrated and review to investigate the inconsistency between the two measurement systems.

The primary (11kV) voltage can be modelled using the following calculation:

$$V_{primary} = (V_{secondary} + V_{transformer\ drop})\times(1+\text{tap position} \times \text{step percentage}) \quad (1)$$

The simulated primary voltage is shown in Fig. 4.

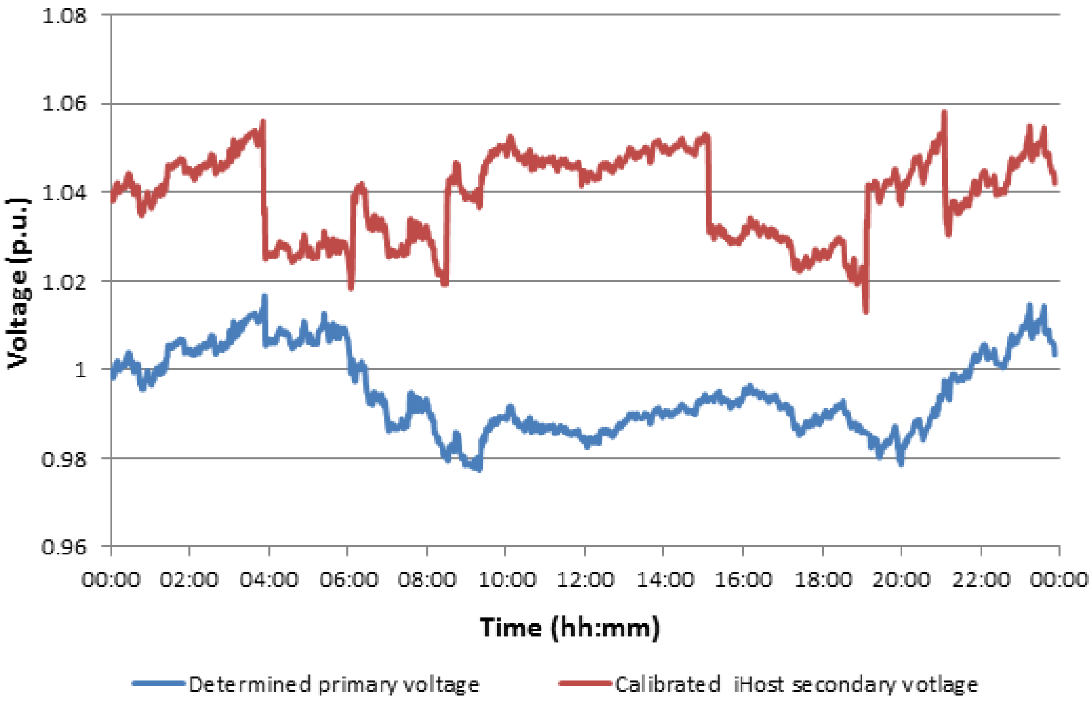

Fig. 4 Primary and secondary voltage profiles for Mortimer Road on 14/02/2014

3.1.3 OLTC Model 1 Results and Discussion

The determined primary side voltage data presented earlier and the real and reactive power data from iHost was used with an initial model to simulate the OLTC's behaviour. The AVR time delay is not considered in this model and can be considered to be a standard steady-state model of an OLTC and is suitable for modelling networks with lower time resolutions. Fig. 5 presents the results of the field trial in comparison with the simulated results using OLTC Model 1.

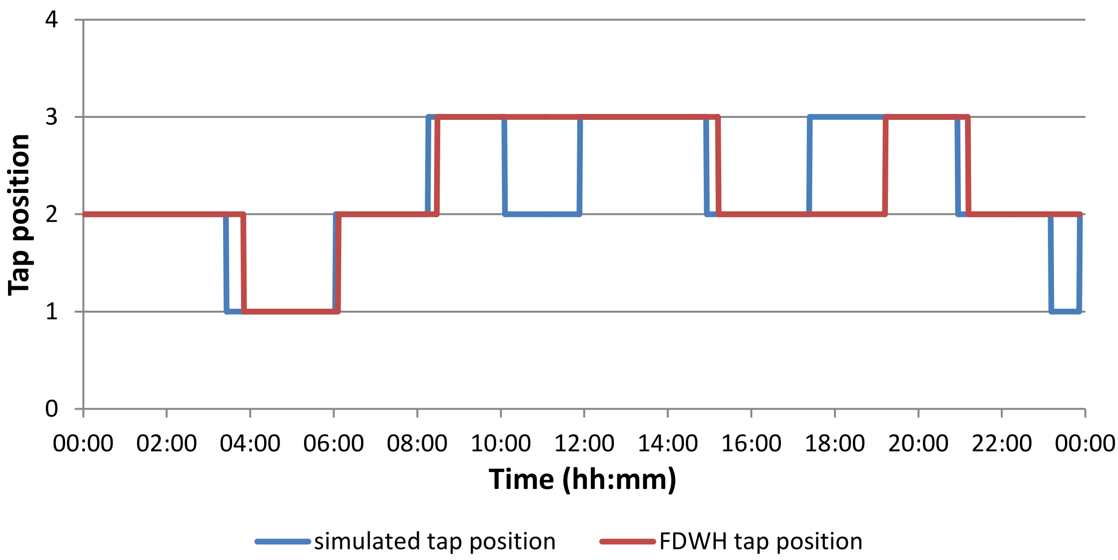

Fig. 5 Measured and Simulated OLTC position on 14/02/2014 (OLTC Model 1)

The simulated tap position was compared with the tap position data extracted from FDWH. It can be seen that there are a number of differences between the field trial results and simulation. The AVRs time delay was identified as a possible reason for these differences therefore an improved model was implemented in IPSA/Python which addresses this limitation of the model.

3.1.4 OLTC Model 2 Results and Discussion

A 2 minute delay was implemented in the IPSA/Python OLTC model. In this model the AVR would initiate a tap change if the measured voltages are outside the bandwidth for over two minutes. Fig. 6 presents the results of the field trial in comparison with the simulated results using OLTC Model 2.

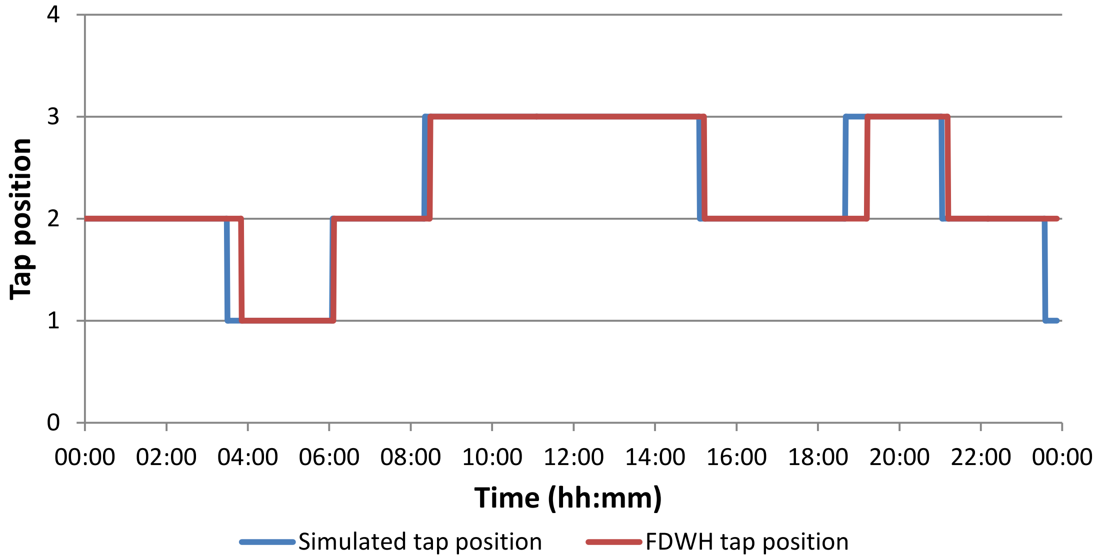

Fig. 6 Measured and Simulated OLTC position on 14/02/2014 (OLTC Model 2)

Fig. 6 shows the simulated tap position when a 2 minute delay was implemented into the IPSA/Python model (OLTC Model 2) in comparison with the observed field trial data. This time delay has the effect of not triggering tapchanger operations when the duration of voltage excursion out of the bandwidth is short duration. Therefore, it is likely to reduce the number of observed tap change operations in the model as illustrated in Fig. 6. It can be seen that the OLTC Model 2 is substantially more accurate in predicting the operation of the tapchanger.

It is likely that much of the remaining differences in operation can be explained by inaccuracies in the estimation of primary voltage using iHost data and inaccuracies in the voltage measurements observed by the AVR. Further reasons for the differences in the operation between the systems include assumptions of balanced operation and the impedances of the transformer.

3.2 LV Regulator results

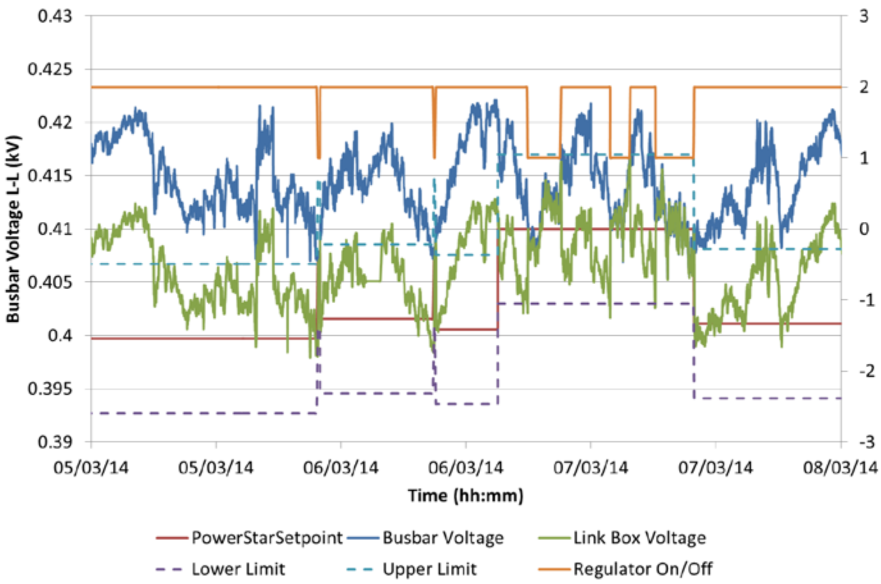

Fig. 7 Regulator and Busbar Voltage for Sidgate Lane 5th March 2014 – 8th March 2014 from iHost and FDWH

The response of the LV regulator at Sidgate Lane in response to a dynamic setpoint input from the VVC system is illustrated in Fig. 7. In this case, when the *Regulator On/Off* trace has a value of 2 this implies that the regulator is on i.e. there is a voltage reduction. When the *Regulator On/Off* trace has a value of 1 this implies that the regulator is off i.e. there is no voltage reduction downstream of the regulator. There is a hysteresis bandwidth around the target voltage setpoint, supplied by the GUS system, above which or below which the regulator does not act. Study of the characteristics of the LV regulator indicates, if appropriately located on the feeder with greatest voltage variation, there is little benefit in integrating this with the GUS system. The validated model of this device was developed validated using the same methodology developed in the previous section.

3.3 Validation of GUS voltage control of transformers

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, an LV feeder connected electrical energy storage system, named as EES3 in CLNR, is operated manually to model additional load and generation LCTs as per *23.6 HV/LV OLTC Transformer at Mortimer Road with EES3 as PV generation*. This EES unit is located downstream of the HV/LV tapchanging transformer at Mortimer Road. 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.

3.3.1 Validation approach

For Field Trial 23.11, similar approach is applied for data preparation. A more complex tapchanger control algorithm is implemented, which is introduced in the following.

For the tapchanging HV/LV transformer +GUS voltage control, the tapchanger behaviour is simulated by controlling the tapchanger with an optimal voltage control algorithm which duplicates the behaviour of Distribution System State Estimator (DSSE) and Voltage Var Control (VVC) algorithm applied in the field trials. As per the flow chart shown in Fig. 8, the voltage control algorithm includes the following steps:

1. DSSE takes measurement across the network, and calculates the network load condition based on the measurement and the network model within the control system. During the Field Trial 23.11, DSSE is executed periodically with 5 minute cycles. It should be noted that here the network model developed in IPSA2 is used to represent both the real network and the network model in DSSE for simulation, which means the error from DSSE is neglected. After calculation, DSSE passes the network load condition, which is based on the network measurement 5 minutes ago, to VVC;
2. VVC utilizes the network load condition calculated by DSSE and network model to find the optimal voltage control solution, with a deterministic optimization algorithm. This deterministic optimization algorithm, named as oriented discrete coordinate descent method, has been implemented with Python and IPSA2. In Field Trial 23.11, no optimization objective is defined, and the optimization algorithm only solves voltage constraints violation;
3. In the initial modelling of the SIEMENS control system applied in CLNR, the VVC issues an optimal tap position that was calculated to tapchanger directly, according to the specification of the original SIEMENS Spectrum PowerCC system. The CLNR project did not want to allow the system to send tap up / tap down commands directly to the AVC relay, but to send a target voltage setpoint and let the AVC relay tap around that value. The VVC, therefore worked out the current voltage and tap position, from that worked out what the voltage would be if it was at the optimum tap position and sent that value out as a target voltage set point. Therefore, an additional algorithm, which converts tap position to target voltage, has been added to represent this change in the implementation. Since the exact mechanism of converting tap position to target voltage is not clear, a simple method is used in this work instead. This method is shown in the flow chart shown in Fig. 8 and can be replaced with a model of the exact mechanism from SIEMENS when available;
4. The AVC relay operates the on-load tapchanger in response to the target voltage setpoint. A standard AVC algorithm is implemented here and is modelled as detailed previously, which means tap operation will be executed if the transformer secondary voltage is out of the new voltage range for over 2 minutes.

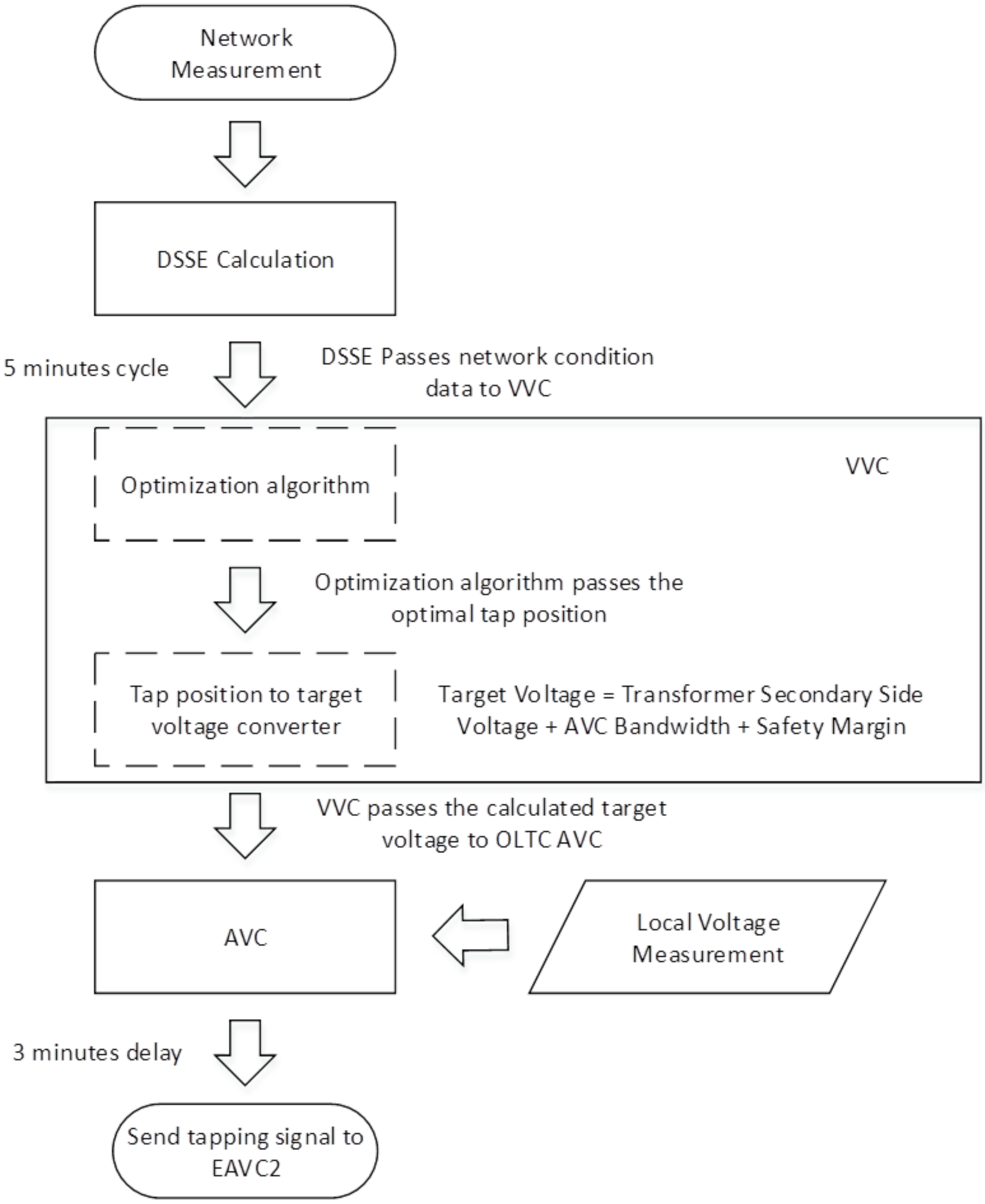

Fig. 8 GUS Voltage Control Model Flow Chart

3.3.2 GUS voltage control results

Trial results for Field Trial 23.11 on 17th September 2014 are shown in Fig. 9.

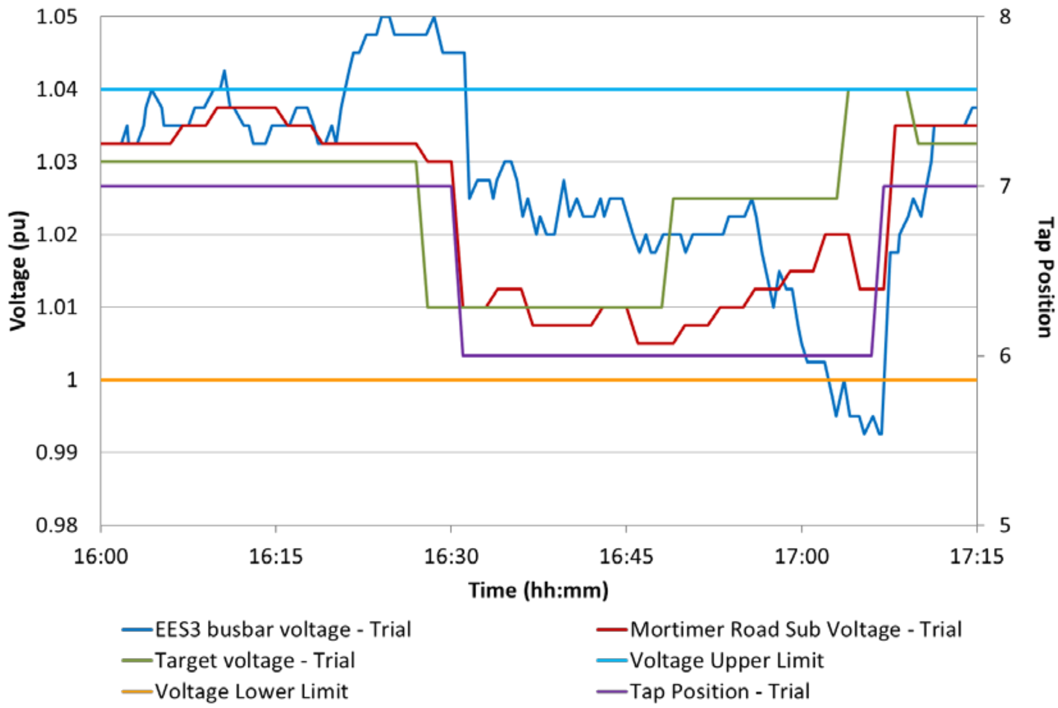

Fig. 9 Voltage profiles and tap position of Mortimer Road on 17th Sep 2014 from FDWH

It can be seen from the trial results that the control algorithm changes the target voltage for the transformer, responding to voltage constraints violation at the EES3 connection point which is the node where the lowest/highest voltages are likely to be found due to its location deep within the LV network and the presence of extra load/generation. This node can be seen as the remote end node for this analysis. The AVC relay changes the tap position in response to the new target voltage and the voltage measurement at the transformer secondary side. It should be noted that there is a target voltage change after 16:45, which does not lead to tap operation, this is due to a short duration voltage constrains violation, which happens at other busbars. The details will be explained later in this section.

The simulation results with the primary voltage, network demand, EES3 real output, tap position, target voltage and remote end node data are shown in Fig. 10. It can be seen that generally the simulation results are relatively consistent with the trial results shown in Fig. 9.

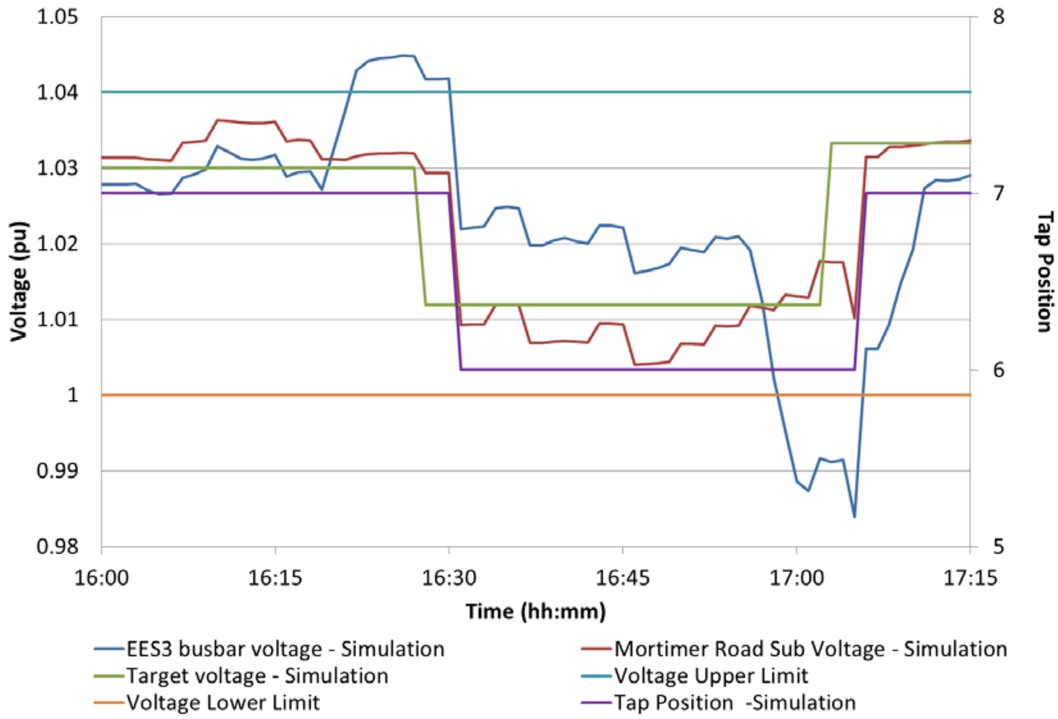

Fig. 10 Simulaton results for Field Trial 23.11 at Mortimer Road on 17th Sep 2014

In the following, network voltages, target voltage and tap position are compared separately. The trial and simulation results are compared in Fig. 11, for voltages at the secondary substation of Mortimer Road and remote end (EES3 connection busbar).

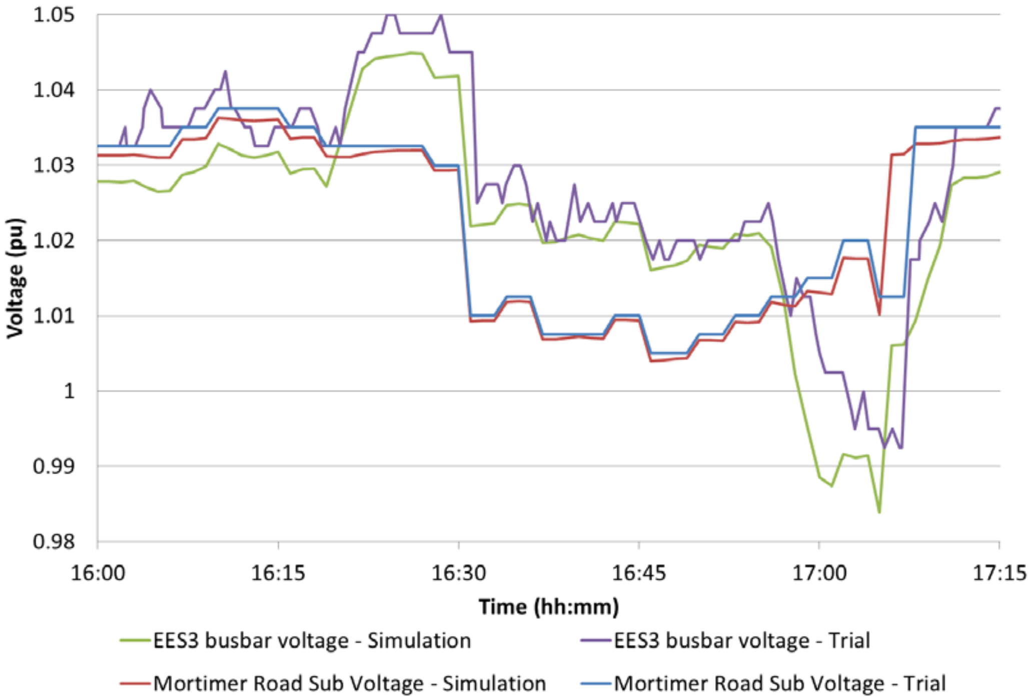

Fig. 11 Trial and Simulation Voltage Profiles

It can be seen that voltages from simulation are close to that from trials. It can be seen that the voltage profile of the remote end busbar from the field trial has more variations than other voltage profiles. This is due to the fact that the voltage at the remote end from the trial has a higher temporal resolution.

Fig. 12 illustrates the target voltage changes from simulation and field trial.

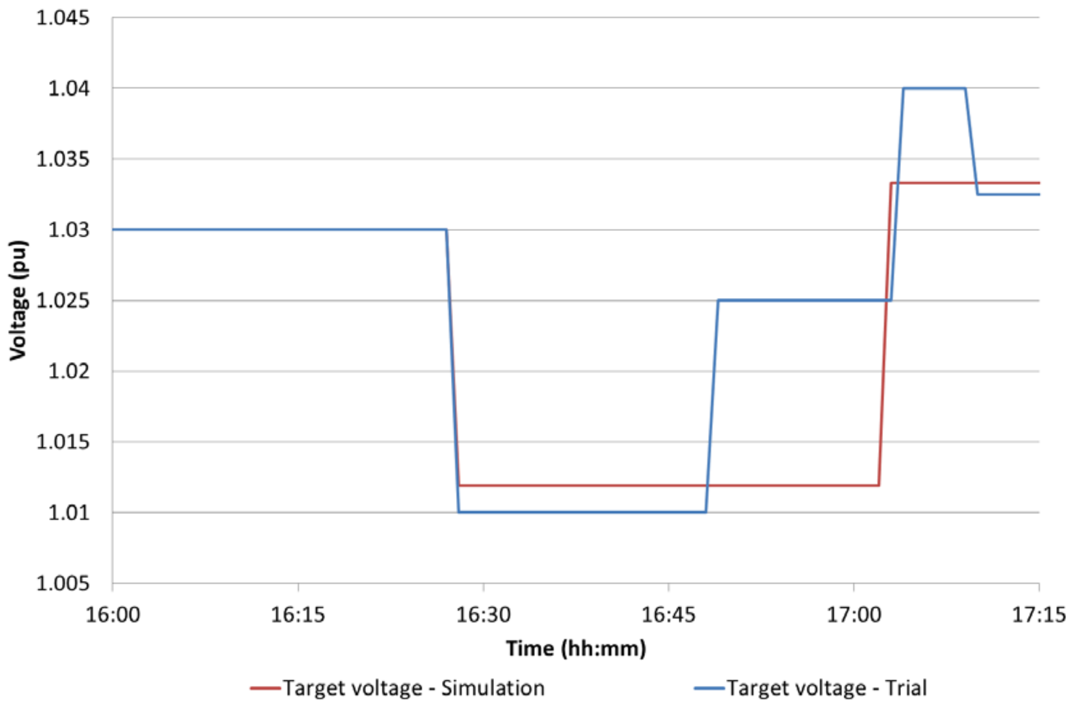

Fig. 12 Trial and Simulation Target Voltage

As shown in Fig. 12, the target voltages from simulation are not exactly the same as that from field trials. This is partially due to the method used in simulation to calculate new target voltage is not the same as that used by SIEMENS in field trials. In addition, there are four target voltage changes in field trial results while there are only two target voltage changes in simulation results. This is explained as follows:

1. For the target voltage change happened around 16:45 in field trial, the target voltage change is initialized by the voltage constraints violation at another busbar. This busbar is in the middle of the LV feeder to which EES3 is connected, and the voltage profile of this busbar (BusbarN11) from simulation is shown in Fig. 13.
2. It can be seen from Fig. 13 that actually there is also voltage constraints violation in simulation. However, this 3 minutes voltage constraints violation is skipped by DSSE and VVC, which have a 5 minutes execution cycle.
3. For the last target voltage change from the field trial, it may be due to the mechanism used by SIEMENS to convert tap position to target voltage. Also, at this period the tap position is changing from tap position 6 to tap position 7, which may lead to a short period target voltage value.

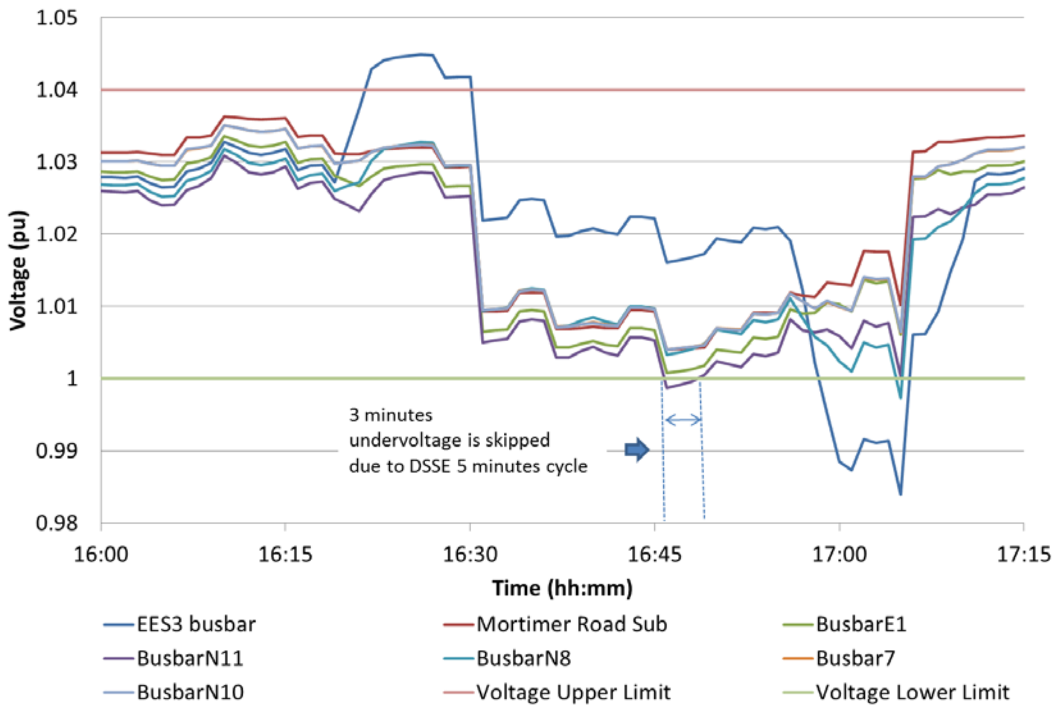

Fig. 13 All critical busbar voltage profiles from simulation

The tap positions from field trial and simulation are shown in Fig. 14. It can be seen that although there are some differences between the target voltages from field trial and simulation, the tap operations from simulation are close to that from field trial. The operation mechanism of AVC mitigates the error from the network model and the method used for converting tap position to target voltage.

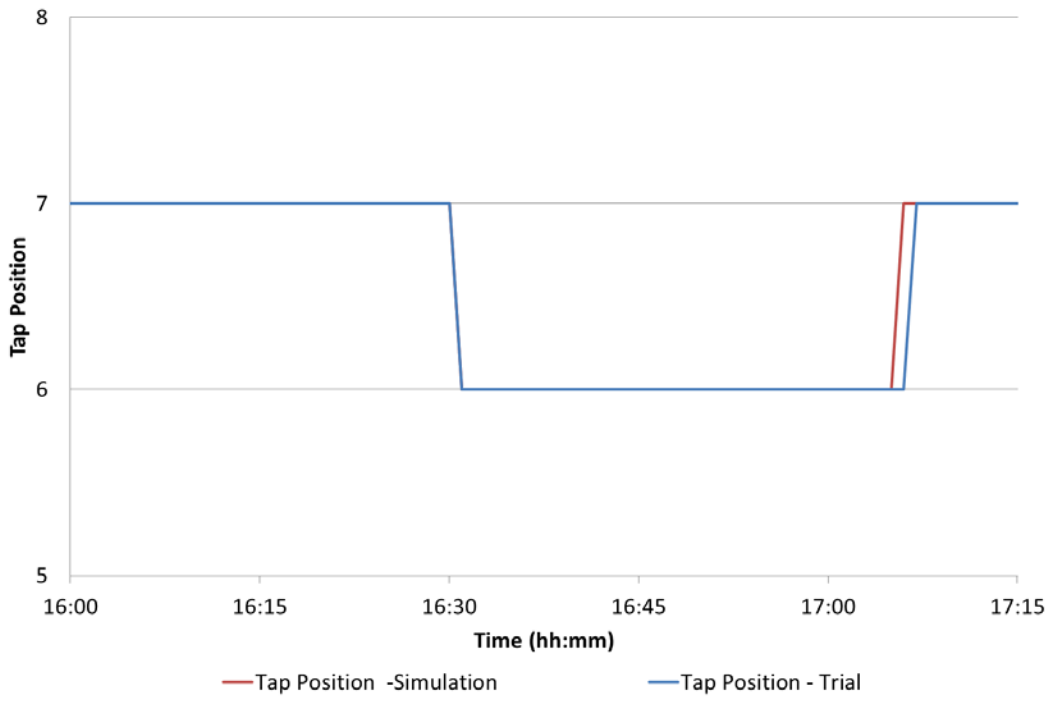

Fig. 14 Trial and Simulation Tap Position

3.4 Discussion

For the trials on the tapchanging HV/LV transformer, the following conclusions have been drawn:

- The FDWH voltage measurements for this study are derived from the AVR relay (rather than iHost voltage measurement) which operates the tapchanger. This is important as it is the voltage observed by the AVR that determines the operation of the secondary transformer OLTC in the autonomous voltage control.
- There are differences between the iHost and GUS measurement data. However, it should be noted that the accuracy of both systems is well within the tolerances of the measurement systems.
- Planning of systems utilising OLTC equipped secondary transformer operating autonomously need to be cognisant of the possible measurement error of the local busbar voltage. For example if the measurement tolerance is +/-1%, when considering high load/high generation scenarios, simulated remote end network voltages should not drop below 0.95pu and should not rise above 1.09pu to ensure that the customers do not experience voltages outside of the statutory limits.
- The sample rate of the data from FDWH is inconsistent which presents practical difficulties in analysis of large data sets.
- Two models are presented in the validation of autonomous operation of tapchanging HV/LV transformer study. OLTC Model 2 more closely predicts the operation of the OLTC especially

with data with temporal resolutions greater than 1 sample/min. It should be noted that these characteristics of the model can be only be adequately modelled if the sample rate of the input data (voltage, real and reactive power) is at least 1 sample/min. Lower sample rates are likely to underestimate the number of tapchanger operations. This could be a particular characteristic of OLTC equipped secondary transformers as primary transformers are likely to observe less noise on the voltage, real and reactive power traces due to the diversity of the load. Data at a high sample rate from LV substations, HV feeders and substations as well as analysis of the data from LO1 will clarify the impact of this effect.

For the trial on the GUS control of the tapchanging HV/LV transformer, additional conclusions are listed in the following:

- 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 trial.
- The simulation results achieved demonstrate that the control algorithm developed in Python and IPSA2 can generally represent the control algorithm used in field trial for further study.
- There are some differences between target voltages from simulation and field trial, 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 trial, 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 trial.
  - 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 the field trial results are detailed. The results from the validation phase are extended, enhanced, extrapolated and generalised using the validated Wooler St Mary's LV network model within the larger Denwick HV system which has a larger number of customers than the Mortimer Road network.

Feeder A of Wooler St Mary Substation is modelled in detail, as this feeder has the largest number of customers and would therefore be likely to see the biggest effect if all the customers had PV installed. The remaining two feeders in this system are modelled as lumped load.

A generation unit representing a number of PV microgeneration units is added to node 7, which has domestic customer connected. The rating of this generation unit is decided by the number of domestic customers, the rated power of single domestic PV generation system and the PV penetration rate. No generation unit is connected to node 10, as node 10 only has non-domestic customers connected. Furthermore, no generation units are connected to the customers on the rest feeders.

Fig. 15 shows the HV/LV cluster scenario for PV penetration rate study. It can be seen from Fig. 15 that the PV penetration is applied to all the domestic customers under this HV/LV substation.

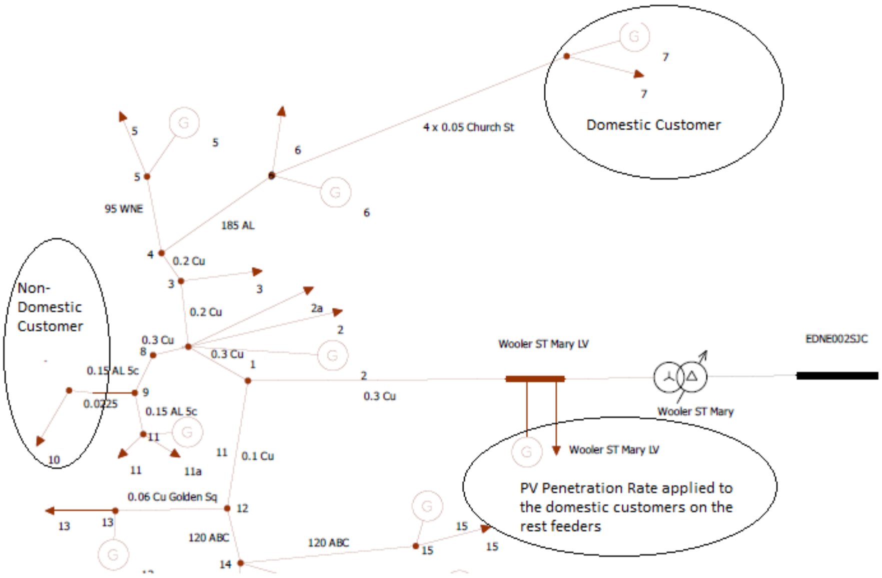

Fig. 15 HV/LV Cluster Scenario

4.1.1 Winter and summer load profiles

The winter and summer HV system loading profiles are presented in Fig. 16 and Fig. 17. As known, the winter loading is heavier than summer time's. Consequently, the winter load would be used to estimate the penetration of EV and heat pump connected to grid. And the summer load would be used to determine the PV penetration.

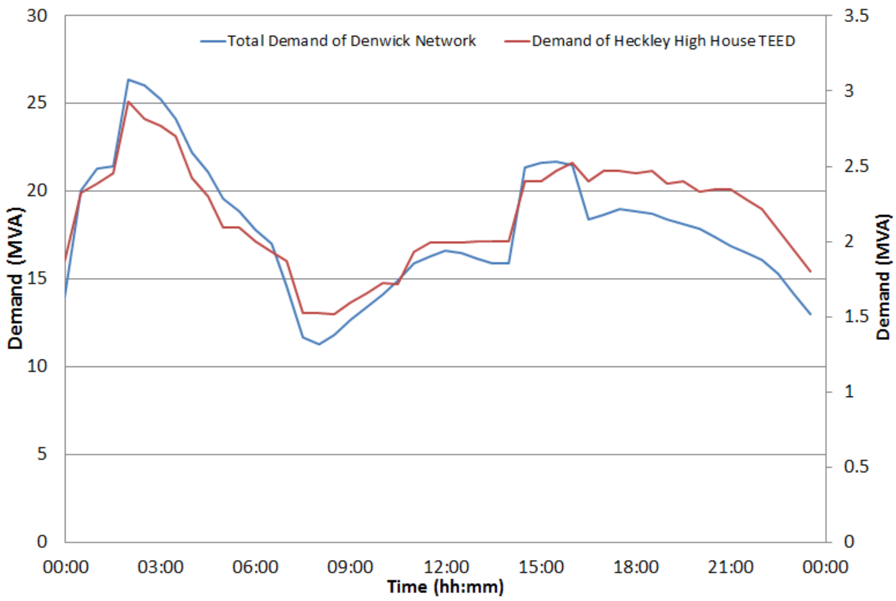

Fig. 16 Existing daily demand profile of the Denwick HV system (Winter Peak)

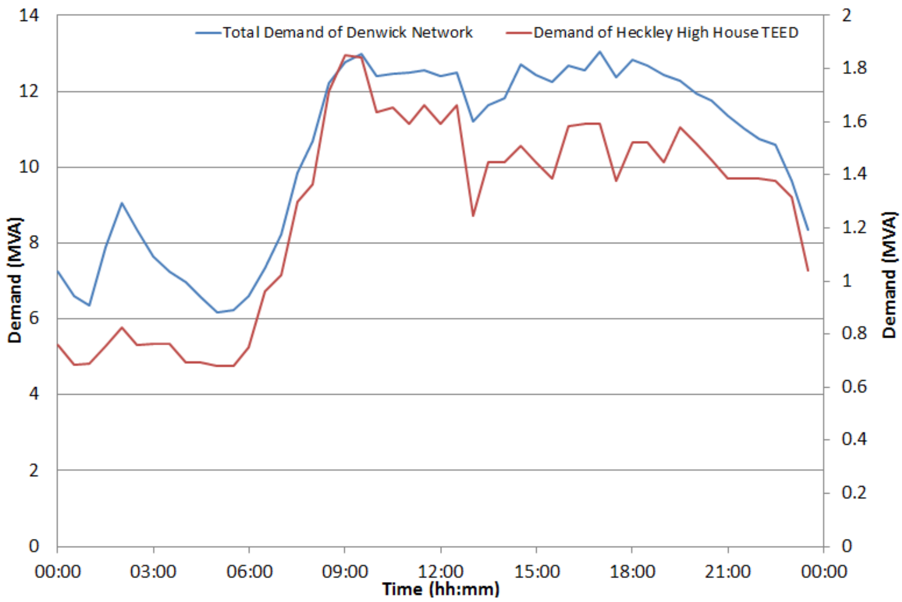

Fig. 17 Existing daily demand the Denwick HV system (Summer Minimum)

4.1.2 Air Source Heat Pump Model development

Thermal profiles for various types of buildings, including detached, semi-detached and flat, have been derived and aggregated in previous work [2]. In this report, the electrical profiles of air source heat pumps (ASHPs) in detached and semi-detached houses are generated based on thermal profiles. A coefficient of performance (COP) value of 2.5 has been applied.

Fig. 18 shows the typical domestic profile derived from the smart meter data in conjunction with an ASHP profile.

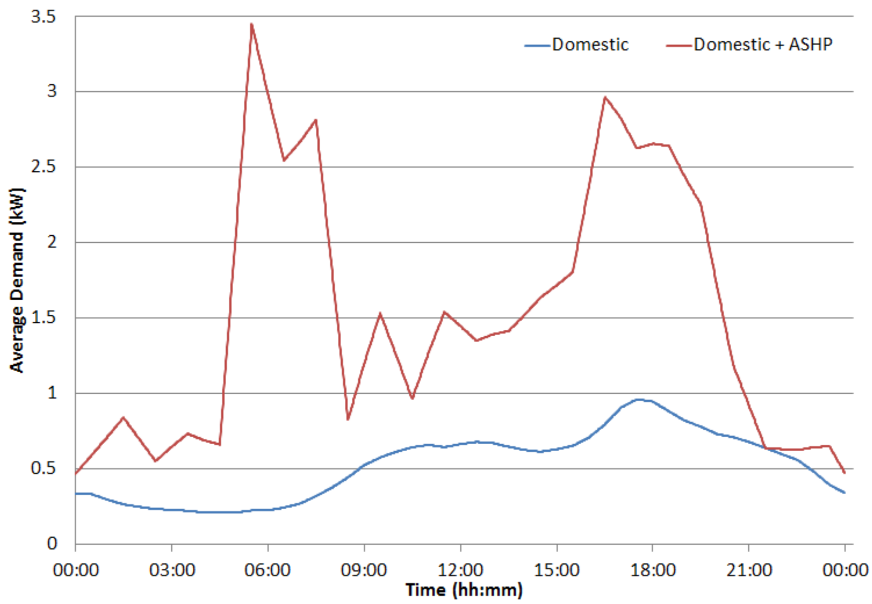

Fig. 18 Domestic profiles in combination with ASHP load

4.1.3 EV Model Development

The EV consumer model used in this work was based on profiles developed previously in [3]. 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 [3] which is in line with the average trip commute distance for the case study area [4]. 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.

Fig. 19 shows the typical domestic profile derived from the smart meter data in conjunction with an EV profile.

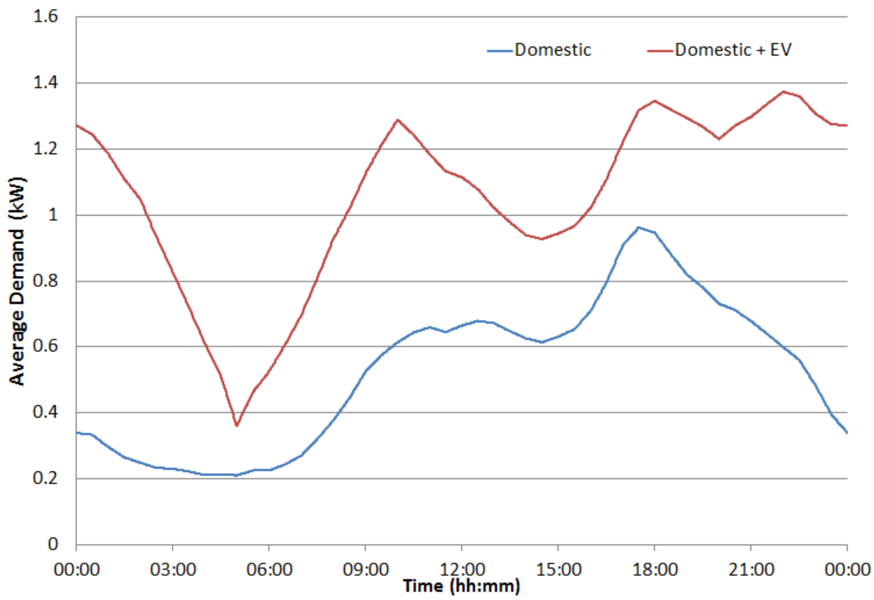

Fig. 19 Domestic profiles in combination with EV load

4.1.4 PV Consumer Model Development

Real PV data from a premise on Durham is used to derive profiles for use in the summer minimum load scenario. Data is available from June to October 2012 and maximum daily profile is derived.

Fig. 20 shows the typical domestic profile derived from the smart meter data in conjunction with a PV profile.

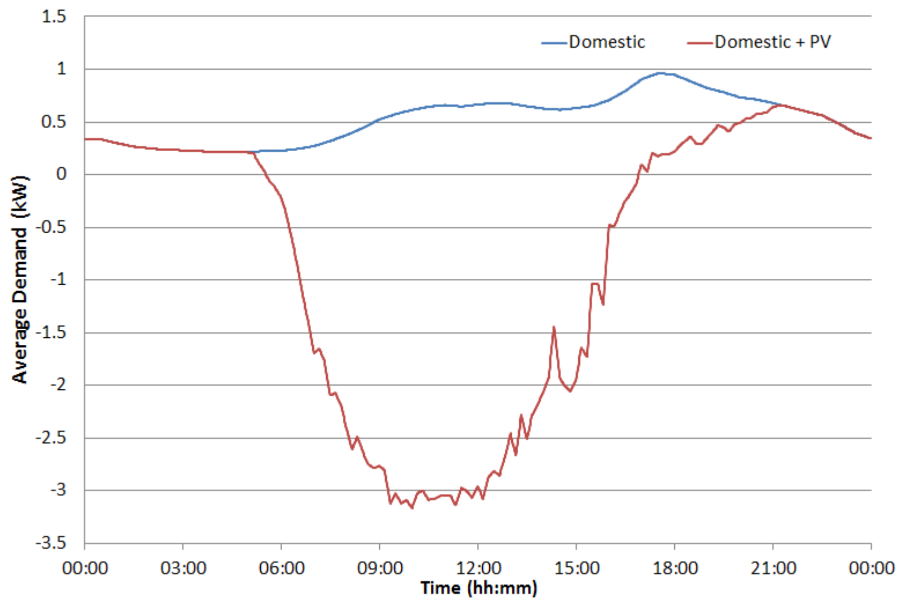

Fig. 20 Domestic profiles in combination with PV Generation

4.2 Extension

4.2.1 Headroom

The annual SCADA data from Northern Powergrid, consumer modelling described previously 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 3.

Table 3 Baseline Simple Voltage Headroom and Legroom

Location	Voltage Headroom (pu %)	Voltage Legroom (pu %)
Wooler St Mary Substation	0.07	8.14
Wooler Bridge Substation	2.45	6.96
Wooler Bridge Feeder C End	2.58	6.44
HV Feeder End of Heckley High House	4.27	0.44

It can be seen from Table 3 that the voltage headroom in the LV networks are much smaller than the voltage legroom, especially at the LV substation. 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 4 shows the extra headroom and legroom that can be achieved by these network interventions at selected locations based on the validated LV models that have been built of Wooler Bridge and Wooler St Mary. These values are from the load flow results with the network models in

IPSA. Tap ratio setting was changed from 0 to ±8% and the corresponding voltage changes (extra headroom and legroom) are calculated.

Table 4 Additional Simple Headroom and Legroom due to network interventions

Network Intervention	Size	Location	Extra Headroom (pu %)	Extra Legroom (pu %)
LV Voltage Regulator	N/A	LV Feeder	1.5	0
Tapchanging transformer	N/A	HV/LV Substation	8.70	7.40

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It can be seen that the extra headroom and legroom achieved with a secondary tapchanging transformer are not exactly the same as the tap ratio range of the tapchanging transformer, which are ±8% here. This is because the tap position is changed by changing the winding number at the primary side of the transformer.

The secondary voltage can be calculated with the following equation if the voltage drop across the transformer is neglected:

$$V_{sec} = V_{pri} \frac{N_2}{(1-k) * N_1}$$

Where V_{pri} and V_{sec} are the voltages at the primary and secondary side of the tap changing transformer; N_1 and N_2 are the winding numbers of the primary and secondary side and k is the tap position change in percentage.

If the per unit system is utilized, the equation above can be written as:

$$V_{sec} = V_{pri} \frac{1}{1-k}$$

If V_{pri} is assumed as 1pu, V_{sec} can be calculated for k = ±8%. When k is set as +8%, then Vsec is 0.926pu, which gives the voltage difference as 0.074pu from the voltage value when k is set as 0. Similarly, Vsec is 1.087pu when k = -8%, and the voltage difference is 0.087pu.

4.2.2 Tapchange Operations

The 1-minute data from the iHost data in combination with the tapchanger model presented in the previous section enables an accurate assessment of the impact of bandwidth on the number of tapchanger operations at an HV/LV transformer site. Data from Mortimer Road HV/LV substation during the winter period of 2013/2014 is used for this analysis. The analysis is presented in Table 5.

Table 5 HV/LV transformer tapchanger operations during winter period 2013/2014

Data	4% bandwidth	3% bandwidth	Increase in tapchanger operations
Nov-12	168	608	3.6
Dec-13	84	306	3.6
Jan-14	131	508	3.9
Total	383	1422	3.7

It can be seen from Table 5 that there is an average increase of 3.7 fold increase in tapchanger operations when a narrower bandwidth of 3% is employed over the period of the study. Reducing the bandwidth can increase the available practical headroom and legroom available to an intervention. For example, if a heavily loaded LV, load only, network is considered it is desirable to set the voltage at the busbar to the highest voltage possible without the possibility of causing violations of the statutory limits. In the case of a transformer tapchanger with a 4% bandwidth, the maximum target voltage setpoint can be 1.080pu. If a 3% bandwidth is used the maximum target voltage setpoint can be 1.085pu.

4.3 Extrapolation and Enhancement

To ensure that the results from this analysis are as useful and concise as possible the extrapolation and enhancement sections are presented together in this report. The studies use Wooler St Mary substation as this has a much larger number of customers than Wooler Bridge and would therefore have a more realistic possibility of the deployment of LCT causing voltage rise/drop issues.

4.3.1 ASHP Penetration clustered on LV feeders

Using the clustering scenarios described previously in conjunction with the consumer profiles and ASHP consumer profiles, the allowable ASHP penetration rates with and without the application of HV/LV OLTC transformer are shown in Table 6. The penetration rate of ASHP is defined as the number of domestic customers having ASHP divided by the total number of domestic customers. The additional ASHP penetration is defined as the difference between the penetration achieved in the scenario with network intervention and the penetration achieved in the baseline study.

Table 6 **Allowable ASHP Penetration RatesScenario**	**Allowable ASHP Penetration**	**Allowable ASHP Customer Number**	**ASHP Penetration Increase on BAU (%)**	**Allowable ASHP Customer Number Increase on BAU**
Baseline	50%	73	-	-
Autonomous	131%	190	81%	117
Single + GUS	131%	190	81%	117

Fig. 21 shows the voltage profiles of the busbar voltages at the HV/LV substation and the LV feeder, when 50% ASHP penetration rate is applied under the HV/LV cluster scenario baseline study.

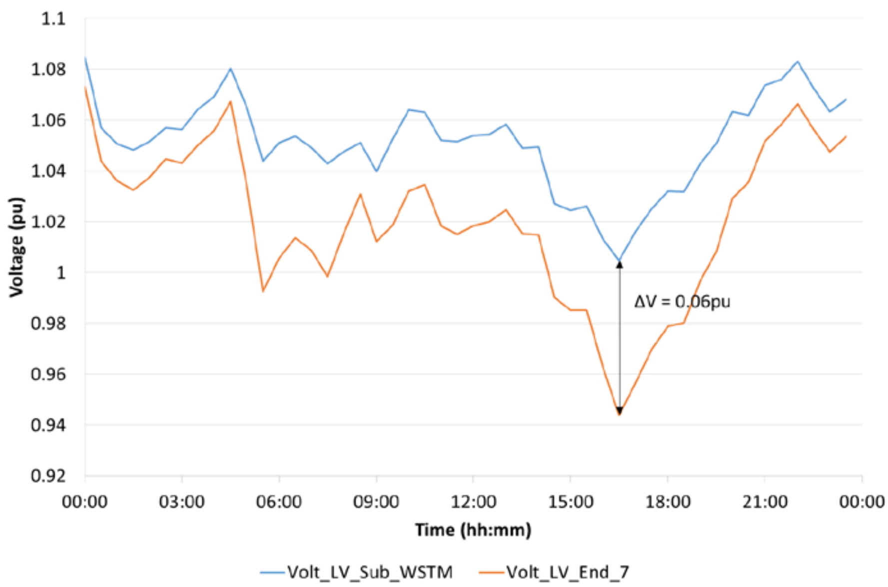

Fig. 21 Voltage Profiles from ASHP HV/LV Cluster Baseline Study (50% ASHP Penetration)

It can be seen from Fig. 21 that for the baseline study, the voltage difference between the voltage at the HV/LV substation and the voltage at the LV feeder end drops to 0.06pu.

The target voltage of the tapchanging HV/LV transformer in the local control mode is set as 1.08pu in this study.

4.3.2 EV Penetration clustered on LV feeders

Using the clustering scenarios described previously in conjunction with the consumer profiles and EV consumer profiles, the allowable EV penetration rates with and without the application of HV/LV OLTC transformer are shown in Table 7. The allowable EV penetration rates can reach 100% of the tapchanging HV/LV transformer, for the HV/LV cluster scenario. Here the 100% EV penetration rate means the each domestic customer has one and only has one EV. Therefore the penetration rate can be higher than 100% if each domestic customer has more than one EV.

Table 7 **Allowable EV Penetration RatesScenario**	**Allowable EV Penetration**	**Allowable EV Customer Number**	**EV Penetration Increase on BAU (%)**	**Allowable EV Customer Number Increase on BAU**
Baseline	190%	276	-	-
Autonomous	432%	626	242%	350
Single + GUS	439%	637	249%	361

Fig. 22shows the voltage profiles of the busbar voltages at the HV/LV substation and the LV feeder, when 237% EV penetration rate is applied under the HV/LV cluster scenario.

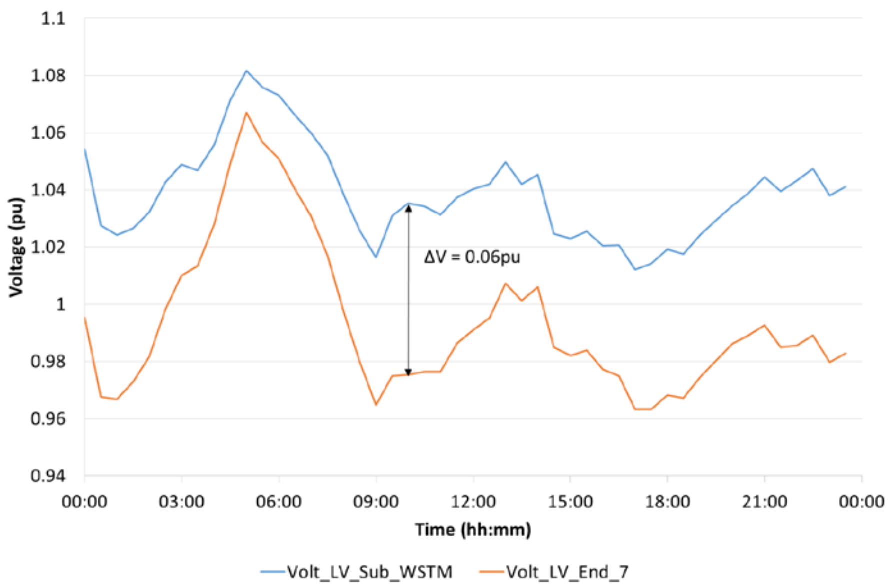

Fig. 22 Voltage Profiles from EV HV/LVLV Feeder Cluster Baseline Study (190% EV Penetration)

It can be seen from Fig. 22 that for the baseline study, the voltage difference between the voltage at the HV/LV substation and the voltage at the LV feeder end drops to 0.06pu.

The target voltage of the tapchanging HV/LV transformer in the local control mode is set as 1.08pu in this study.

4.3.3 PV Penetration clustered on LV feeders

Using the clustering scenarios described previously in conjunction with the consumer profiles and PV consumer profiles, the allowable PV penetration rates with the application of HV/LV OLTC transformer are shown in Table 9. The penetration rate of PV is defined as the number of domestic customers having PV generation system divided by the total number of domestic customers.

Table 8 Allowable PV Penetration Rates with LV Voltage Regulator

Scenario	Allowable PV Penetration	Allowable PV Customer Number	Allowable PV Customer Number (including diversity)	PV Penetration Increase on BAU (%)	Allowable PV Customer Number Increase	Allowable PV Customer (including diversity) Number Increase
Baseline	57%	83	100	-	-	-
Autonomous	61%	88	107	0.04	5	7
Single + GUS	61%	88	107	0.04	5	7

Table 9 Allowable PV Penetration Rates with Tapchanging Transformer

Scenario	Allowable PV Penetration	Allowable PV Customer Number	Allowable PV Customer Number (including diversity)	PV Penetration Increase on BAU (%)	Allowable PV Customer Number Increase	Allowable PV Customer (including diversity) Number Increase
Baseline	52%	75	91	-	-	-
Autonomous	89%	129	155	37%	54	64
Single + GUS	128%	186	224	76%	111	133

Fig. 23shows the voltage profiles of the busbar voltages at the HV/LV substation and the LV feeder, when 52% PV penetration rate is applied under the HV/LV cluster scenario.

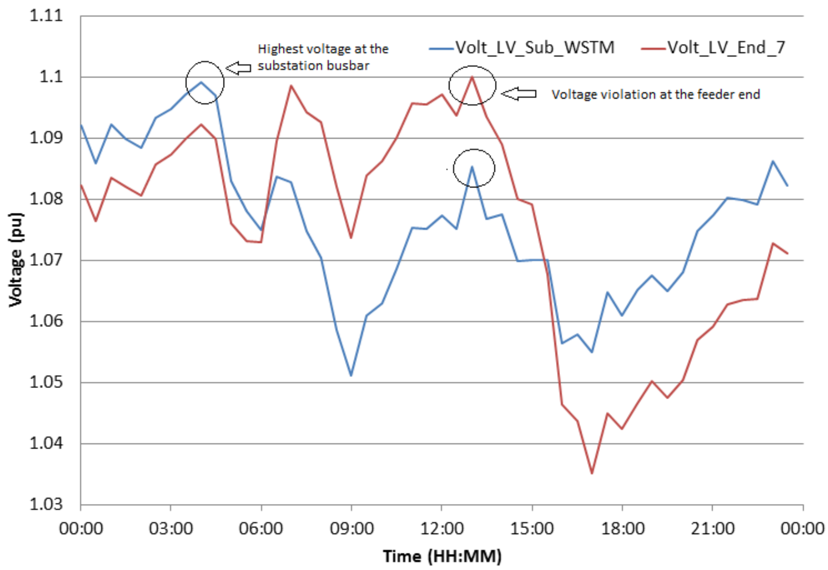

Fig. 23 Voltage Profiles from PV HV/LV Cluster Baseline Study (52% PV Penetration)

It can be seen from Fig. 23 that the lowest voltages at the HV/LV substation and at the LV feeder end don't happen at the same time. And the substation voltage at that time when the voltage violation happens (1.085pu) is lower than the lowest voltage at the substation (1.099pu).

The target voltage of the tapchanging HV/LV transformer in the local control mode is set as 1.05pu in this study.

4.4 Generalisation

The results from the previous sections made design assumptions about the target voltage setpoint for the EV, ASHP and PV scenarios for the Wooler Ramsey LV network. However, using 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 these 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.

Previously 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 [5], as shown in(1):

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

Voltage sensitivity factors relate the change in voltage at a network node due to a change in real or reactive power at a particular load or generation node elsewhere in the network. In this work they 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 10 DVSFs and % voltage increase at remote end due to evenly distributed penetrations of PV on CLNR and UK Generic networks

Secondary Substation	DVSF (%/kW)	DVSF (Normalised)	10% 3kW PV	30% 3kW PV	50% 3kW PV
Wooler Ramsey	6.97	1.00	2.1%	6.3%	10.5%
Wooler St Mary	2.32	0.33	0.7%	2.1%	3.5%
Wooler Bridge	0.64	0.09	0.2%	0.6%	1.0%
High Northgate	4.87	0.70	1.5%	4.4%	7.3%
Harrowgate Hill	6.67	0.96	2.0%	6.0%	10.0%
Darlington Melrose	4.71	0.67	1.4%	4.2%	7.1%
Mortimer Road	1.56	0.22	0.5%	1.4%	2.3%
Sidgate Lane	0.34	0.05	0.1%	0.3%	0.5%
UK Generic Network	3.90	0.56	1.2%	3.5%	5.9%

The DVSF therefore can be used to roughly evaluate the impact on remote end voltage of additional distributed generation or load. For example the DVSF would predict that assuming a voltage headroom of 5% it would be possible to connect a 24% penetration of PV generation assuming 3kW peak installations per customer. This is less than the figures discussed in the extrapolations sections of this work but this is expected as this analysis does not assume zero load during the period of peak PV generation.

This also enables generalisation of the enhanced and extrapolated results to other networks. For example, the extrapolation results predict a 32% increase in the capability of the Wooler Ramsey network to accept PV generation with an autonomously controlled tapchanger equipped HV/LV transformer with a target voltage of 1.05pu. For the UK generic network, using the normalised figures, the DVSF predicts that, an autonomously controlled tapchanger equipped HV/LV transformer with a target voltage of 1.05pu would increase the capability of this network to accept PV generation by 18% assuming the baseline condition was a conventional HV/LV tapchanger set to 1.08pu at no load.

5 Discussion and conclusions

New to the UK, taphchanging HV/LV transformers were deployed at three sites during the CLNR trial programme. Two operating modes were evaluated during the trials and subsequently in the post-trial analysis:

1. Autonomous control mode (using local measurement only as inputs to the taphchanger control);
2. GUS control mode (using remote measurements as inputs to the tapchanger control).

5.1 Trial Issues

A number of practical issues were derived from the detailed analysis of the operation of the HV/LV tapchanger operation.

The voltage measurements used as control inputs to the models are derived from the AVR relay (rather than iHost voltage measurement) which operates the tapchanger. This is important as it is the voltage observed by the AVR that determines the operation of the secondary transformer OLTC in the autonomous voltage control. These differences between the iHost and AVR measurement data were found to have impacts on the operation of the model. However, it should be noted that the accuracy of both systems is well within the tolerances of the measurement systems.

Planning of systems utilising OLTC equipped secondary transformer operating autonomously need to be cognisant of the possible measurement error of the local busbar voltage. For example if the measurement tolerance is +/-1%, when considering high load/high generation scenarios, simulated remote end network voltages should not drop below 0.95pu and should not rise above 1.09pu to ensure that the customers do not experience voltages outside of the statutory limits.

The sample rate of the data from FDWH is inconsistent which presents practical difficulties in analysis of large data sets.

5.2 Post-Trial Analysis

Two models of the HV/LV tapchanging transformer were developed and were presented in the validation of autonomous operation of tapchanging HV/LV transformer study. OLTC Model 2 more closely predicts the operation of the OLTC especially with data with temporal resolutions greater than 1 sample/min. It should be noted that these characteristics of the model can be only be adequately modelled if the sample rate of the input data (voltage, real and reactive power) is at least 1 sample/min. Lower sample rates are likely to underestimate the number of tapchanger operations. This could be a particular characteristic of OLTC equipped secondary transformers as primary transformers are likely to observe relatively less “noise” on the voltage, real and reactive power traces due to the diversity of the load.

A validated model of the closed loop GUS voltage control system operating 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 [1]. 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 trial.

- The simulation results demonstrate that the OPF (Optimised Power Flow) control algorithm developed in Python and IPSA2 is a useful and accurate representation of the OPF based control algorithm deployed as part of CLNR.
- As expected there are differences between the target voltages observed from simulation results and field trial results. This is due to the following:
  - The method used for converting tap position to target voltage is not exactly the same as that used in GUS system, as the method used by SIEMENS has not been clarified;
  - Small differences between the network and load models implemented in simulation and those used by GUS during the field trials.

Future work has been identified which would seek to improve the realism of the model of the control algorithm by replacing the existing method with the method from SIEMENS for converting tap position to target voltage.

The installation of the tapchanging HV/LV transformer has been shown to increase the voltage headroom and legroom on the network as per Table 11.

Table 11 Additional Simple Headroom and Legroom due to network interventions

Network Intervention	Size	Location	Extra Headroom (pu %)	Extra Legroom (pu %)
LV Voltage Regulator	N/A	LV Feeder	1.5	0
Tapchanging transformer	N/A	HV/LV Substation	8.70	7.40

The impact of changing the bandwidth on HV/LV transformers, using the validated models developed as part of this work and the 1-minute time resolution data from the trial sites, was evaluated. It was found that decreasing the bandwidth from 4% to 3% increases the number of tapchanger operations by a factor of 3.7. However, it should be noted that decreasing the bandwidth from 4% to 3% has the impact of increasing the effective legroom and transformer by 0.5%.

The installation of the tapchanging HV/LV transformer has been shown to substantially increase the allowable penetration rates of LCT installations above BAU. The incremental change in the LCT penetration rates depend on the profile of LCTs and their location.

The capability of the tapchanging HV/LV transformer was improved further when integrated with the GUS system particularly when comparing PV installations with autonomous voltage control and single + GUS voltage control. Line drop compensation (LDC) techniques could be used to provide some of the benefits of voltage control using the GUS system however, LDC would not be able to provide the same level of capability to connect LCT as it relies on a simple static model of the downstream LV network which has limitations considering the: -

a. the anticipated non-uniform, unplanned growth in PV, ASHP and EV in LV networks;
b. dynamic distributions of loads due to possible changes in the geographical distribution of EV load;
c. variations in EV charging load due to customer behaviour changes.

The concept of the distributed voltage sensitivity factor (DVSF) is introduced in this work. This metric represents and relate the voltage change at the remote end of distribution network due to the real power import/export of all customers in the network. This enables us to evaluate the impact of increasing penetrations of LCT on different LV networks. DVSFs for the trial LV networks in CLNR and the UK generic networks given to illustrate the impact the distribution and number of customers and network topology have on remote end voltage in UK LV networks.

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