Customer-Led Network Revolution

EES1 and EAVC1 Voltage Control

CLNR Trial Analysis

DOCUMENT NUMBER
CLNR-L119

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ISSUE DATE
29 December 2014

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Executive Summary

This report details the analysis of autonomous and GUS control trials, using the VEEEG methodology, utilising the 2.5MW/5.0MWh EES unit (EES1) installed at Rise Carr the and enhanced automatic voltage control 33/6kV Transformers at Rise Carr substation.

The operation of the GUS system has previously been validated using results from trials on the operation of GUS with HV/LV transformers. The GUS system interacts with the EAVC1 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 the operation of the GUS system with the EHV/HV transformers has broad applicability.

Analysis of the trial data from the GUS controlled collaborative operation of EAVC1 and EES1 demonstrates agreement with the models developed as part of the CLNR project programme.

In addition, pre-trial simulation is conducted to determine the appropriate settings for the EES1 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 Customer Led Network Revolution (CLNR) Project.

The load data for the VEEEG study cases are derived from actual data from the CLNR monitoring systems 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 GUS trials for EES1 and EAVC1 on the CLNR trial network at Rise Carr as per the trial design methodology [1, 2]. In addition, the baseline trial that is required to evaluate the headroom uplift accruing to the network interventions can be evaluated.

EES1 for autonomous voltage control has been evaluated under two criteria, tap operation reduction and the capability of the network to accommodate low carbon technologies (LCTs).

Key findings:

1. Reactive power for Rise Carr substation 6kV busbar voltage control is more effective than real power;
2. Voltage change due to import of real/ reactive power is greater than that of exporting real or reactive power;
3. In an autonomous voltage control mode of a primary busbar, which neglects the voltage at the end of HV feeders, the numbers of LCTs that can be accommodated is limited by the thermal rating of the transformer;
4. The initial investigation indicates that doubling the capacity of the energy storage can result in a 5% reduction in tapchange operations. This is an additional benefit of collaboratively controlling energy storage units with upstream tapchangers.
5. Reactive power is more effective for controlling voltage even in rural HV networks.

1 Introduction

This report details the analysis of voltage control trials, using the VEEEG methodology, of the collaborative operation of the GUS controlled primary transformer EHV/HV transformer tapchanger (EAVC1) and the 2.5MW/5.0MWh EES unit (EES1) installed at Rise Carr substation.

The collaborative operation of EAVC1 and EES1 units have been evaluated under two criteria, tap operation reduction and the capability of the network to accommodate low carbon technologies (LCTs). This has been achieved by using a validated IPSA2 Rise Carr network model and a combination of real load data from the Customer Led Network Revolution (CLNR) Project [3], data from the CLNR domestic LCT customer trials and prior literature.

The field trials, which have been expanded and augmented through trial analysis using the VEEEG methodology, are given in Table 1.

Table 1: List of EAVC1 and EES voltage control field trials at primary substation in Rise Carr

Trial No.	Control Type	Trial Name
22.40	GUS	Open loop GUS real power voltage control system at EES1 (Rise Carr)
22.41	GUS	Closed loop GUS real power voltage control system at EES1 (Rise Carr)
22.42	GUS	Open loop GUS reactive power voltage control system at EES1 (Rise Carr)
22.43	GUS	Closed loop GUS reactive power voltage control system at EES1 (Rise Carr)
22.44	GUS	Closed loop GUS real and reactive power voltage control system at EES1 (Rise Carr)
22.61	GUS	Closed loop GUS voltage control system at Darlington Melrose HV/LV OLTC, EES2, EES3, DSR, EES1 and Rise Carr 33/6kV transformers

In section 3, the VEEEG methodology is summarised. Load and LCT profiles used in this work are given and introduced in section 4. Detailed results from the pre-trial simulation are presented in section 5. Conclusions are drawn in the final sections of this document.

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. This approach is derived from previous experience of trials. It is required that the results from the trials are firstly used to validate the network and network component models [2, 4-6]. 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 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 Figure 1.

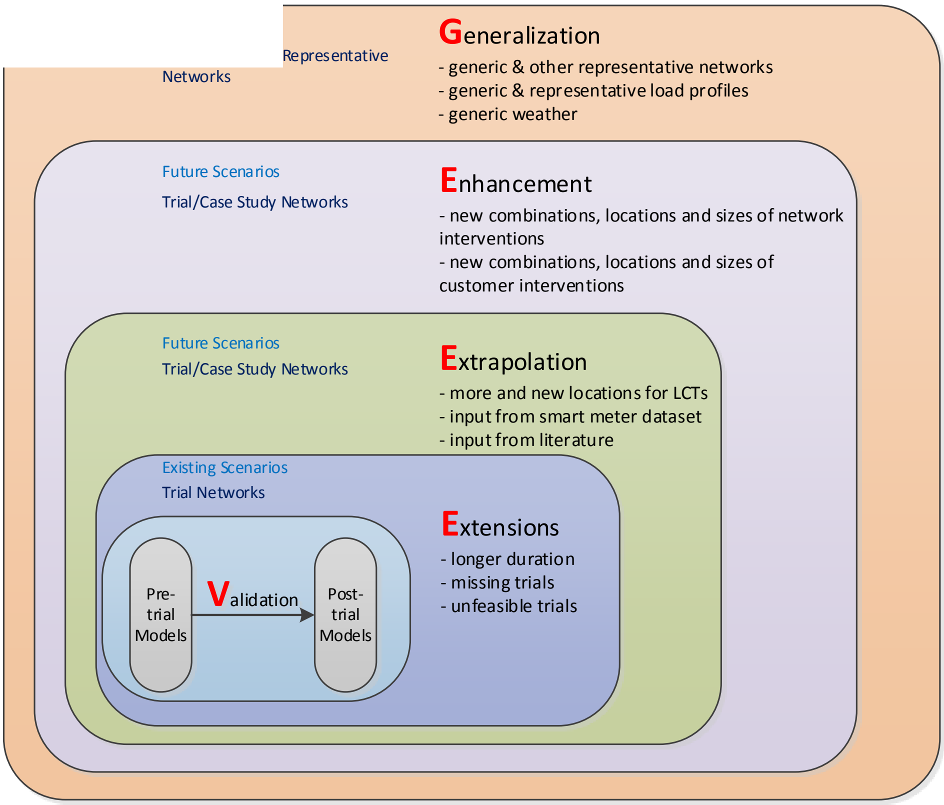

Figure 1 Post-trial analysis methodology (VEEEG)

For further details of the post-trial analysis methodology please refer to [2, 5, 6].

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3 Trial Results

At Rise Carr primary, the current tap steps of the primary transformers are 1.5% and the bandwidth is 1.67%, based on 6.4kV. In this analysis the tap step is 1.6% and the bandwidth is 1.78% based on 6kV so that the settings are as per the trial. These relationships are given below:

$$Tapstep_{new} = Tapstep \times \frac{Vbase}{Vbase_{new}} = 1.5\% \times \frac{6.4kV}{6.0kV} = 1.6\%$$

$$Deadband_{new} = Deadband \times \frac{Vbase}{Vbase_{new}} = 1.67\% \times \frac{6.4kV}{6.0kV} = 1.78\%$$

Table 2 Settings of EAVC1

Target Voltage (pu)	Tap	Tap step	Bandwidth (%)	Time delay (min)
GUS (Limit 6.01 – 6.03kV)	Unlock	1.5%	1.78	2
GUS (Limit 6.01 – 6.03kV)	Unlock	1.5%	1.78	2

Field trial results from 30th September are presented to illustrate the collaborative GUS controlled operation of the EES1 unit and primary transformer tapchanger control at Rise Carr.

Field trial results are shown in Figure 2, Figure 3 and Figure 4.

In Figure 2 and Figure 3 it can be seen that initially during the *high voltage event* period, the EAVC1 target voltage setpoint is reduced. The upper and lower voltage limits within the GUS system during this period are shown in Table 3.

Table 3 Upper and lower voltage limits within GUS system for 30th September 2014

	Upper Limit	Lower Limit
HV System	1.15 pu	0.9 pu
LV System	1.07 pu (0.428kV)	0.99 pu (0.396kV)

The GUS system has called for assistance from the EAVC and EES1 in response to a violation somewhere in the downstream HV and LV networks of the upper voltage limit set within the system. As stated in Table 2, the target voltage that can be issued by GUS in this trial has been limited to between 6.01 and 6.03 kV in order to ensure the GUS system is forced to request a response from the EES1 unit. It can be seen from Figure 3 that this did not result in a change in tap position of the tap changer as the transformer secondary voltage did not exceed either the lower or upper limits of the AVC as defined by the AVC bandwidth.

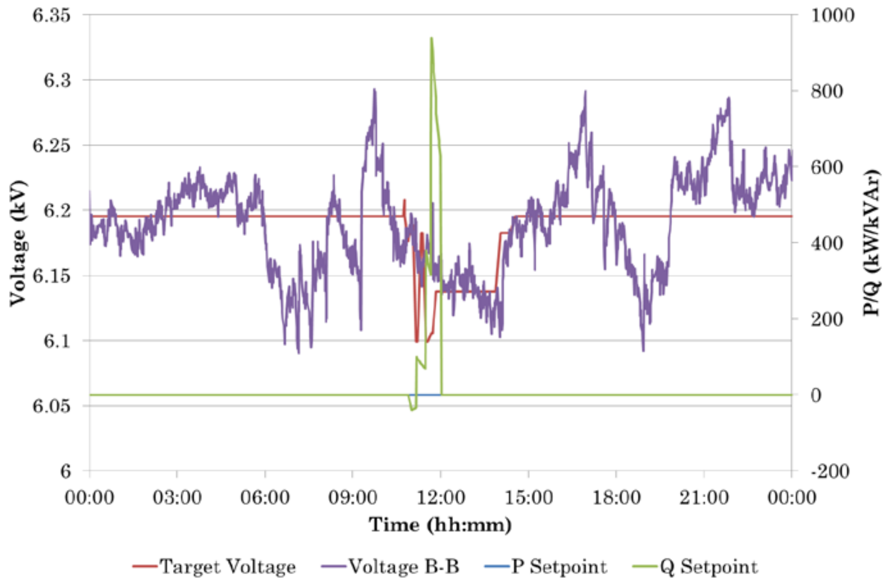

Figure 2 GUS Control setpoints during trial

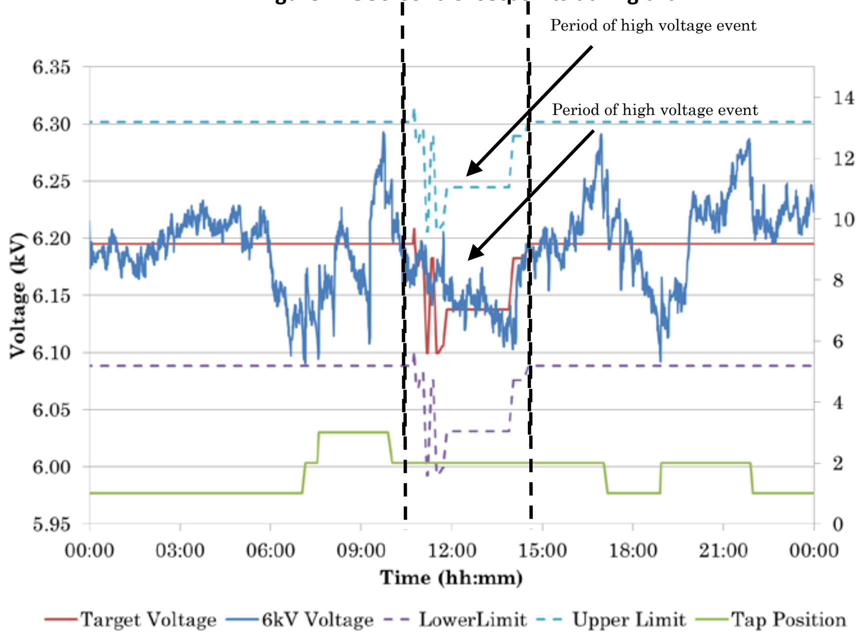

Figure 3 EAVC1 voltages and tap-position

The GUS system calculates that reactive power is also required as illustrated in Figure 2 and Figure 4. This is a request to absorb reactive power (inductive) that acts to reduce the voltage on the 6kV busbar at Rise Carr and consequently reduces the voltage of the busbar(s) where the state-estimator estimates that the voltages are above limits. This is consistent with models of the GUS system developed and described in [reference EAVC2 report].

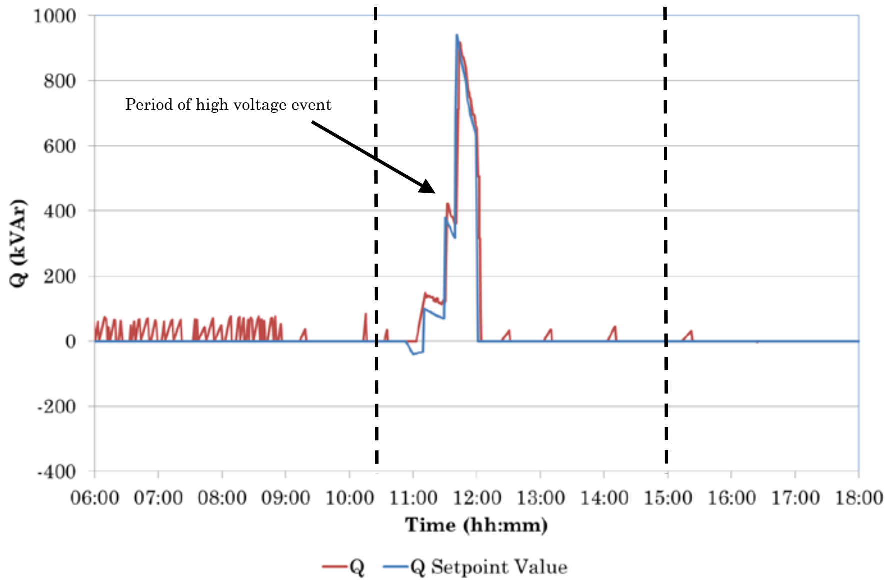

Figure 4 Reactive Power (Q) EES Output and Setpoint

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

4.1 Introduction

In the following sections, the results from an application of the VEEEG methodology, using a combination of the validated model of the GUS system [7], the validated model of the Rise Carr HV network and LCT models derived from CLNR LO1 studies and literature.

4.2 Summer and Winter Demand Profile

Data for the Rise Carr network from 1st December 2010 to 2nd March 2013 has been provided by Northern Powergrid. A peak load day and a minimum load day profile have been chosen and used in in this analysis.

4.2.1 Peak Day Demand Profile

During this period, the highest load measured is 12.83MVA at 12:30, 18th July 2011. However, by comparing the daily peak load of three winter months (December 2010, 2011, 2012) and two summer months (July 2011, 2012), as shown in Figure 5, it can be seen that, the daily peak consumption in winter is always higher than the daily peak load in summer and the peak load that occurred on the 18th July 2011 is atypical and is ignored for this work.

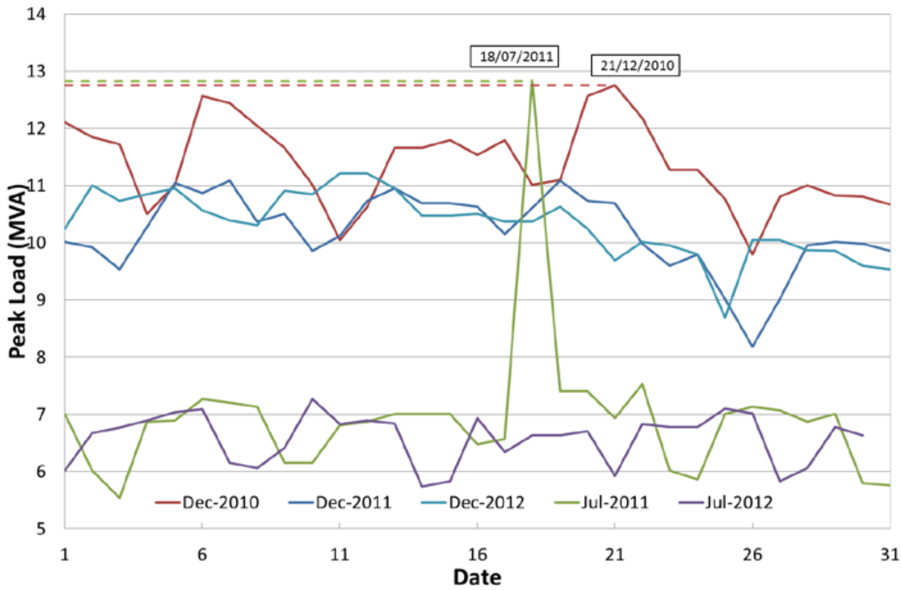

Figure 4 Summer and Winter Peak Daily Load Profile of Rise Carr Primary Substation

As a result, the load profile of 21st December 2010 has been used in this work. The 24 hour load profile of 21st December 2010 is plotted in

Figure 6. This profile has been used for in the following post-trial analysis when assessing peak load conditions.

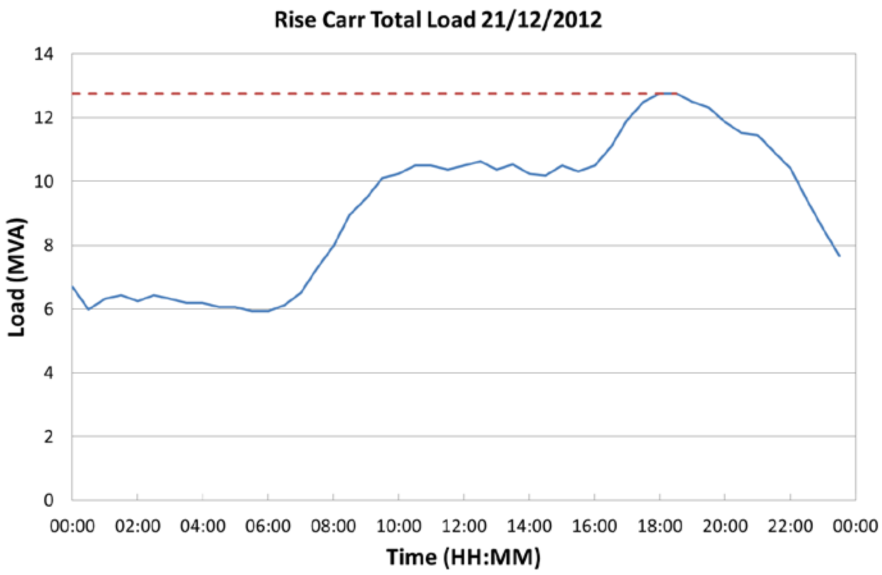

Figure 5 Rise Carr Peak Daily Load Profile

4.2.2 Early Morning Demand Profile

The minimum load observed within this dataset is during the late night/ early morning period (00:00 to 06:00) on a summer morning at 05:00, 31st July 2011. This load profile is plotted in Figure 7.

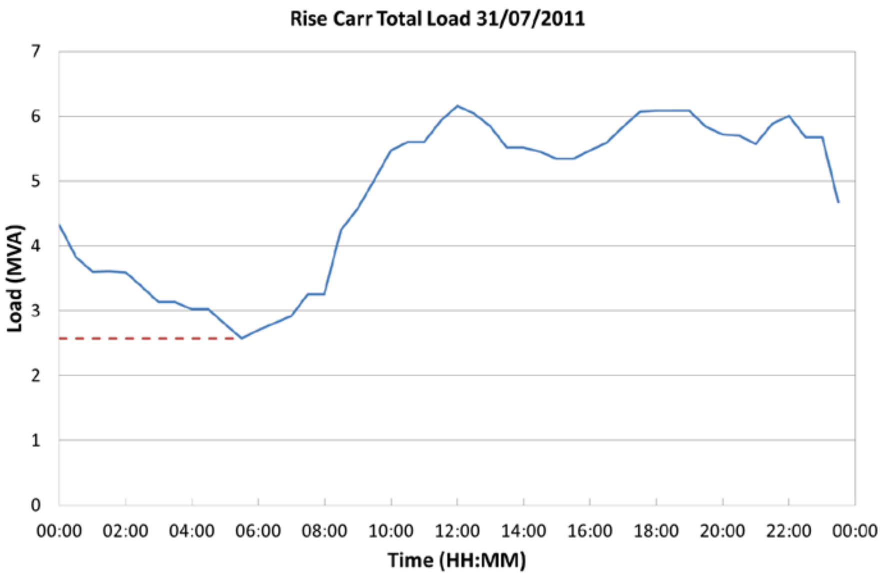

Figure 6 Rise Carr Summer Minimum Daily Load Profile Load

This profile has been used in the following post-trial analysis when assessing summer minimum conditions.

4.2.3 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* [8]. The 95th percentile profile on 17th Jan 2013 is used in this VEEEG study to represent the conservative assessment in terms of loading this network. This profile is shown in Figure 8.

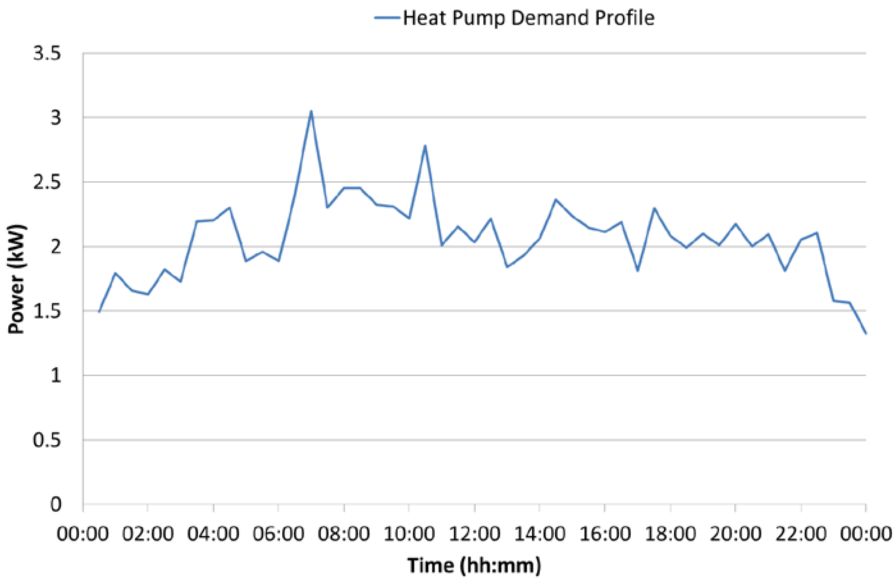

Figure 7 Typical ASHP daily consumption profile (95th percentile)

4.2.4 Electric Vehicle Load Model Development

The EV consumer model used in this work was based on profiles developed previously in [9]. 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 [9] which is in line with the average trip commute distance for the case study area [10]. 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 Figure 9.

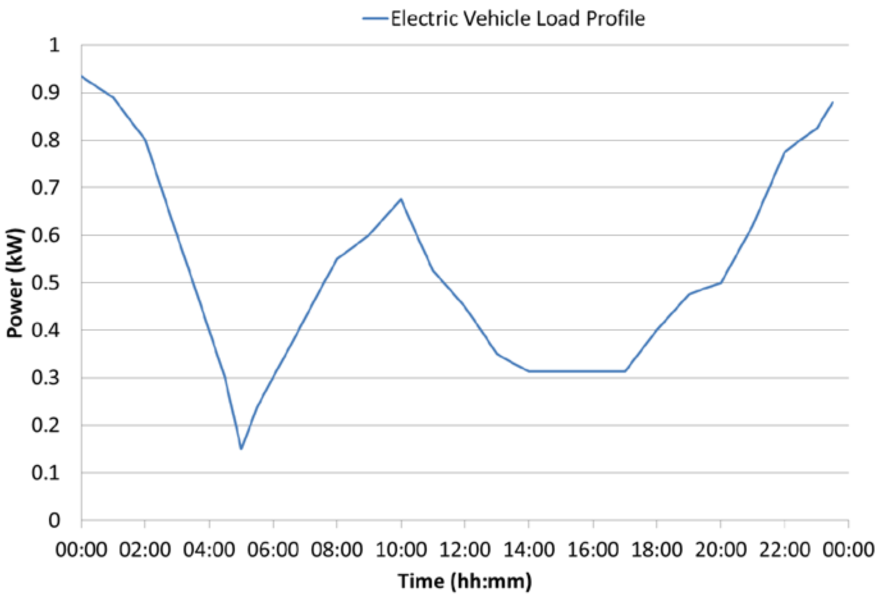

Figure 8 Typical EV daily consumption profile

4.2.5 PV Generation Model Development

PV generation profile is from *Initial Load Profiles form CLNR Intervention Trials* [11]. 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 Figure 10.

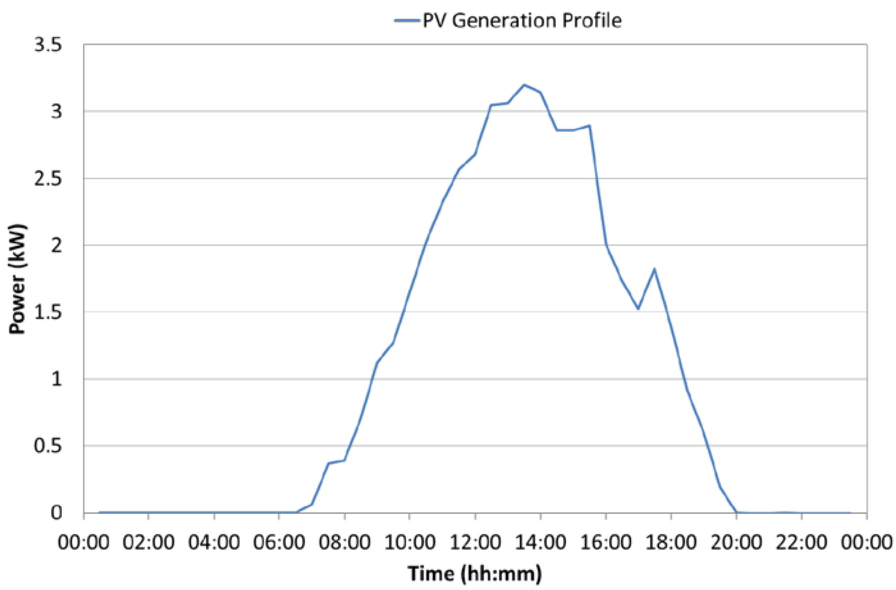

Figure 9 PV Daily Generation Profile for peak day (Summer Minimum) (95th percentile)

4.2.6 Network Model

The initial trial analysis has been conducted with Rise Carr IPSA2 network model. A geographic overview of the network model is shown in Figure 11.

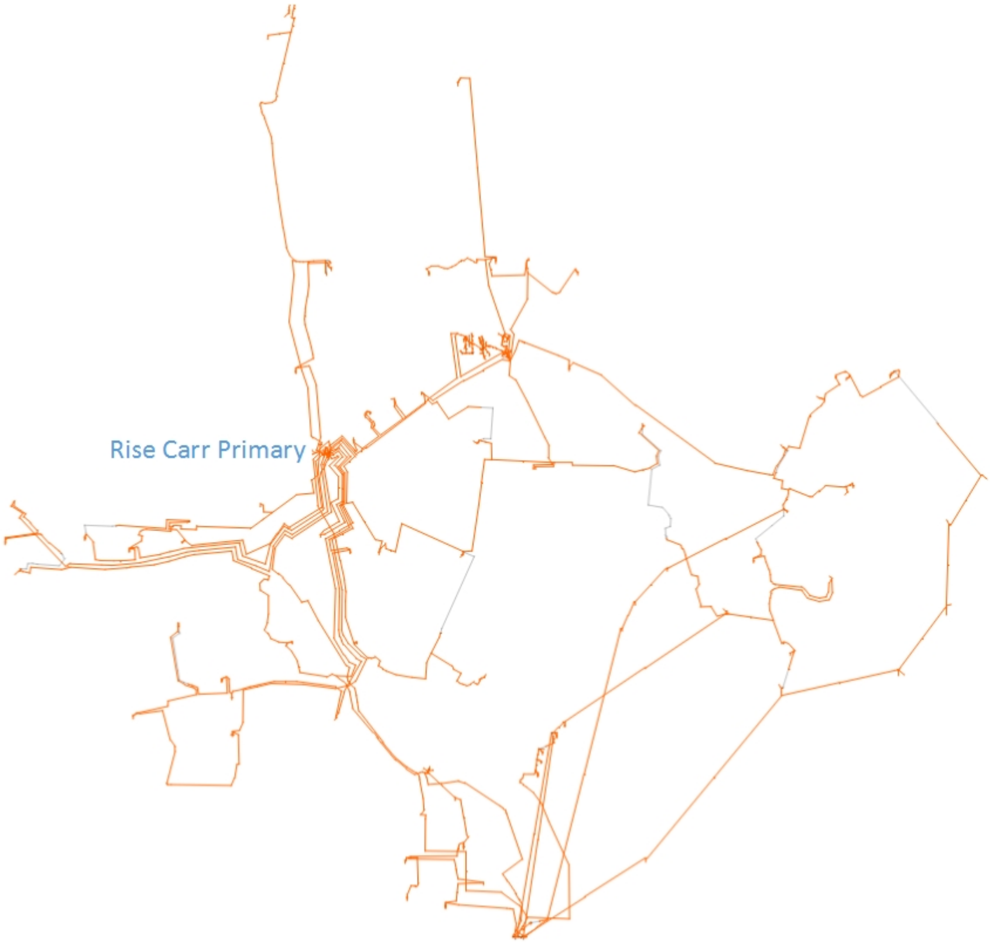

Figure 10 Geographical overview of Rise Carr network model in IPSA2

The contents and aims of the pre-trial analysis are listed in Table 12. Whole year SCADA data of 2011 has been to evaluate the use of EES1 on reducing OLTC tap operation.

4.3 Extension

4.3.1 Baseline –I (Type 3 Autonomous Voltage Control Trials)

Baseline studies for voltage control have been carried out using a peak day load profile and the proposed Type 3 voltage control was evaluated under peak load conditions. The configuration/settings for these trials are illustrated in Table 4. Type 3 voltage control uses the EES1 unit to control voltage at the EHV busbar at Rise Carr without the assistance of the transformer. In this table, EES1 positive indicates exporting real/reactive power.

The learning from these simulations include developing a baseline simulation, building confidence in the actual trials that were carried out and evaluate the effectiveness of using real and reactive power from EES1 for primary busbar voltage control.

Table 4 Baseline study results

	Name	EAVC			EES	
		Target voltage (pu)	Bandwidth (%)	Tap	Real power (MVA)	Reactive power (MVAr)
a	EAVC1 voltage control	1.03	1.78	Unlock	0	0
b	EAVC1 Lock Tap	Lock at -1.6%			0	0
c	EES1 Real Power Discharge	Lock at -1.6%			2.5	0
d	EES1 Real Power Charge	Lock at -1.6%			-2.5	
e	EES1 Reactive Power Discharge	Lock at -1.6%			0	2
f	EES1 Reactive Power Charge	Lock at -1.6%			0	-2
g	EES1 Real and Reactive power Discharge	Lock at -1.6%			1.5	2
h	EES1 Real and Reactive Power Charge	Lock at -1.6%			-1.5	-2

Results for simulation b (baseline), c (real power discharge, 2.5 MW) and d (real power charge, 2.5 MW) are illustrated in Figure 12. It can be seen that the voltage increase due to real power import (0.0013pu on average) is approximately double the voltage reduction due to real power export (0.0006pu on average). It should be noted that these figures are very small and approach the magnitude resolutions limits of the simulation.

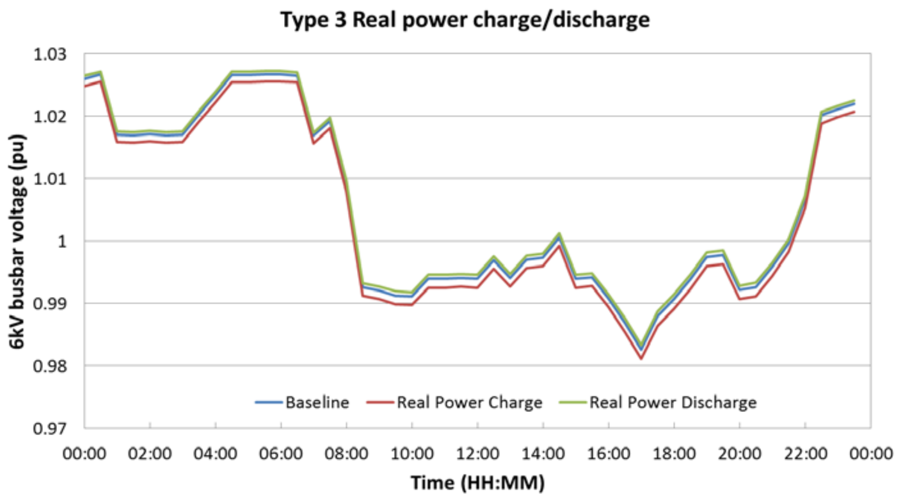

Figure 11 Baseline voltages and with 2.5MW real power import and export

The voltage profiles of Rise Carr primary substation EHV busbar in simulation e (reactive power discharge, 2MVAr) and f (reactive power charge, 2MVAr) are plotted in Figure 13. Average voltage reduction due to EES1 reactive power export is 0.0079pu and average voltage increase due to EES1 reactive power import is 0.0074pu.

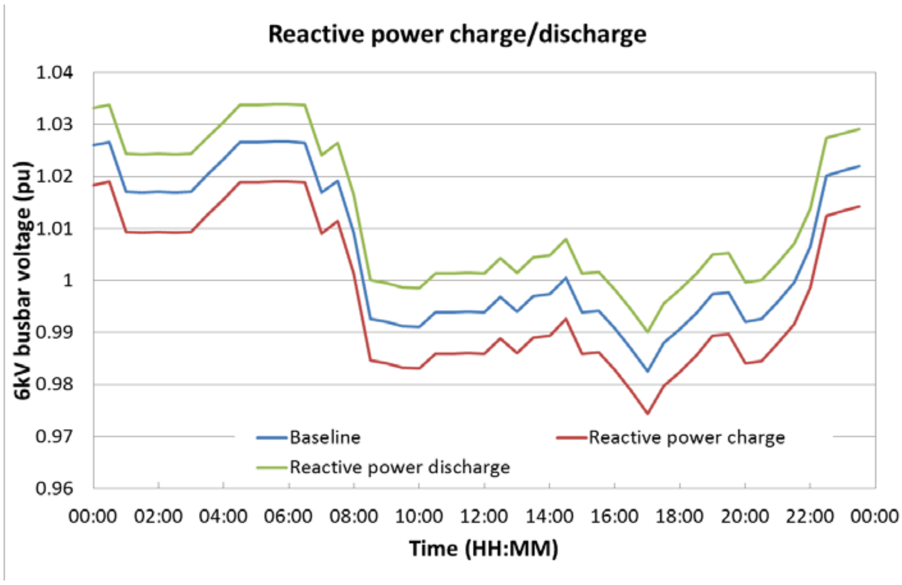

Figure 12 Baseline voltages and with 2.0MVAr reactive power import and export

At Rise Carr 33/6kV primary substation reactive power has been shown to have a greater impact than real power in controlling voltage at this substation. This is due to the high X/R ratio of the primary transformer and the topology of the upstream 33kV network. The reactance and the resistance of this transformer is 0.74707 pu and 0.0375 pu respectively, and thus the X/R ratio of the transformer is given by: -

$$X/R\% = \frac{0.74707pu}{0.0375pu} \approx 19.9$$

The simple single line diagram of the upstream Norton 33kV network is illustrated below in Figure 14.

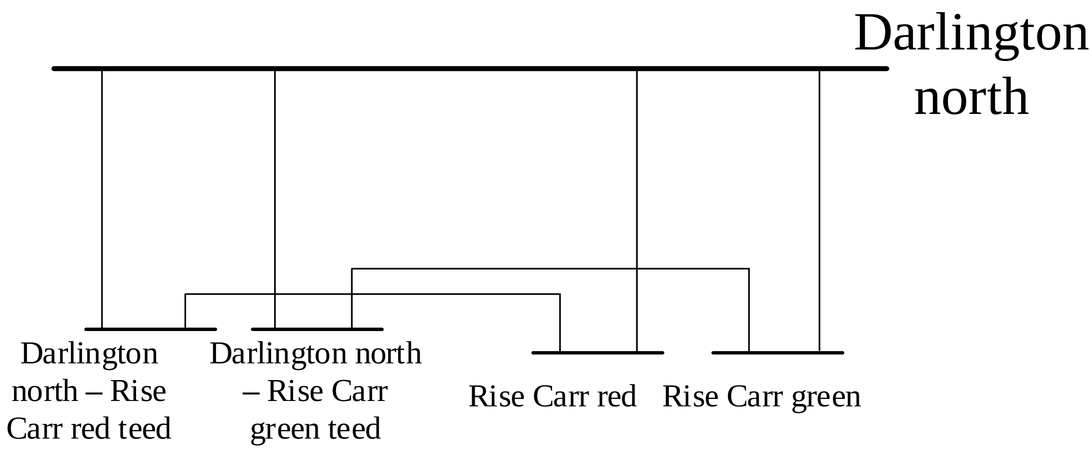

Figure 13 Simplified Norton network 33kV schematic

There are four 33kV feeders supplying Rise Carr primary. In addition, the geographical and electrical distance between Darlington North 33/6kV substation and Rise Carr 33/6kV substation is short so the impedance is small (0.0128pu for each feeder which equate to 0.064pu if both feeders are considered in parallel). Moreover, the fault levels at Darlington North 33kV busbar and Rise Carr 33kV busbar are relatively high, 398.84MVA and 245.6MVA respectively (RMS) as per the model.

4.3.2 Type 3 Autonomous Control of EES1 (Reactive Power only)

The studies in the previous section, indicate that real power import/export from EES1 has almost no effect on voltage and therefore is not considered in the following analysis. The tap position of EAVC1 is locked at -1.6% as per the previous studies. The bandwidth of EES1 voltage control is set as 1% with a target voltage of 1.035. The voltage profile is plotted in Figure 15. It can be seen that the EES unit is unable to control the voltage at this busbar.

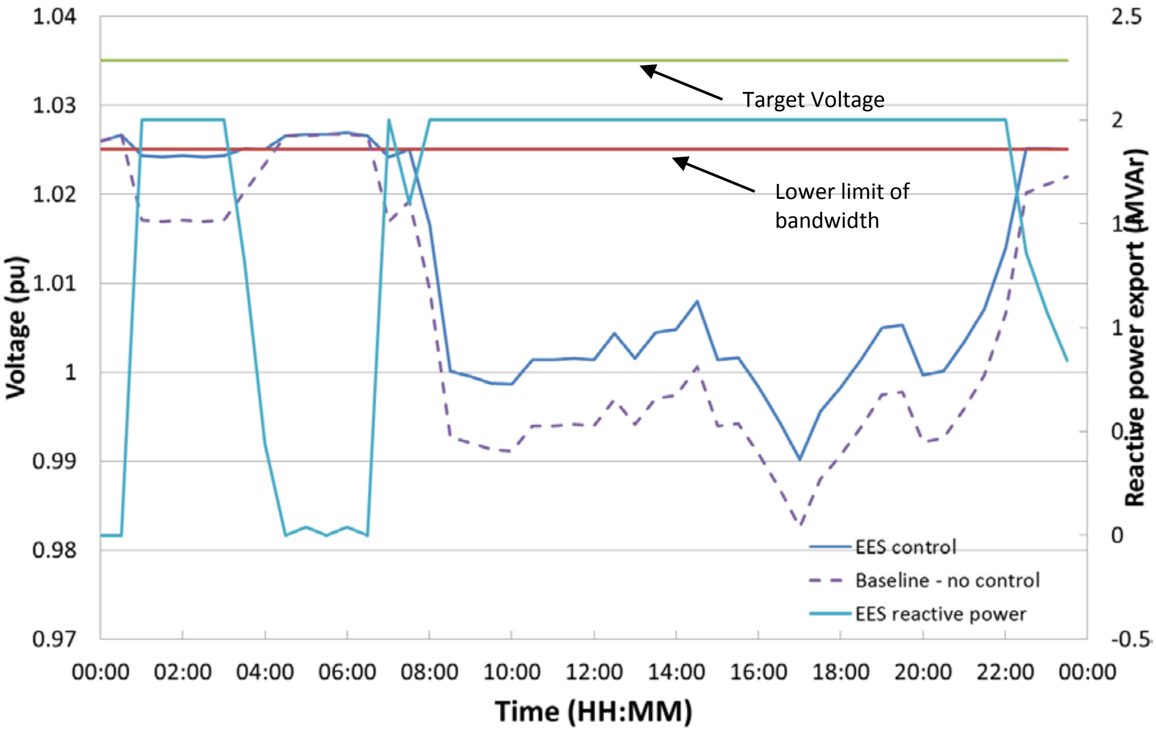

Figure 14 Type 3 Autonomous Voltage Control of EES1 (Reactive power) – 2.5MVA EES1 unit

The results of an enhancement study in which the rating of the EES unit is doubled and increased to 5MVA are given in Figure 16. These show that, by exporting reactive power, EES1 is again able to assist primary busbar voltage control but is again unable to maintain busbar voltage within the defined bandwidth.

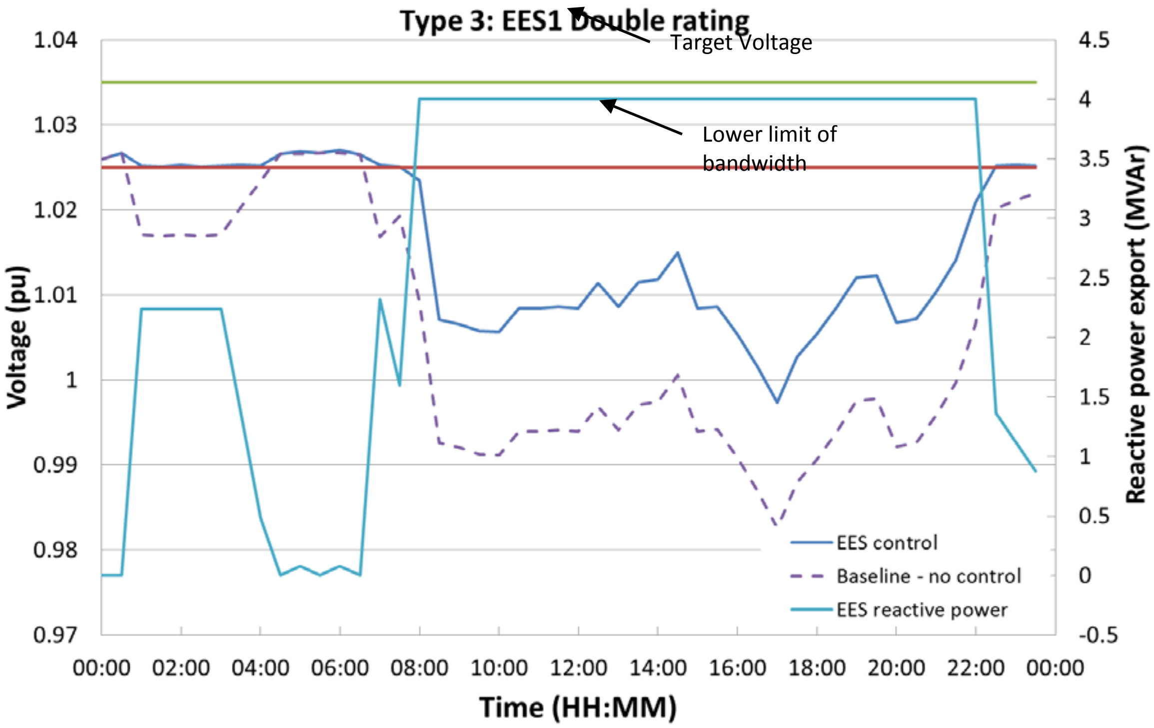

Figure 15 Type 3 Autonomous Voltage Control of EES1 (Reactive power) - 5MVA EES1 unit

4.4 Extrapolation and Enhancement (Headroom)

LCT profiles as described in earlier sections have been used in conjunction with the SCADA data for the peak day to synthesise future scenarios in the Rise Carr 6kV network where large numbers of LCTs are connected. There are 9,937 customers in Rise Carr primary area. It is assumed that all the customers are domestic and LCTs are distributed evenly across the entire network. The criteria that are used in this study to determine when the number of LCT connections has reached its limit within this network are as follows:

1. Minimum voltage across the observed LV networks connected downstream of the Rise Carr primary substation 6kV busbar is 0.94pu
2. No branches or transformers are overloaded

It should be noted that in this section the EHV/HV transformer tapchangers operate collaboratively with the EES1 unit to increase the capability of the network to accommodate LCT.

4.4.1 ASHP clustered downstream of Rise Carr HV busbar

The size of the EES1 was reduced to 1.25MW/2.5MWh and increased to 5MW/10MWh to investigate the impact that these changes have on the headroom. A summary of the simulation results are listed in Table 5.

In this table, the numbers of LCTs that can be accommodated have been tabulated. Extra numbers of LCT that can be accommodated due to the use of EES1, compared to baseline are worked out. The headroom is worked out as following:

$$Headroom = \frac{Additional\ Customers\ No.}{Baseline\ Customer\ No.} \times 100\%$$

For example, for ASHP, without EES1, 15,610 ASHP can be accommodated on the Rise Carr area. Using EES1 for autonomous voltage control, 15,610 ASHP can be adopted on the Rise Carr network. The extra number of ASHP that can be accommodated are:

$$Additional\ Customer\ No. = 15{,}610 - 15{,}004 = 606$$

And the headroom created by EES1 is

$$Headroom = \frac{606}{15004} \times\ 100\% \approx 4.04\%$$

Table 5 Summary of enhancement and extrapolation studies for ASHP HV cluster (Rise Carr)

		Number of installations	ΔInstallations/ ΔPenetration (%)
Baseline		15,004	-
+EES1	1.25MW/2.50MWh	15,332	318/2.12%
+EES1	2.50MW/5.00MWh	15,610	606/4.04%
+EES1	5.00MW/10.0MWh	16,097	1,093/7.28%

4.4.2 EVs clustered on HV network (Rise Carr)

Similar studies were carried out for the peak day but this time adding EVs to the downstream HV cluster at Rise Carr.

Table 6 Summary of enhancement and extrapolation studies for EV HV cluster (Rise Carr)

		Number of installations	∆Installations/ ∆Penetration (%)
Baseline		16893	-
+EES1	1.25MW/2.50MWh	17,251	358/2.12%
+EES1	2.50MW/5.00MWh	17,569	676/4.00%
+EES1	5.00MW/10.0MWh	18,125	1,232/7.29%

It should be noted that the amount of LCTs which can be adopted is limited by the thermal rating of the Rise Carr primary transformers instead of the voltage on the HV busbar. As a result, smaller quantities of LCTs can be accommodated by EES1. The capability of the EES unit to address the thermal constraints of the transformer is investigated in other work within CLNR [12].

4.5 Extrapolation and Enhancement (Tapchange Operations)

4.5.1 Baseline

A baseline study is carried out on a series of automated load flows (17,520 load flows) using half-hourly load data from 00:00 1st January 2011 to 23:30 31st December 2011 from NPG. This data is used to derive load data for each load node in the network model during the analysis.

The setting of EAVC1 is consistent with the current setting (Unlock tap, 1.6% tap step, target voltage 1.03 pu, bandwidth 1.78%). EES1 is not used in baseline studies.

4.5.2 Extension

Type 1 voltage control trials (trial 22.18 and 22.19) will not be run in the final trial programme as they have been deemed to be operationally unfeasible by NPG. In addition, the impact that the control of GUS on the EES1 to reduce tapchange operations, by adjusting the cost functions, was not run for an extended period of time. Therefore, running this trial in simulation and for a longer duration is considered an extension. In this analysis the bandwidth of EES1 is smaller than that of EAVC1, and is therefore more ‘sensitive’ to voltage change. Even though the delay time of EES1 is longer than the delay time of EAVC1, EES1 will respond to a smaller voltage change earlier than EAVC1. As a result, the number of tap operations is reduced. It should be noted that reactive power is considered only because real power has been shown earlier in this analysis to have very limited effect on the voltage on the Rise Carr HV busbar.

Sample results from the analysis are presented in Figure 17. Figure 17 shows tap positions of the baseline study and tap positions with the addition of EES1 controlling voltage for ten days.

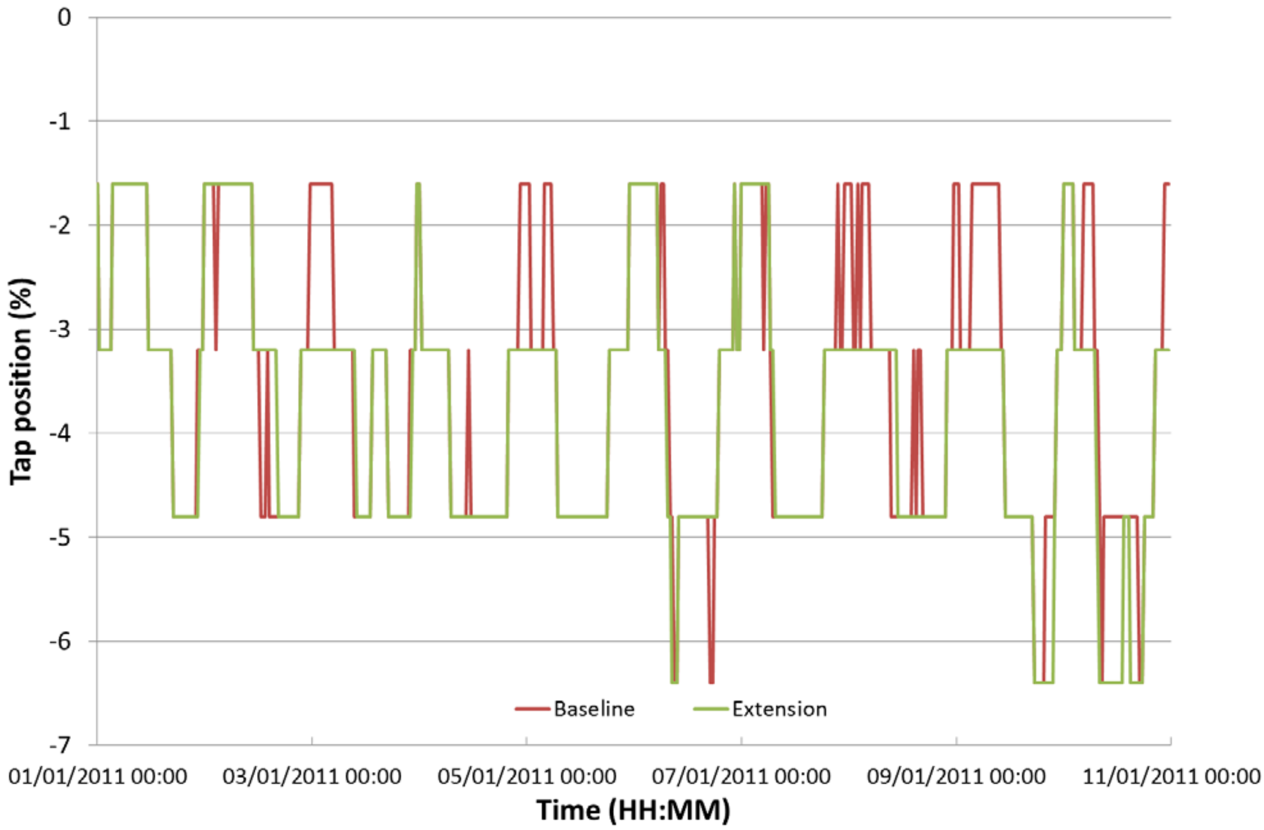

Figure 16 Baseline and Type 1 tap positions from 01/01/2011 to 11/01/2011

It can been seen that the number of tapchange operations was reduced.

4.5.3 Enhancement

The size of the EES1 was reduced to 1.25MW/2.5MWh and increased to 5MW/10MWh to investigate the impact that these changes have on the number of tap change operations. A summary of the results from these simulations are given below in Table 7. As can be seen in the table, tap operations can be reduced by using EES1 for voltage control. Moreover, if the rating of the EES1 unit is increased by a factor of 2 the number of tapchange operations decreases by approximately 6%.

Table 7 Tap operation with different EES1 rating

	EES1 Rating (MVA)	Number of operation	Max Tap (%)	Min tap (%)	ΔReduction
Baseline	No	2752	0	-6.4	-
Extension	2.5	1861	0	-6.4	32%
Enhancement	5	1688	0	-6.4	38%

Enhancement	1.25	2008	0	-6.4	27%

4.6 Extension (Type 2 Voltage control)

4.6.1 Validation and Baseline

In Type 2 voltage control, the tap position of EAVC1 is limited to +1.6%, which means EAVC1 can only lower 6kV busbar voltage.

A baseline study was carried out on a series of automated load flows (17,520 load flows) using half-hourly load data from 00:00 1st January 2011 to 23:30 31st December 2011. NPG SCADA data was used to derive load data for each load node in the network model.

4.6.2 Extensions

EES1 was used to control the Rise Carr 6kV busbar voltage with the same setting as in the Type 1 voltage control scheme. The number of tap operations and the lowest voltage seen on the Rise Carr HV busbar are shown in Table 8.

Table 8 Type 2 Numbers of Tap operations and Lowest Voltage on Rise Carr 6kV busbar

	Tap operation	Lowest voltage (pu)
Baseline (No EES)	188	0.983
Extension	62	0.99

As can be seen in this table, tap operations can be reduced and the lowest voltage measured at the 6kV busbar of Rise Carr substation is higher.

4.7 Enhancement (Relocation to Denwick HV Network)

Previous work, detailed in this report has illustrated the limited impact on voltage that EES1 has on the HV network at Rise Carr. To address this, the EES1 unit from Rise Carr is moved, in simulation, to a location within the validated network model at Denwick which is a rural network. LCT profiles as described in earlier sections have been used in conjunction with the SCADA data for the peak day to synthesise future scenarios in the Denwick 20kV network where large numbers of LCTs are connected. There are 2,124 customers on Heckley High House 20kV feeder in Denwick primary area. It is assumed that all the customers are domestic and LCTs are distributed evenly across the entire network. The criteria used in this study to determine when the number of LCT connections has reached its limit for this network are as follows:

1. Minimum voltage across the observed LV networks connected downstream of the Heckley High House 20kV feeder is 0.94pu;
2. No branches and transformers are overloaded.

It should be noted that in this section that the EHV/HV transformer tapchangers operate collaboratively with the EES1 unit to increase the capability of the network to accommodate LCT. However, in this case the EES1 unit is now located at the location of the capacitor bank at Hedgeley Moor. It was found however, that simple replacement of the existing capacitor bank with the EES1 unit actually results in voltages at the remote end of the LV feeders going below the statutory limit therefore it is assumed in this analysis that a capacitor bank with a rating of 4MVAr is connected.

In this study, real power was not considered due to its limited impact on voltage. In addition, a baseline study is not included as the existing switched capacitor bank has been replaced by a combination of fixed capacitor bank and energy storage. The results of the study are given in Table 9.

Table 9 Summary of enhancement studies for HV feeder cluster (Denwick)

	Autonomous control	GUS control	ΔInstallations/ ΔPenetration (%)
ASHP	411	483	72 (17.39%)
PV	1807	1878	72 (3.96%)
EV	1614	1848	234 (14.47%)

It can be seen that GUS control, as expected, provides additional capability to connect LCT but this additional capability needs to be cognisant of the thermal limitations of the circuit that are often violated at lower penetrations of LCT.

4.8 Generalisation

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 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.

Previously, a 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 [13], 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 a change in real or reactive power at a particular load or generation node elsewhere in the network.

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 10, e.g. 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 10 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, 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 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 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 on an LV substation).

Table 11 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.

5 Discussion and conclusions

The following findings have been derived from the analysis detailed in this work:

- Analysis of the trial data from the GUS controlled collaborative operation of EAVC1 and EES1 demonstrates agreement with the models developed as part of the CLNR project programme.
- Reactive power for Rise Carr substation 6kV busbar voltage control is more effective than real power;
- Voltage change due to importing real/ reactive power is greater than that of exporting real or reactive power;
- In an autonomous voltage control mode of a primary busbar, which neglects the voltage at the end of HV feeders, the numbers of LCTs can be accommodated is limited by the thermal rating of the transformer;
- The coordinated use of EES1 and EAVC1 can reduce tap operations. A greater size of EES1 can achieve greater reduction. The initial investigation indicates that doubling the capacity of the energy storage can result in a 5% reduction in tapchange operations. This is an additional benefit of collaboratively controlling energy storage units with upstream tapchangers.
- Reactive power is more effective for controlling voltage even in rural HV networks.

Appendix A - Pre-trial Studies

Baseline studies for Type 4 voltage control have been carried out with a summer minimum morning load profile. The scenarios listed in Table 12 have been carried out. In these studies, EES1 positive output means discharge. The learning from these simulations include building baseline and confidence from actual trials to be carried out and the effectiveness of using real and reactive power from EES1 for primary busbar voltage control.

Table 12 Type 4 Voltage control baseline simulations

	Name	**EAVC**			**EES**	
		Target voltage (pu)	Bandwidth (%)	Tap	Real power (MVA)	Reactive power (MVAr)
a	EAVC1 voltage control	1.03	1.78	Unlock	0	0
b	EAVC1 Lock Tap	1.03	-	Lock	0	0
c	EES1 Real Power Discharge	1.03	-	Lock	2.5	0
d	EES1 Real Power Charge	-	-	Lock	-2.5	
e	EES1 Reactive Power Discharge	-	-	Lock	0	2
f	EES1 Reactive Power Charge	-	-	Lock	0	-2
g	EES1 Real and Reactive power Discharge	-	-	Lock	1.5	2
h	EES1 Real and Reactive Power Charge	-	-	Lock	-1.5	-2

Simulation results for charging and discharging EES with 2.5MW real power are plotted in Figure 18.

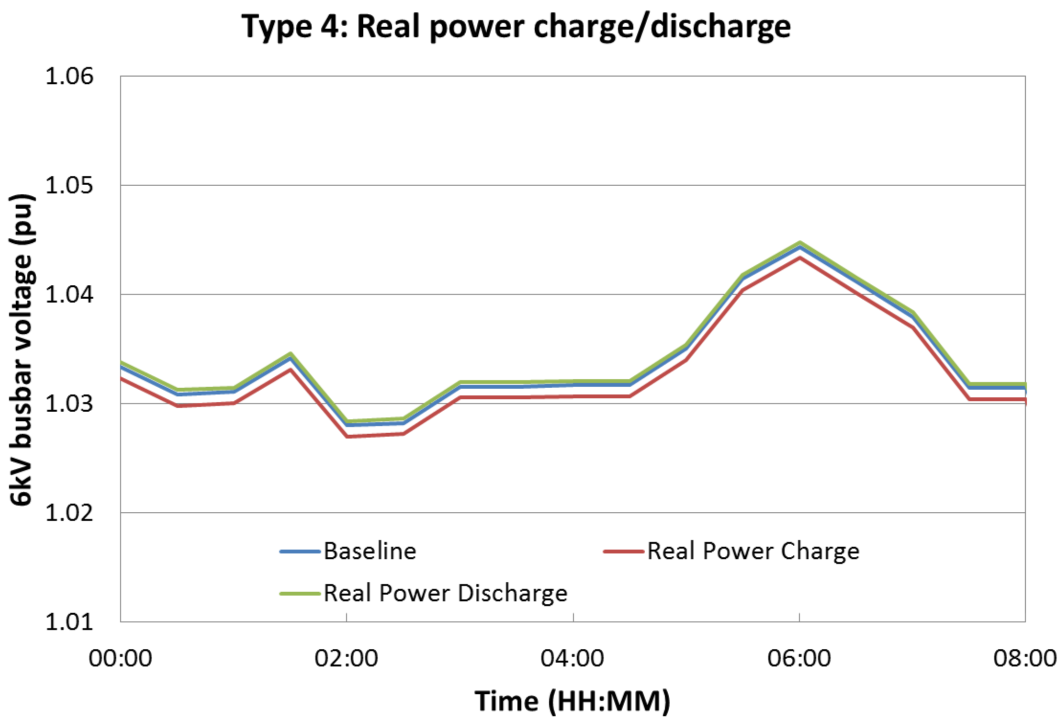

Figure 17 Type 4: Baseline Real Power Charge and Discharge under summer minimum load

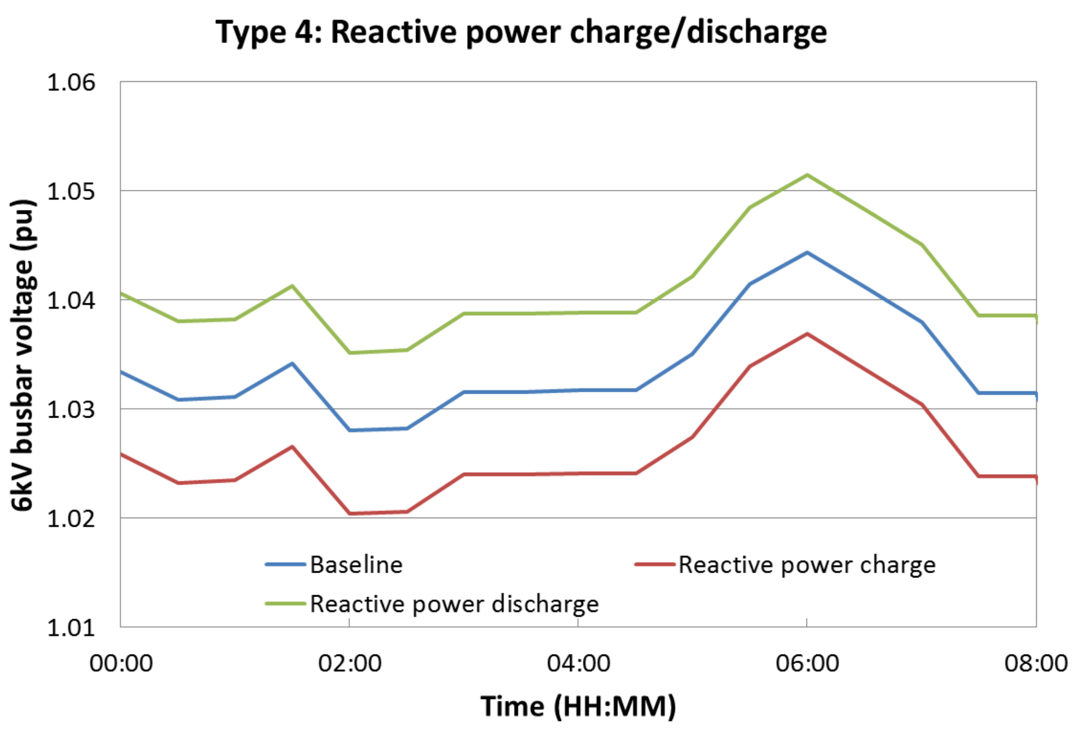

Figure 18 Type 4 Baseline reactive power import and export under summer minimum load

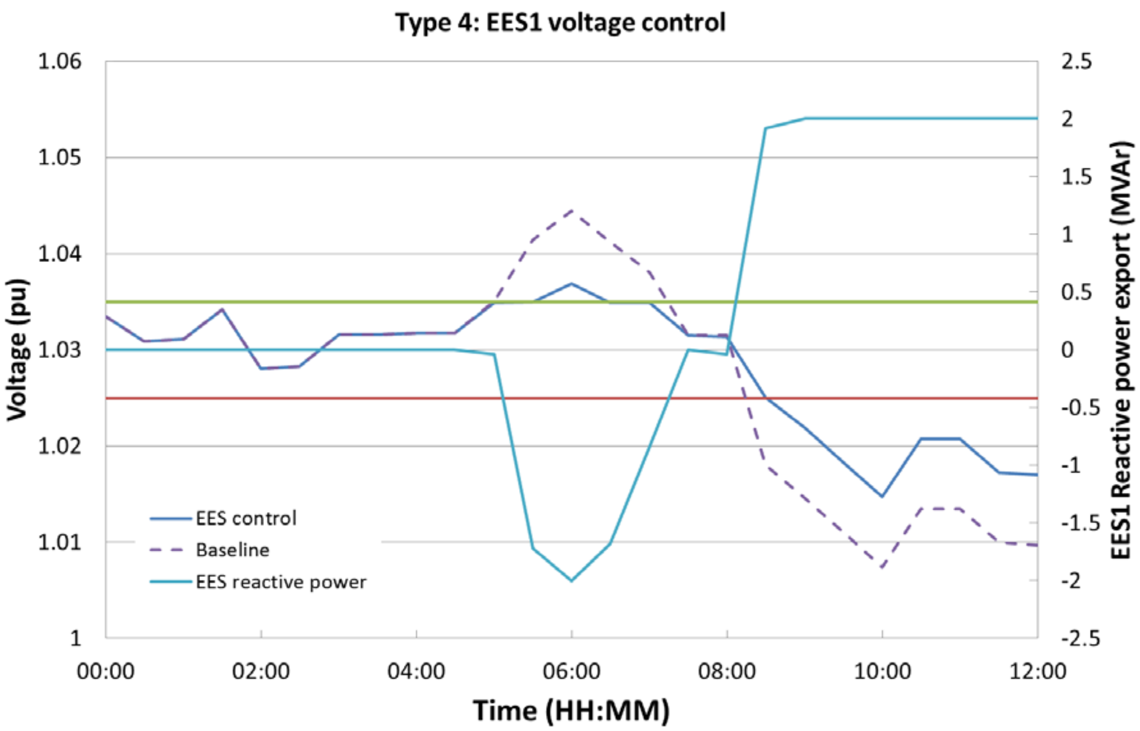

Figure 19 EES1 pre-trial Type 4 voltage control (Summer Minimum)

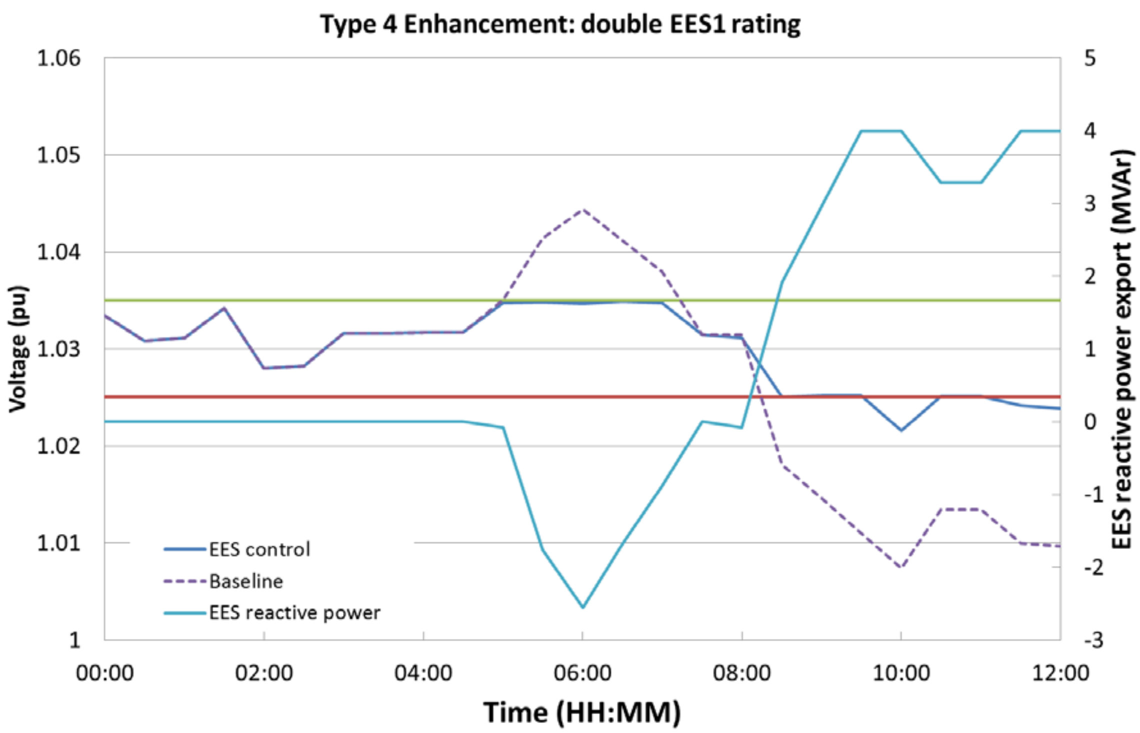

Figure 20 Type 4 Enhancement: 5MW/10MWh EES1 rating

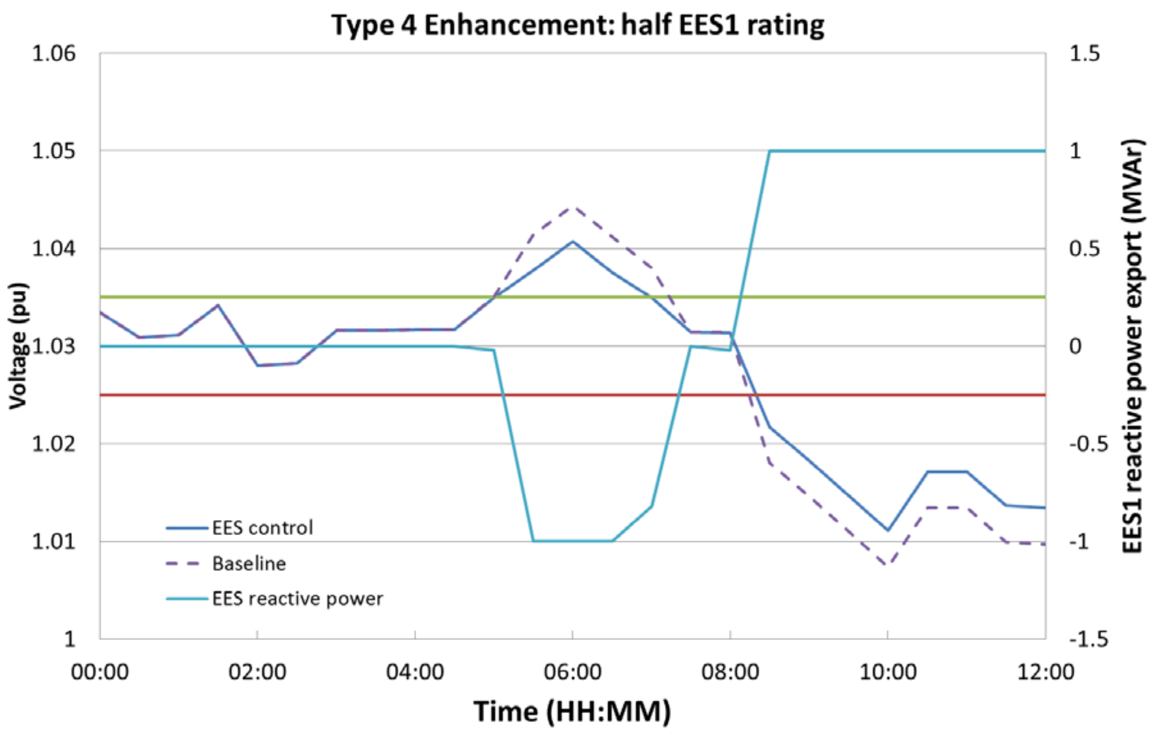

Figure 21 Type 4 Enhancement: 1.25MW/2.5MWh EES1 rating

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