Customer-Led Network Revolution

CLNR Trial Analysis

Electrical Energy Storage 1 (2.5MVA/5MWh) Powerflow Management at Rise Carr

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Executive Summary

As part of the Customer Led Network Revolution (CLNR) project, an Electrical Energy Storage (EES) facility was installed in the primary substation at Rise Carr, Darlington. The primary substation feeds 9,937 domestic customers. The EES facility, titled EES1, has a converter rated at 2500 kVA and a battery rated at 5000 kWh. Trials of EES1, under autonomous control, were carried out during May 2014. This report details the Validation, Extension, Extrapolation, Enhancement and Generalization (VEEEG) of these trials.

The EES was effective in mitigating current excursions on the transformer, subject to capacity limitations. The EES1 unit was controlled by the Grand Unified System (GUS) system and was therefore able to use data from the RTTR calculation embedded in the control system. The trial therefore demonstrated the capability of the EES unit to act collaboratively with transformer RTTR systems.

An IPSA2 simulation was used to model the network. There was general agreement between trials and model, but some differences were apparent. These were due to the autonomous controller using terminal voltage to estimate the battery state of charge, which gives lower accuracy SOC readings than the alternative methodology used in the model.

The model was run utilising end user input data for the following low carbon technologies:

- Air Source Heat Pump (ASHP) loads,
- Electric Vehicle (EV) charging and
- Photovoltaic (PV) generation.

The headroom of the existing network, with additional load can be calculated, both with and without EES1. In each case, the addition of EES1 is shown to increase the headroom and therefore allowed the connection of additional customers. In the case of ASHPs and EVs, the additional headroom provided by EES1 could accommodate an extra 497 and 1591 customers respectively. Further enhancement of the control system, described in detail in the body of the report, can accommodate a further increase of 198 and 99 customers on the network for ASHP and EV LCTs respectively.

1 Introduction

The work detailed in this document is the post-trial analysis of the Electrical Energy Storage (EES) system EES1, a 2.5MVA, 5MVAh facility. The system is autonomous and incorporates a single & Grand Unified Scheme (GUS) power flow management at Rise Carr. This work was conducted using the IPSA2 models of Rise Carr network to evaluate the capability of the primary 23MVA transformer to accommodate Low Carbon Technologies (LCTs) under the N – 1 condition, following the deployment of EES1. The EES installation at the Rise Carr primary substation is introduced in chapter 2. Field trial results of autonomous EES1 facility for power flow management are presented in chapter 3. The error in the State of Charge measurements has been explored. The load and low carbon technology (LCT) profiles used in this study are detailed in the next chapter. In this work, the load profile is derived from the real measurements from flexible data warehouse (FDWH). LCT profiles are based on the output of CLNR project and previous studies. The post-trial analysis methodology including Validation, Extension, Extrapolation, Enhancement and Generalization (VEEEG) is carried out with the validated network model along with the load and LCT profiles. The final section discusses the conclusions drawn from the trial.

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 Figure 1.

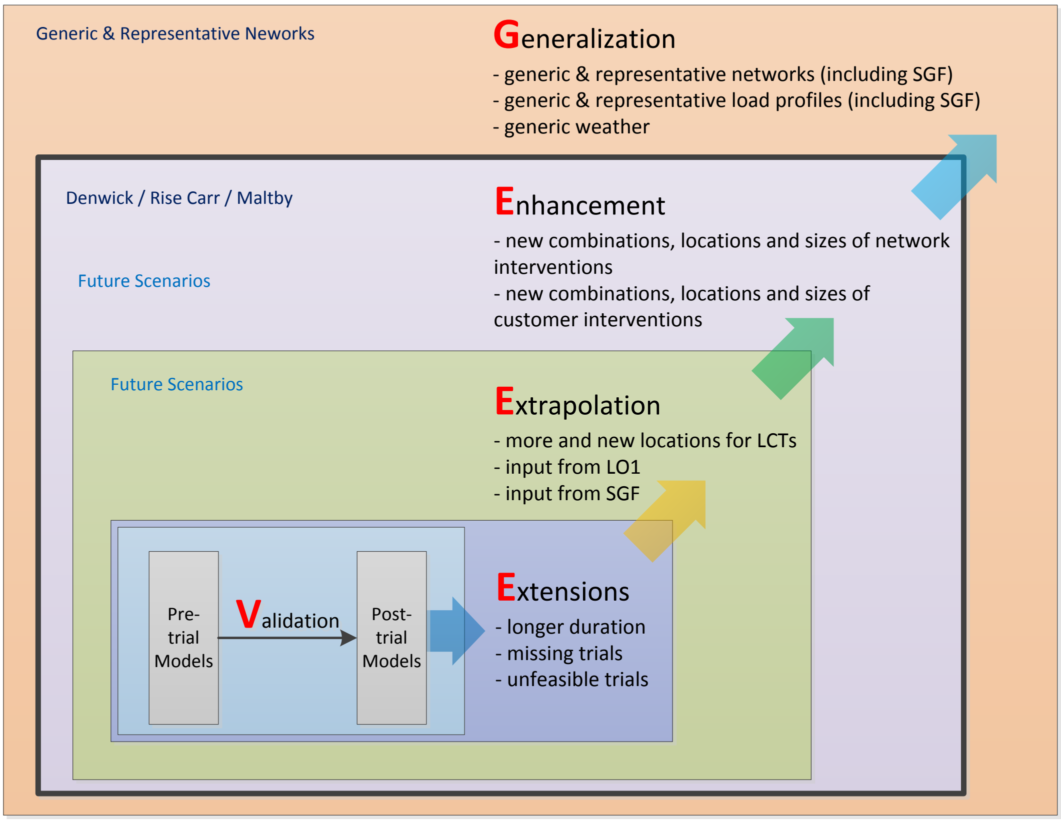

Figure 1 Post-trial methodology VEEEG

3 Trial Results and Validation

3.1 EES installation at Rise Carr

Figure 2 is a schematic of Rise Carr primary substation transformers and upstream networks. This primary transformer is connected with 9,937 domestic customers.

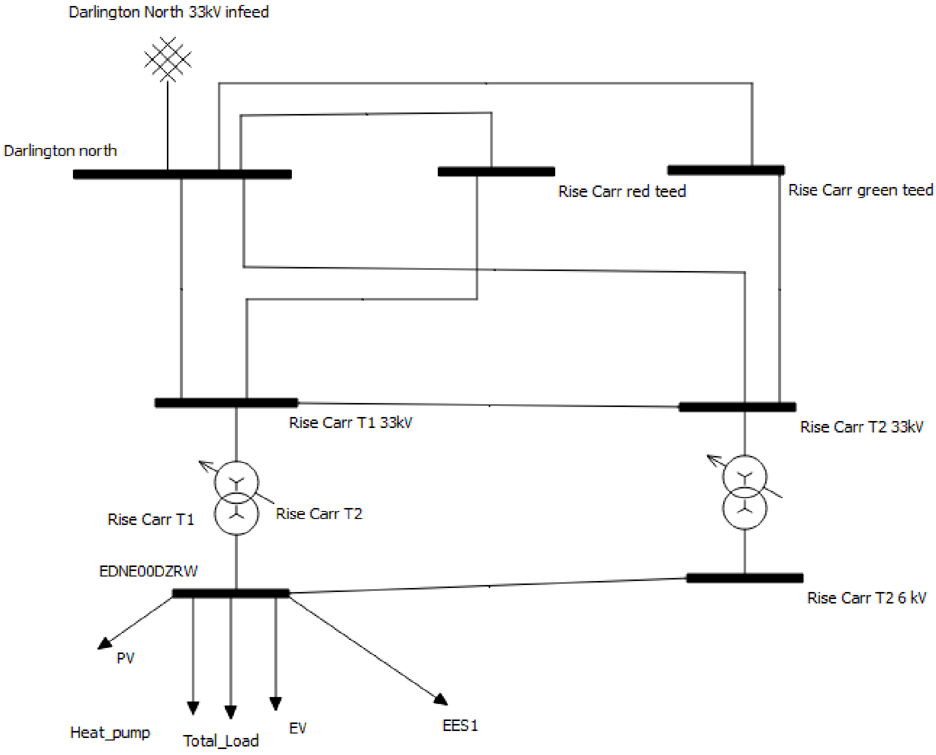

Figure 2 Rise Carr 23MVA primary transformer

3.2 Trial results

Trial results from 23/05/2014 are summarised below. Figure 3 shows the ampacity of transformer T1, T1 current and EES current during the trial. The State-of-Charge (SoC) of EES is plotted in Figure 4. The static rating of the transformer has been reduced to 230A and the maximum ampacity is set to 1.5 times of its static rating, 345A.

As can be seen from Figure 3, from 00:00 to 06:00, no thermal excursion is found and EES1 is instructed to charge. During this period, the SoC low limit increases by 500 kWh per hour. The SoC of EES1 is always lower than the SoC low limit.

The first overload is found at 09:00 and EES starts to discharge. Export from EES1 varies to keep the transformer current below its ampacity. During the second excursion at 16:00, however, EES is not able to discharge due to its low SoC. After 23:00, the EES starts to charge as seen in Figure 4.

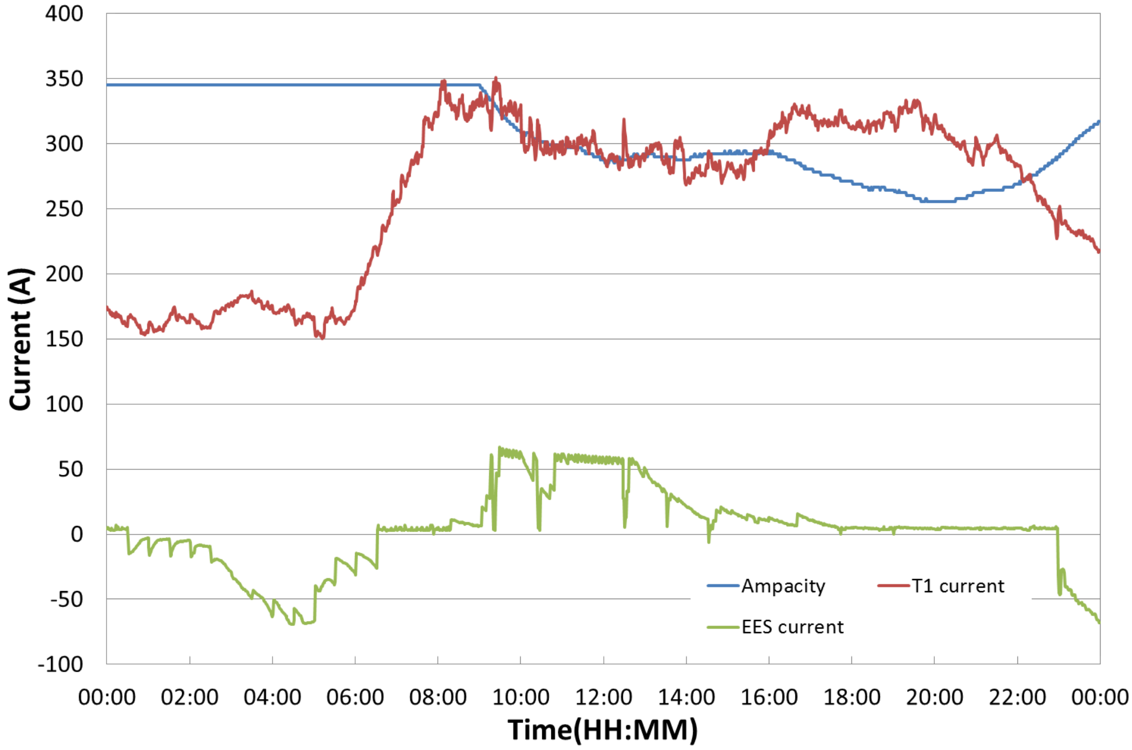

Figure 3 Trial result: Ampacity, Transformer Current and EES Current

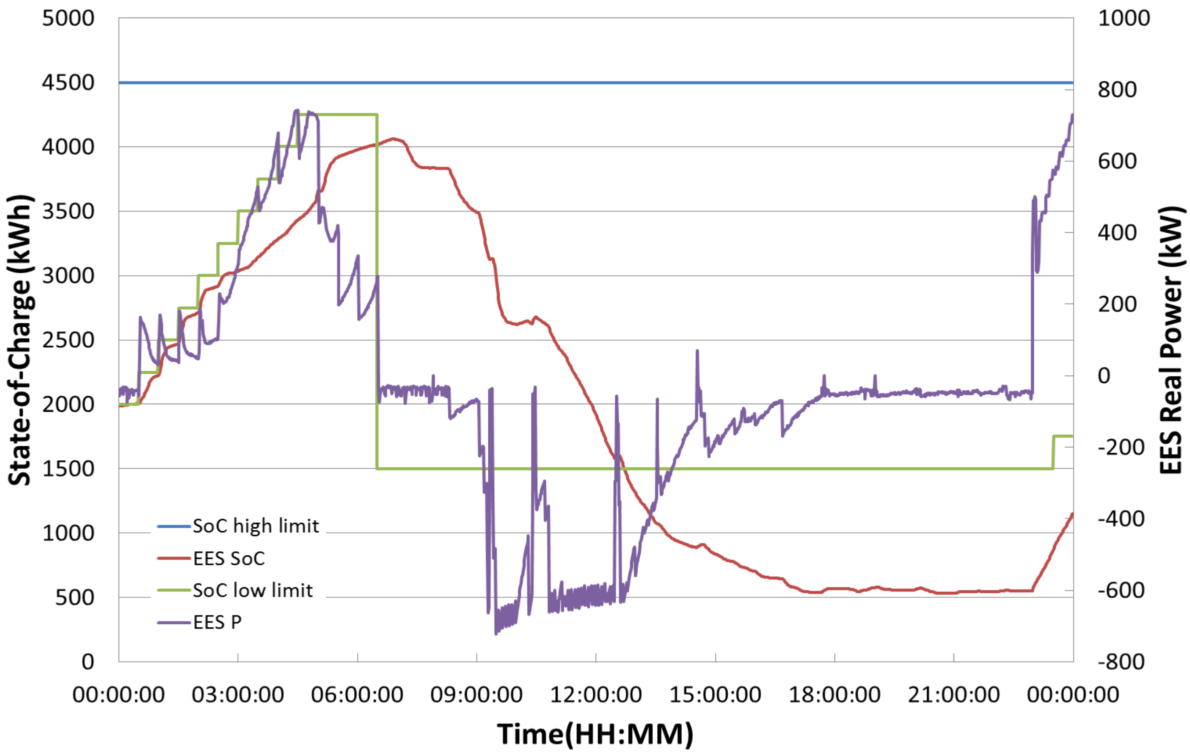

Figure 4 SoC of EES

3.3 EES SoC Measurement Error

In Figure 4, the SoC is the real measurement from FDWH, which is determined by the terminal voltage of the batteries. However, this measured SoC differs from the calculated SoC, which is given by

$$SoC_t = SoC_{t-1} + P_{t-1} * \Delta T, \quad (3.1)$$

Where SoC_{t-1} and $\mathrm{SoC_t}$ are the calculated SoC at times $t-1$ and t respectively. P_{t-1} is the import power of EES1 at t-1. $P > 0$ if EES1 is charging and $P < 0$ when discharging. The duration of charge or discharge is given by ΔT . The calculated SoC has a more accurate measure rather than the real SoC of the EES.

The calculated SoC and the measured SoC are compared in Figure 5. The maximum error between the measured SoC and the calculated SoC is 33.2%. The correlation coefficient between the error and EES real power export is 0.72, which indicates a strong correlation between the SoC error and the power export of EES1.

However, as can be observed, during charge, the measured SoC is always higher than the calculated SoC while the measured SoC is always lower than the calculated SoC during discharge. At this approximately constant discharge rate, the calculated and measured SoC values are the same, as can be seen at 00:00, 08:00 and at 23:30 hrs. When the battery is discharging and charging at higher rates, the measured and calculated SoC results do not match, with the calculated SoC curve lagging the measured SoC curve.

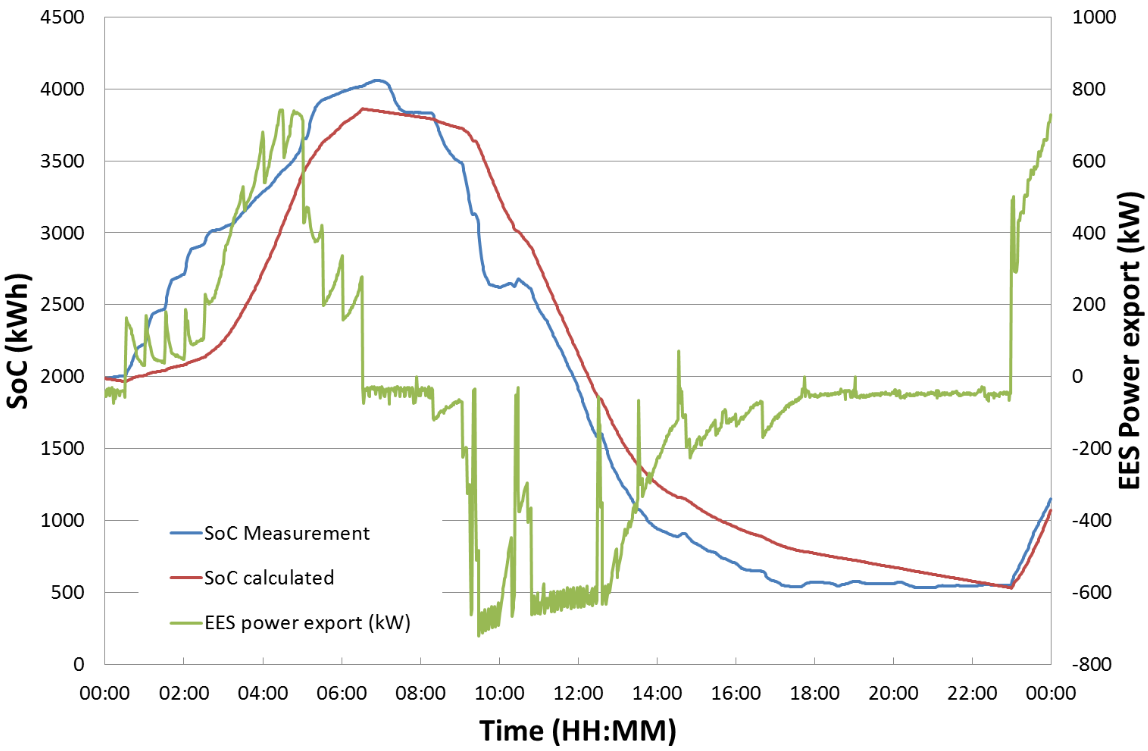

Figure 5 Measured and calculated SoC

3.4 Validation

The Rise Carr IPSA model for transformer T1 power flow study has been validated in a previous report [2]. The power flow management algorithm used in this trial has been realised in Python, based on the information provided by Northern Powergrid.

The algorithm is tested with the derived load profile in equation (4.2). Simulation result and the trial result are compared in Figure 6.

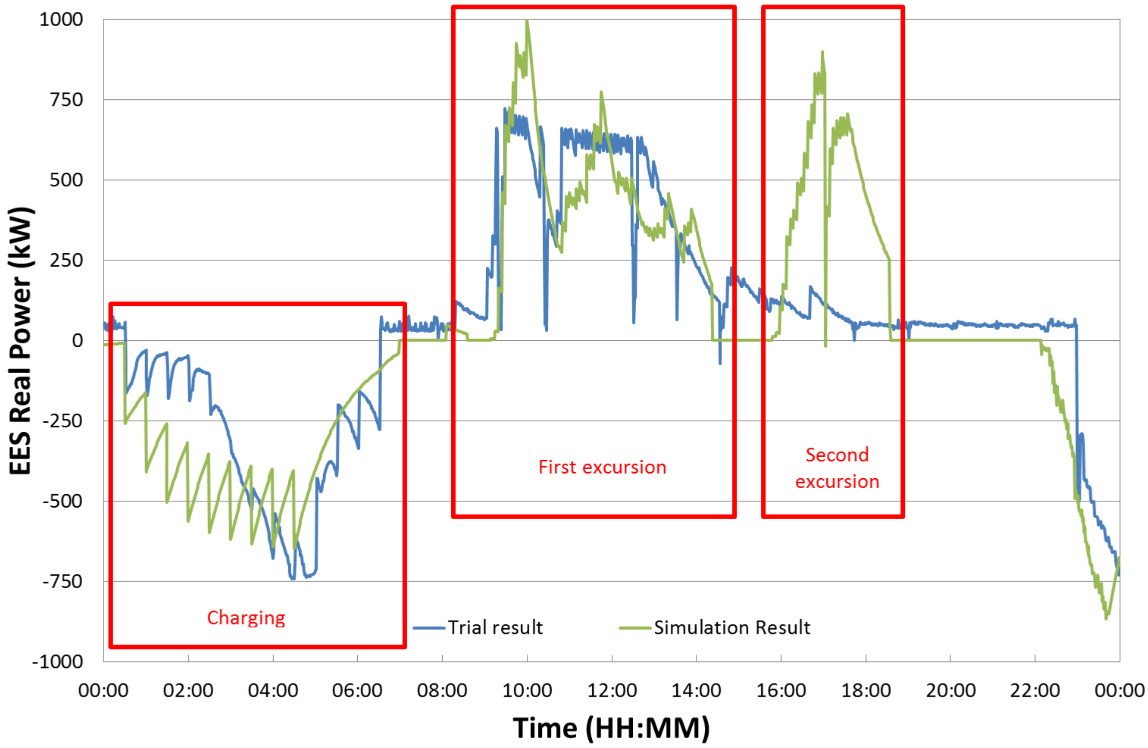

Figure 6 EES Power Export: Trial Result and Simulation Result

The SoC of EES1 during the trial and the simulated SoC are plotted in Figure 7.

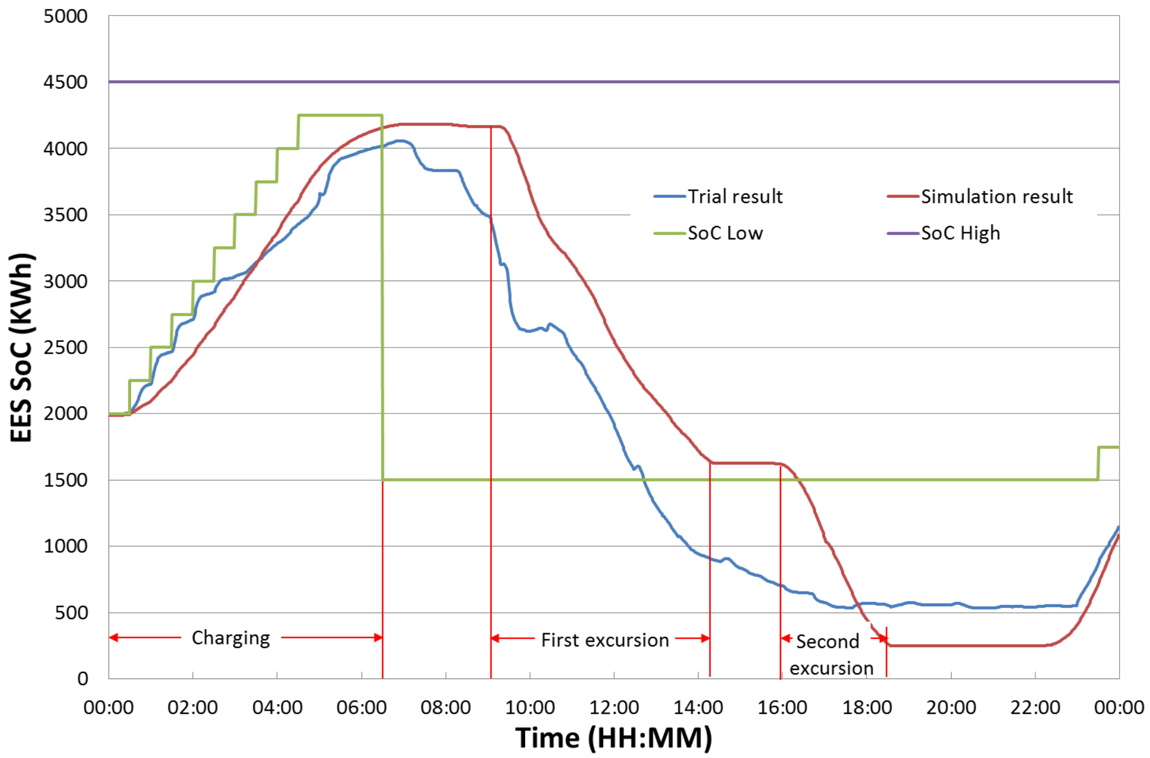

Figure 7 EES SoC: Trial Result and Simulation Result

In the simulation, the SoC is calculated in accordance with equation (3.1). The difference between the simulated SoC and that of the trial result leads to different charging profiles. The charging power $\mathrm{P_{Charge}}$ is decided by the difference between the SoC and SoC low, SoC_{Low}, limit:

$$P_{Charge} = \frac{SoC_{Low} - SoC}{\Delta T}, \quad (3.2)$$

From 00:00 to 04:00, in the simulation, SoC is lower than that of the trial results and thus, the charging power is higher. However, after 04:00, the calculated SoC is lower than trial result and therefore, the charging power is lower.

During the first excursion, the power export from EES1 in the simulation is comparable to the trial result. At the end of the first excursion, the SoC in the simulation (1625kWh) is higher that of the trial result (900kWh). As a result, at the beginning of the second excursion, in the trial, EES was not able to discharge due to its low SoC. In the simulation, however, EES started to discharge for approximately 3 hours until the SoC reached its technical low limit (5%, 250kWh).

The current on transformer T1 in simulation and the trial are depicted and compared in Figure 8.

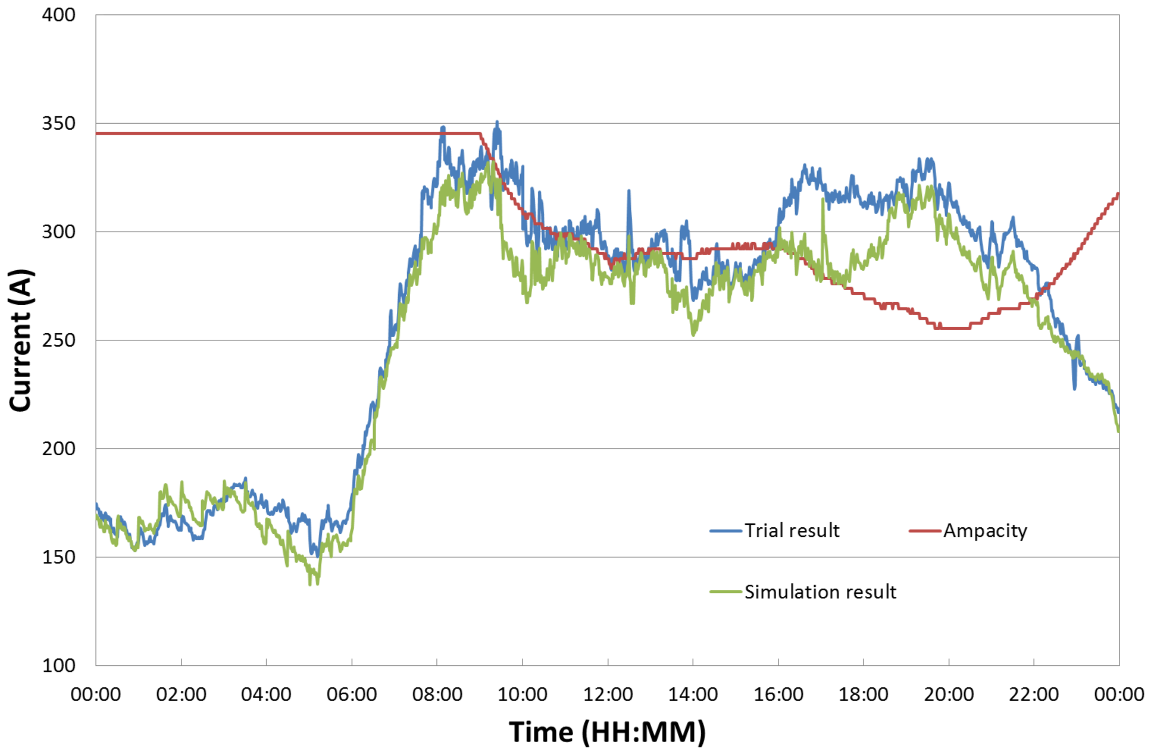

Figure 8 Transformer Current: Simulation Result and Trial Result

As can be seen from the Figure 8, the simulation profile is almost same as the trial result except during 16:00 to 18:00. This discrepancy results from the battery management system. In real trial, the battery management system deems that there is not enough energy to mitigate the excursion, but in simulation, the battery management system informs the controller that there is still plenty of energy that can be used to support the grid.

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

In this chapter, post-trial analysis including validation, extension, enhancement, extrapolation and generalization is carried out. In the validation study, ampacity has been used to validate the algorithm in section 3. In the following analysis, it is assumed that the network is under N-1 condition (transformer T1 only) and the rating of transformer T1 is its static rating of 23MVA.
A thermal excursion of a transformer is defined as the load on the transformer excesses its rating. In this work, thermal excursion is defined as

$$P_{Avg} > P_{Rating}, \quad \textbf{(4.1)}$$

Where P_{Avg} is the 10-minute[1] average load on the transformer and P_{Rating} is the rating of the transformer.

4.1 Profiles

4.1.1 Load profile

The load current (I_{Load}) profile used in this study is derived from transformer current, I_{T_1}, and EES current, I_{EES}:

$$I_{Load} = I_{T_1} + I_{EES}, \quad \textbf{(4.2)}$$

Where $I_{Load}$is the load current. The derived load profile is shown in Figure 9 against the ampacity. Two excursions can be observed, one from 09:00 to 13:00 and one from 16:00 to 22:00.

[1] In this study, a 10-minute average load is chosen. However, the time constant of transformers and overhead lines is around 0.5 - 1 hour and 10 - 15 minutes respectively. Therefore a longer period of averaging is still acceptable in practice.

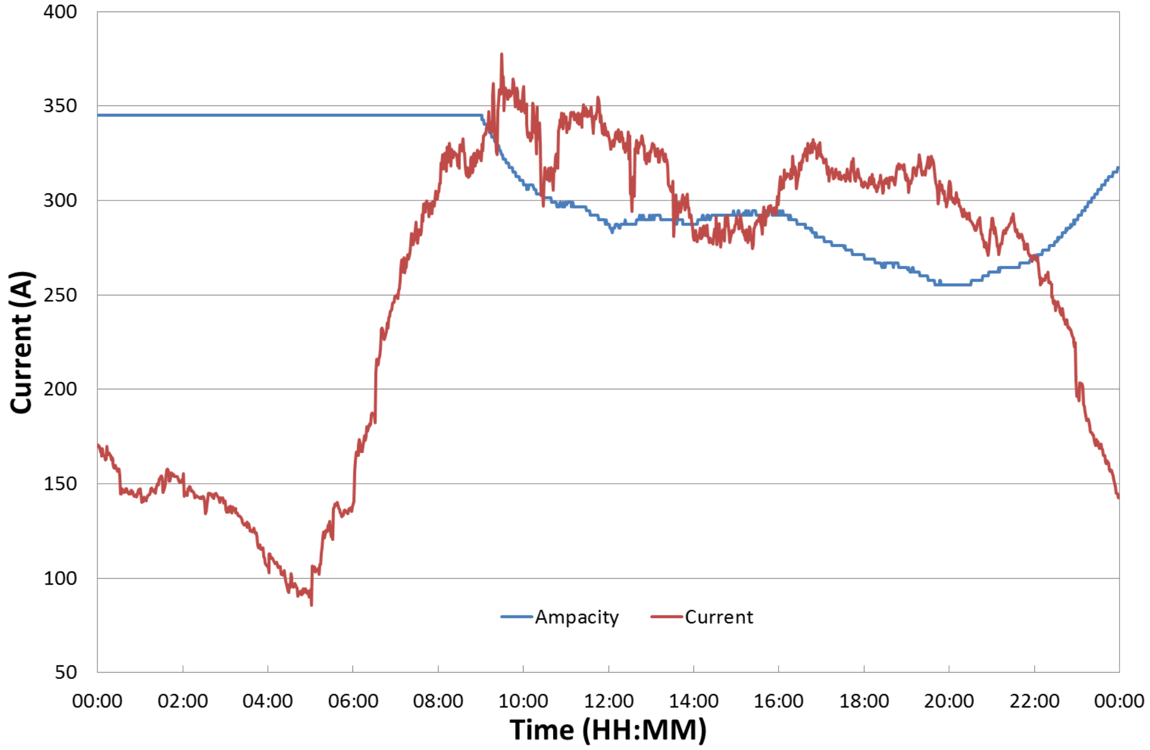

Figure 9 Derived Load Profile

4.1.2 Air Source Heat Pump and Electric Vehicle consumer modelling

Average EV and ASHP load profiles are plotted in Figure 10. The EV consumer model used in this work is based on profiles developed previously in [1]. 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.

An ASHP load model suitable for this analysis is derived from data from the CLNR project programme. 277 households with operational ASHP units have been equipped with disaggregated monitoring equipment that monitor household and ASHP load at a 1-minute time resolution. Analysis of this current dataset established that the 17th Jan 2013 represented the worst case scenario in terms of loading for the ASHP units. Analysis of weather data indicates that this coincided with a cold spell across the UK. In order to develop a model of a future worst case scenario, the 95th percentile profile, as illustrated, is used.

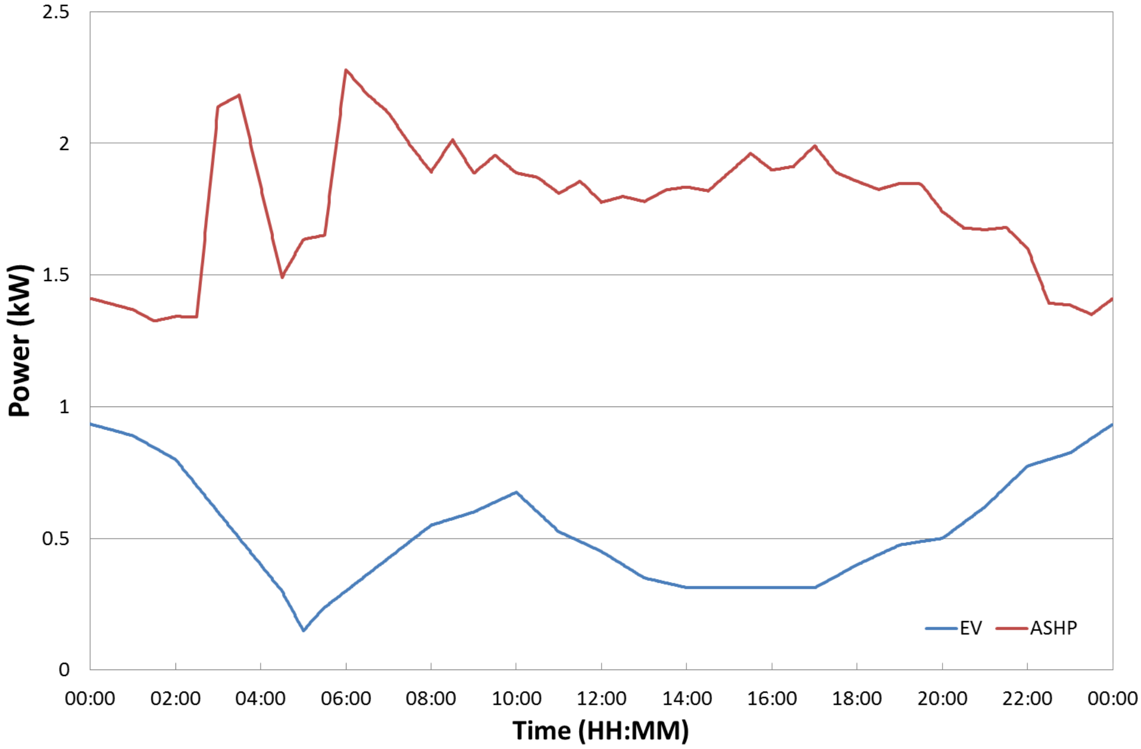

Figure 10 EV and ASHP profiles.

4.2 Extension and Extrapolation

In this section, the numbers of LCTs connected to the network has been increased to evaluate the capability of the primary 23MVA transformer in accommodating LCTs, following the deployment of EES1. The real power rating of EES1 is 2.5MW, while the rating has been set to 1MW in the trial.

4.2.1 ASHP clustering on case study downstream network

The ASHP profile shown in Figure 10 used in this study has been introduced in section 4.1.2. Following the implementation of EES1, the number of ASHPs that can be accommodated increased from 7453 to 7950. The control algorithm has been validated in section 3, it was used in this section to do some extension and extrapolation work. The load profile (with and without control) on transformer T1 with and without EES1 is given in Figure 11.

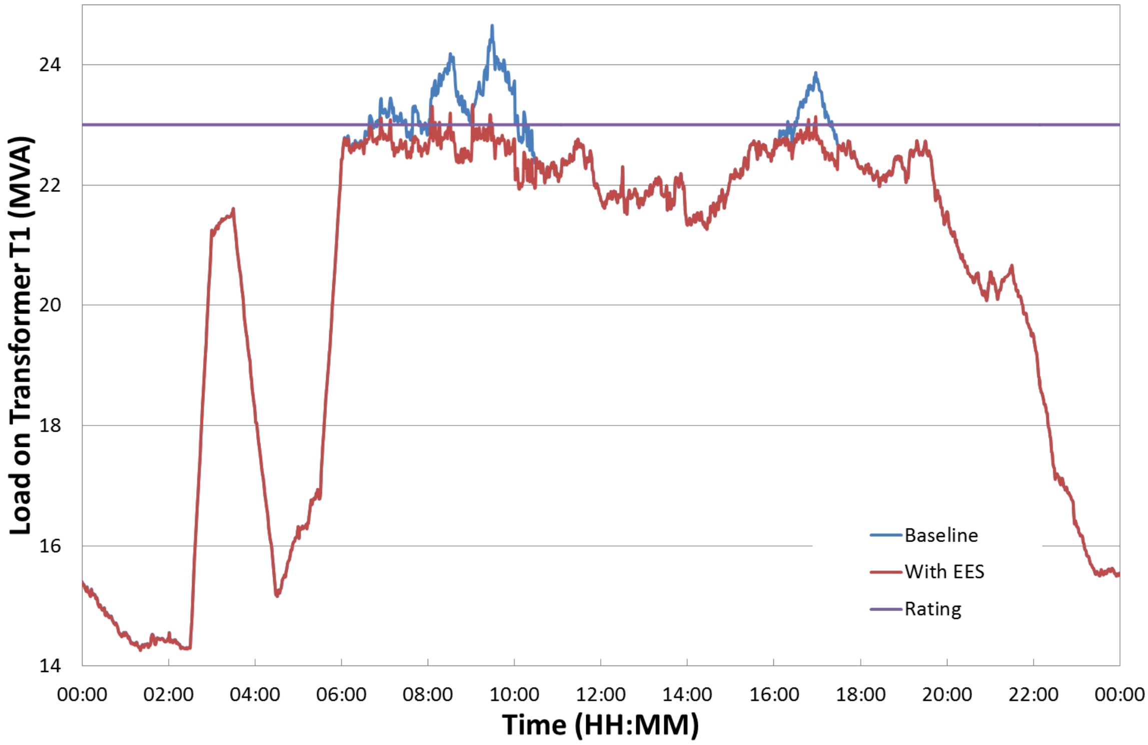

Figure 11 Load on Transformer T1 with and without EES1

The real power export of EES1 during this period is plotted in Figure 12. As can be observed, the state-of-charge of EES1 reduced from 5000 kWh to 1559 kWh. Maximum power export of EES1 is 1.56MW.

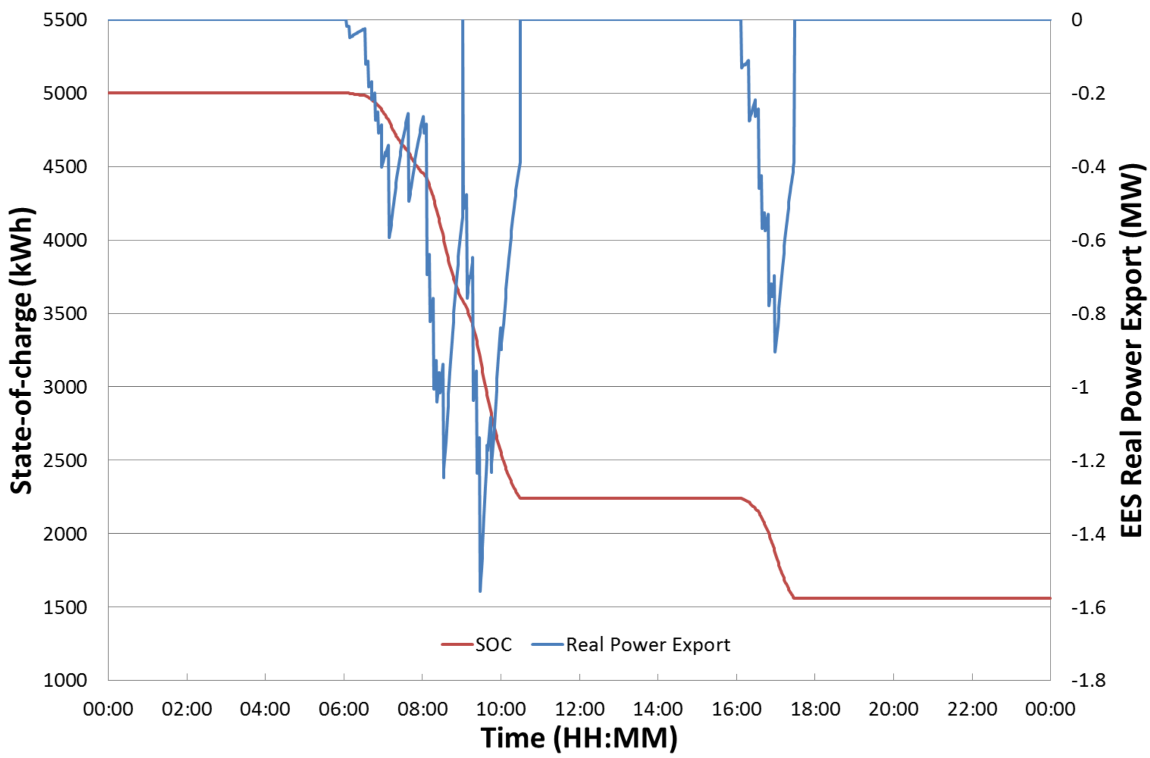

Figure 12 EES Real Power Export and State-of-charge

4.2.2 EV clustering on case study downstream network

The same study as section 4.2.1 has been carried out with the EV profile. Simulation results show that the maximum number of EVs connected to the network increases from 20171 to 21762 following the implementation EES1. The load profile on transformer T1 with and without the control of EES1 is plotted below.

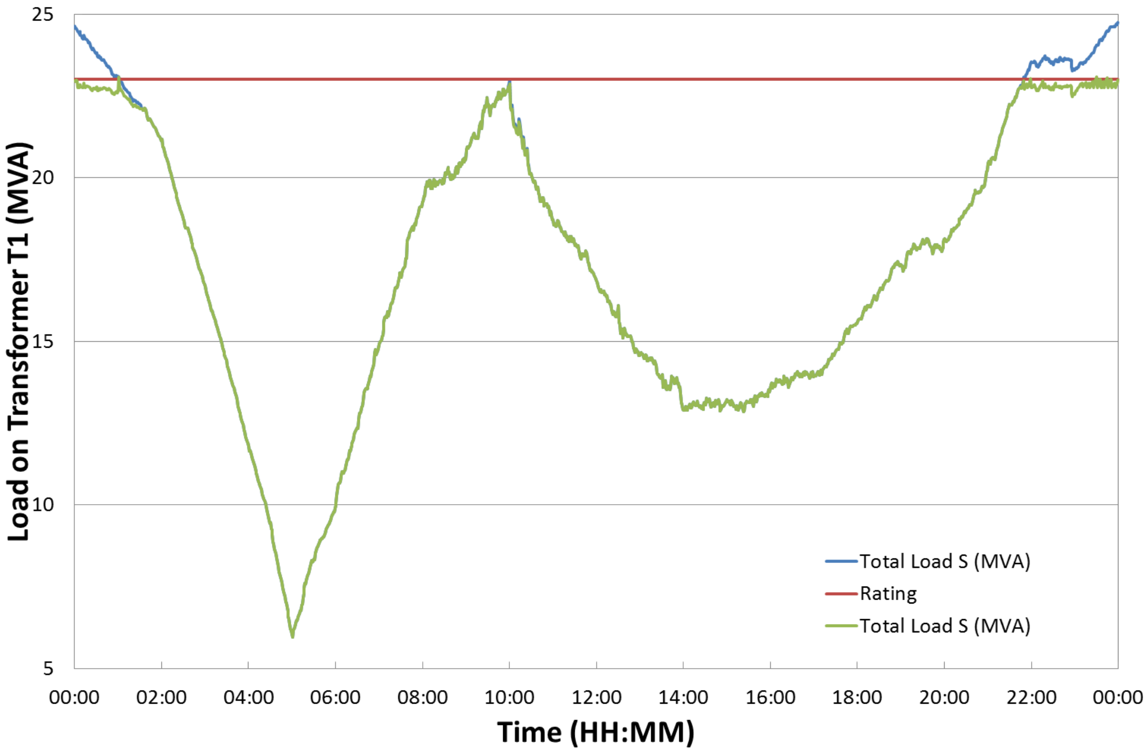

Figure 13 Load on Transformer T1 with and without EES1

Figure 13 shows that the excursion happened at 00:00 to 01:00 and 21:00 to 00:00 was solved by the EES1 The power export and SoC change of EES1 is plotted in Figure 14.

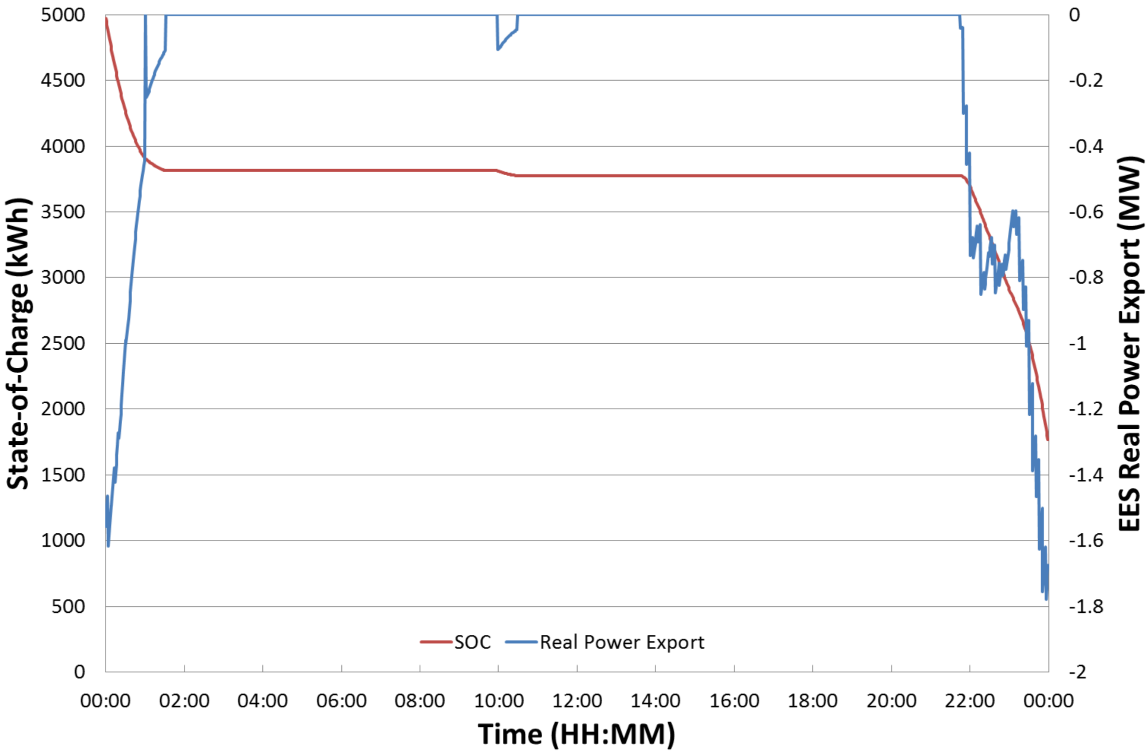

Figure 14 EES Real Power Export and State-of-charge

The initial SoC is assumed to be 100%. During 00:00 to 01:00 and 21:00 to 00:00, the EES1 was exporting the power to support the grid and consequently, the SOC is reduced from 5000 kWh to 1600 kWh.

4.2.3 Discussion

The number of ASHPs is limited by the algorithm design rather than the size and rating of EES1. At time t, once an overload is detected, the controller will calculated the required power export of EES by

$$P_{EES_t} = I_{EES_t} \times V_t, \tag{4.3}$$

Where, P_{EES_t} is the required real power export, I_{EES_t} is the required current export and V_t is the voltage at the 6kV bus bar. I_{EES_t} is given as

$$I_{EES_t} = I_{EES_{t-1}} + k \cdot \Delta I_t = I_{EES_{t-1}} + \left(I_{Tf} - I_{Rating}\right) \tag{4.4}$$

Where $I_{EES_{t-1}}$ is the current output of EES at time $t-1$, I_{Tf} is the current measurement of transformer T1 and I_{Rating} is the current rating of the transformer. k is gain factor, where $k = 1$ in the controller
Once the power export is decided, during the next 5 minute interval, the real power export of EES1 is given as

$$P_{EES_t} = P_{EES_{t-1}} \times 0.98 \tag{4.5}$$

During the decay time, any thermal overload is ignored. At time $t = 6$, the controller will recalculate the required power export. If no excursion is found, the power export will keep decay for another 25 minutes.

As shown in Figure 15, at 09:17 and 09:22, two excursions have been found and the required power is calculated. However, during the 5-minute decay time, the load increase leads to the overload during the decay period. From 09:17 to 09:26, the average load on transformer T1 is 23.17MVA and thus this excursion is defined as a failed control.

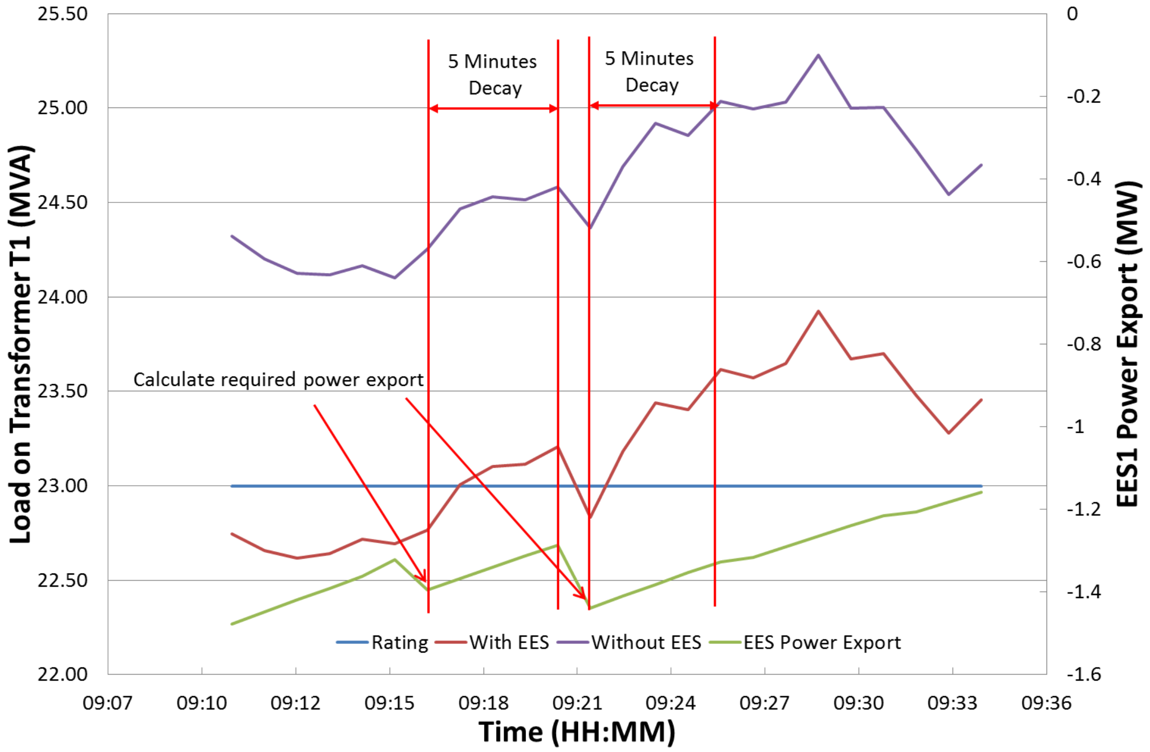

Figure 15 5-minute Decay, Overload Due to ASHP

4.3 Enhancement

As introduced previously in section 4.2.3, a five-minute decay is applied once the required power for EES1 is calculated and implemented. At the end of the five-minute decay, the power export of EES1 will be

$$P_{t_5} = 0.98^5 P_{t_0} \approx 0.904 P_{t_0} \quad \textbf{(4.6)}$$

Where, P_{t_0} is the calculated power export based on equations (4.3) and (4.4).The gain factor, k equals 1 in equation (4.4).

As illustrated in Figure 16, this setting is suitable to solve an overload which decays faster than 98% per minute. In the enhancement study, a new gain factor $k = {}^1/_{0.98^5} \approx 1.11$ is adopted and thus, at the end of the five-minute decay, the export power of EES1 will be

$$P'_{t_5} = 0.98^5 P'_{t_0} = 0.98^5 \cdot k \cdot P_{t_0} = 0.98^5 \cdot {}^1/_{0.98^5} \cdot P_{t_0} = P_{t_0} \quad \textbf{(4.7)}$$

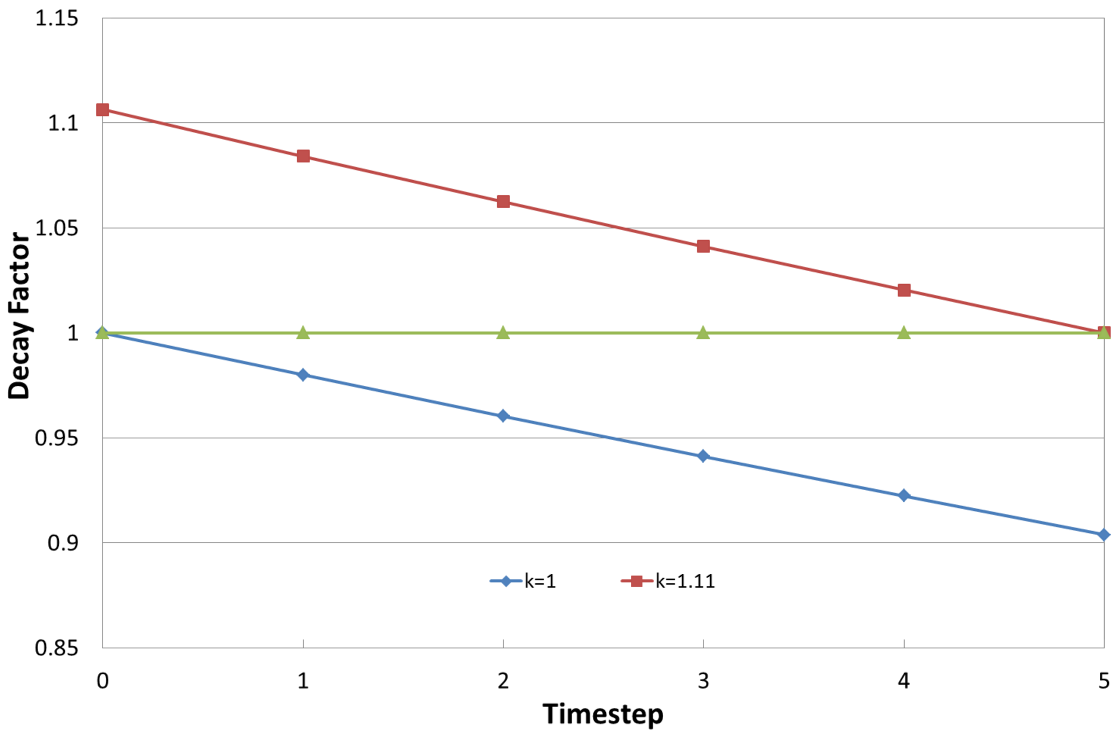

Figure 16 Decay factor

4.3.1 ASHP clustering on case study downstream network

When the gain factor k in equation (4.4) is increased to 1.11, the number of ASHPs that can be accommodated is 8148.

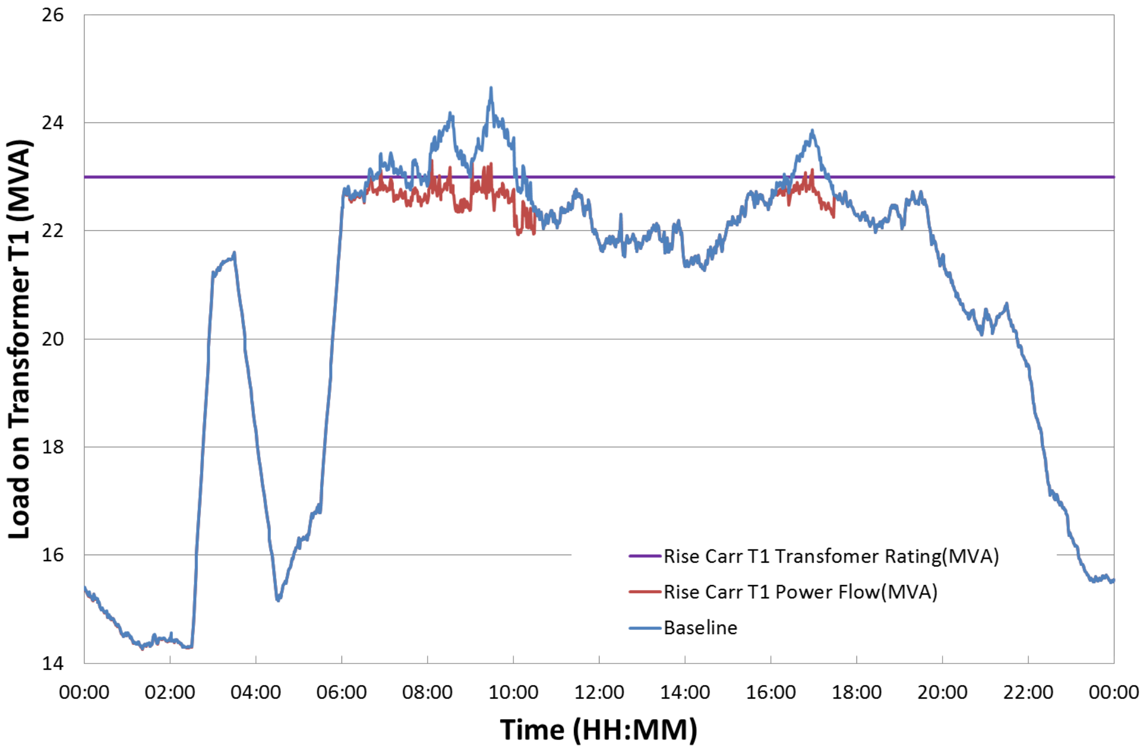

Figure 17 Load on Transformer T1 with and without EES1

The impact of EES1 power flow control on thermal load reduction is shown in Figure 17. It helps to mitigate the excursion happened from 06:00 to 10:00 and 16:30 to 18:00.
The EES real power export and its SoC is plotted in Figure 18.

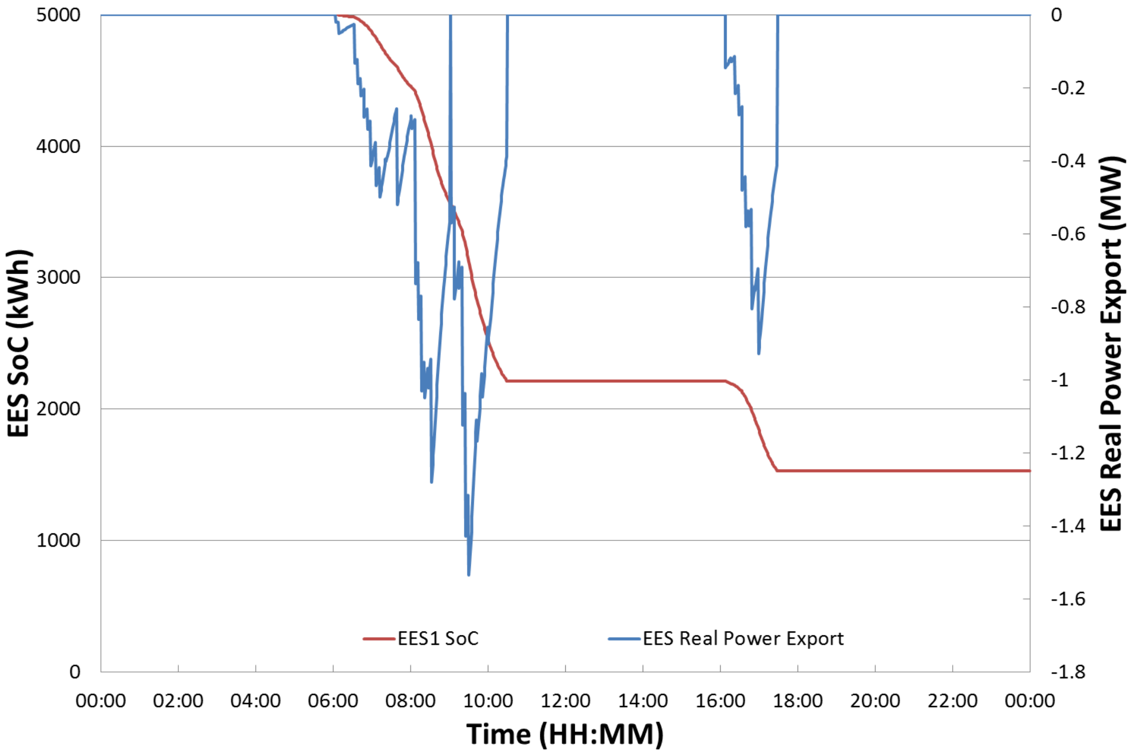

Figure 18 EES Real Power Export and State-of-charge

Due the EES1 power exporting, the SoC is reduced from 5000 kWh to 1700 kWh.

4.3.2 EV clustering on case study downstream network

With the increased gain factor, the number of EVs that can be accommodated increased to 21861. The load on transformer T1 is plotted in Figure 19

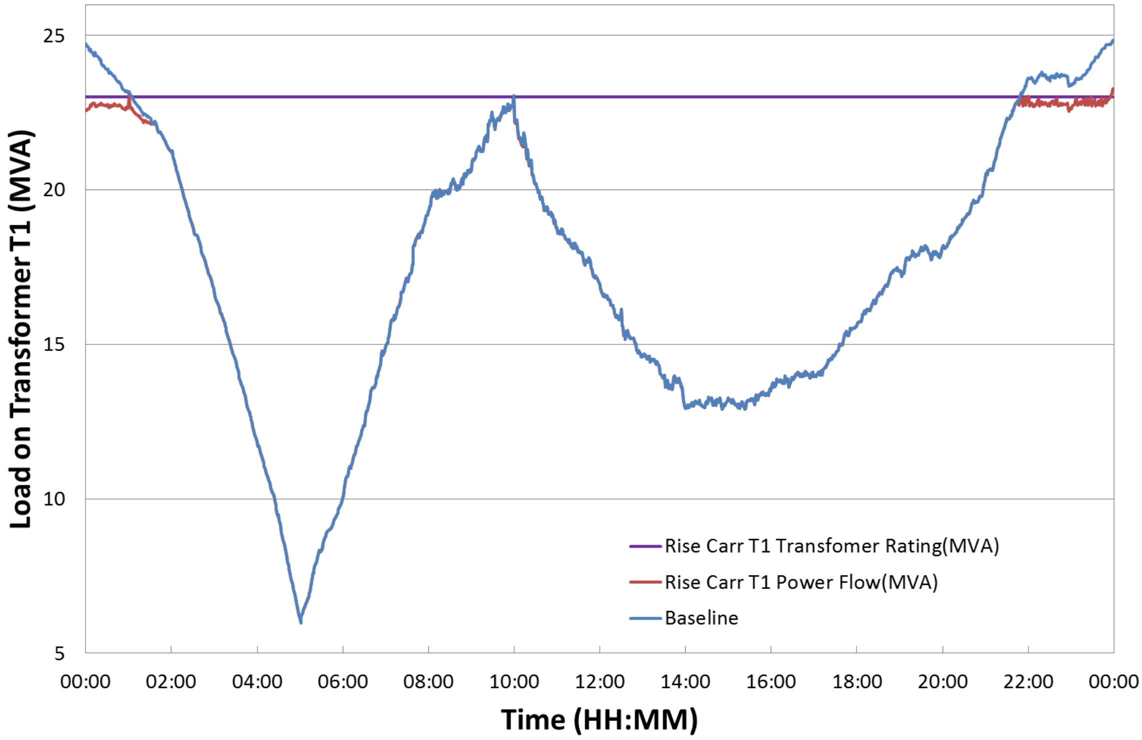

Figure 19 Load on Transformer T1 with and without EES1

The real power export and the SoC of EES1 during this trial are plotted in Figure 20.

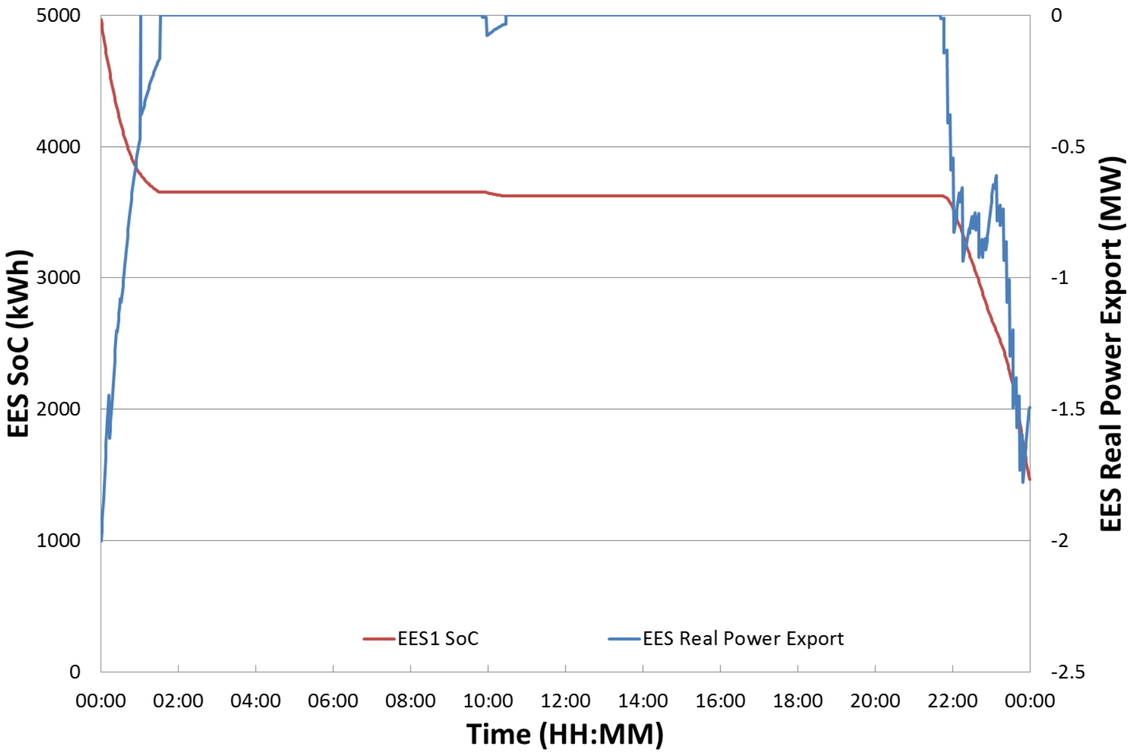

Figure 20 EES Real Power Export and State-of-charge

5 Conclusions

In this report, post-trial analysis of EES1 for power flow management in Rise Carr was carried out to evaluate the capability of the primary 23MVA transformer to withstand connection of LCTs, following the deployment of EES1.

The validated Rise Carr network model was used. The power flow management algorithm has been realised in Python and validated with trial results. The error of EES1 SoC measurement has been explored. Real load profiles, derived from the real network measurements, together with LCT profiles have been used to carry out extrapolation and enhancement study. The numbers of LCTs that can be connected are summarised below in Table 1.

Table 1 Numbers of LCTs

	Baseline	Extrapolation	Enhancement
ASHP	7453	7950	8148
EV	20171	21762	21861

In summary, the conclusions that can be drawn from this work are as follows:

1. During the trial, the power flow management algorithm was able to reduce the current on transformer T1 to below its rating. However, the duration of the trial was limited by the SoC of EES1;
2. The SoC measurement of EES1 had a maximum error of 33.2% compared to the calculated value. A strong correlation was found between the SoC error and the real power export/import;
3. In this report, a thermal excursion was defined as 10-minute average load above the component rating. Thus, any spike in load was ignored;
4. The use of EES1 can increase the numbers of LCTs (1591 more EVs and 497 more ASHPs) that can be accommodated by the Rise Carr network, without causing a thermal violation on the primary transformer under N-1 condition;
5. By increasing the gain factor in the control algorithm, the headroom of the transformer can be further improved by 99 EVs and 198 ASHPs;
6. The headroom created by EES1 depends on the load profile and the LCT profiles; however, a better design of the controller could reduce the size of battery and reduce the required capital investment.

Reference

[1] DECC/OFGEM, "Smart Grid Forum," 2012, 3rd August 2012.
[2] J. Y. S. B. P. Lyons, "DEI-CLNR_DC151 Analysis of I&C DSR for Powerflow Management," 2014.

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