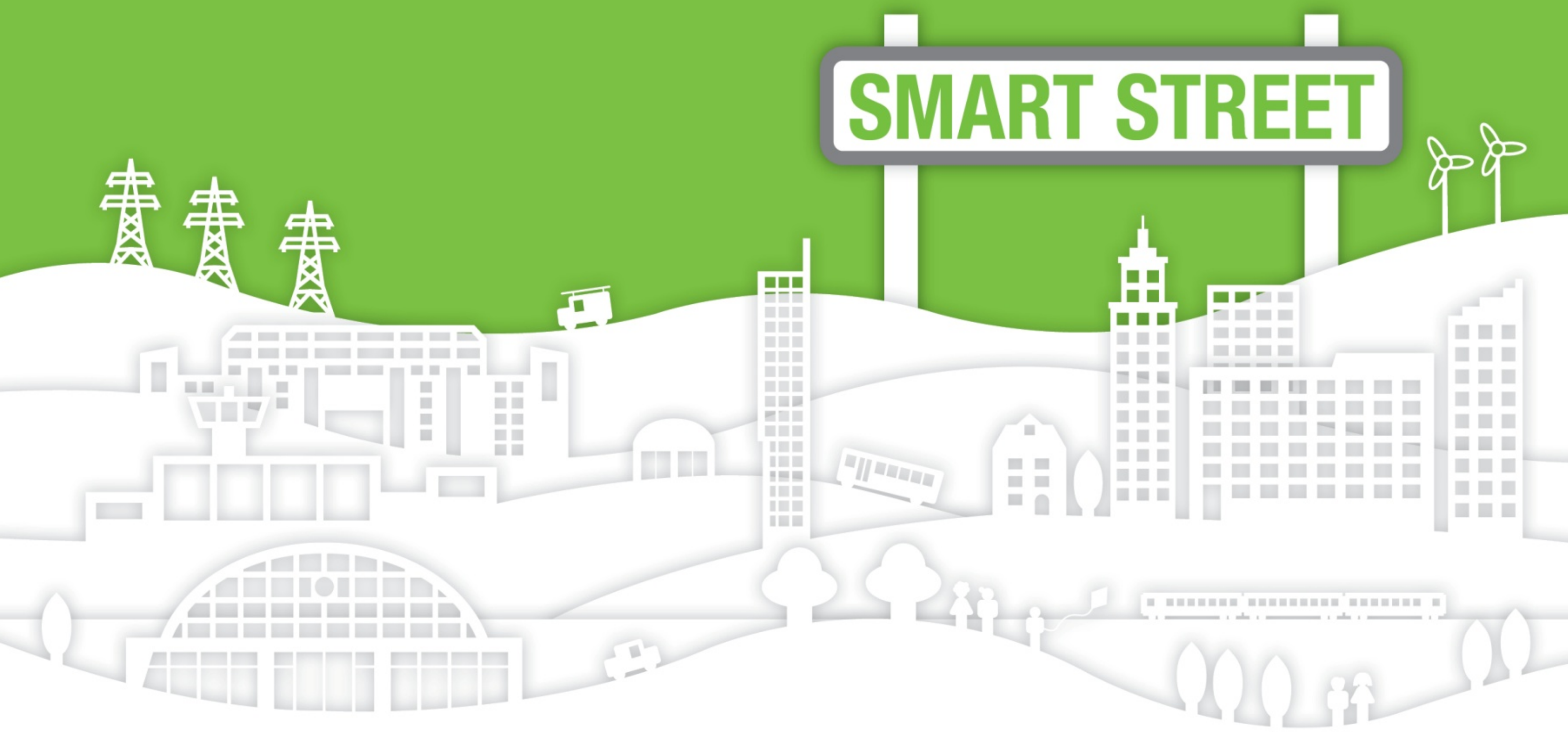
Smart Street

HV and LV Voltage and Configuration Optimisation Study

20 February 2017



VERSION HISTORY

Version	Date	Author	Status	Comments
Version 1	20/02/17	Geraldine Bryson	1.0	

LIST OF ACRONYMS

Abbreviation	Term
CLASS	Customer Load Active System Services (LCNF Tier 2 Project)
COP	Codes of practice
CRMS	Control room management system
CVR	Conservation voltage reduction
DG	Distributed generation
DSSE	Distribution system state estimator
HV	High voltage (11kV / 6.6kV)
LCT	Low carbon technology
LCNF	Low Carbon Networks Fund
LV	Low Voltage (400V / 230V)
NMS	Network management system
OHL	Overhead line
OLTC	On load tap changer
RTU	Remote terminal unit
SCADA	Supervisory control and data acquisition system
SP5	Spectrum Power 5 (Siemens optimisation software)
THD	Total harmonic distortion
VVC	Volt/Var control

CONTENTS

1 INTRODUCTION

1.1 Purpose of document

The purpose of this document is to achieve the associated deliverable related to the following Smart Street **SDRC 9.4.1 – Publish an interim HV and LV Voltage and Configuration Optimisation report on the Smart Street website by February 2017.**

This document describes the methodology employed, simulation work carried out and analysis of trial data to quantify the effects of CVR. The effects are quantified in terms of reduction in voltage, energy consumption and energy losses.

1.2 What is Smart Street

Smart Street aims to utilise advanced real time optimisation software to simultaneously manage HV and LV network assets to respond to customers' changing demands. Voltage management on HV networks will look to reduce network losses while conservation voltage reduction (CVR) on the LV networks will look to reduce energy demand. Capacitor banks on the HV network are being utilised to help manage network losses by adjusting the networks power factor. On the LV network, a mix of capacitor banks and controlled meshing of networks will be integrated to flatten the voltage profile and improve energy efficiency. The meshing of LV networks will also aim to release additional network capacity.

1.3 Conservation voltage reduction (CVR)

Electrical equipment made for the European market, including household appliances and lighting, is designed to operate most efficiently in the region of 230 to 220volts. This equipment can, however, operate adequately at voltages in the region of 200volts. If power is delivered at voltages higher than these optimum levels, then energy will be consequently wasted. Excess voltage can shorten the useful life of electrical equipment, since the excess energy is dissipated as heat. Therefore optimising network voltages reduces overall energy consumption, improves power quality and extends the life of the customer's equipment. Smart Street proposes to optimise network voltages by using CVR on the LV trial networks.

CVR on a distribution network is defined as a reduction of energy consumption resulting from a decrease in feeder voltage. Smart Street proposes to optimise the voltage by utilising on-load tap changing (OLTC) transformers. These transformers will be able to regulate the voltage along the feeder while maintaining statutory limits. This will allow for the peak load to be reduced, hence reducing the annual energy consumption.

Additionally Smart Street will utilise shunt capacitors on the LV feeders to allow for a voltage boost at the end of the circuit to reduce voltage drop. This will allow for a flatter voltage profile, allowing for the OLTC to tap closer to the lower limit.

1.4 LV network meshing

In addition to the proposed CVR techniques, Smart Street will assess the benefits of meshing LV networks to balance load while releasing network capacity at times of high demand.

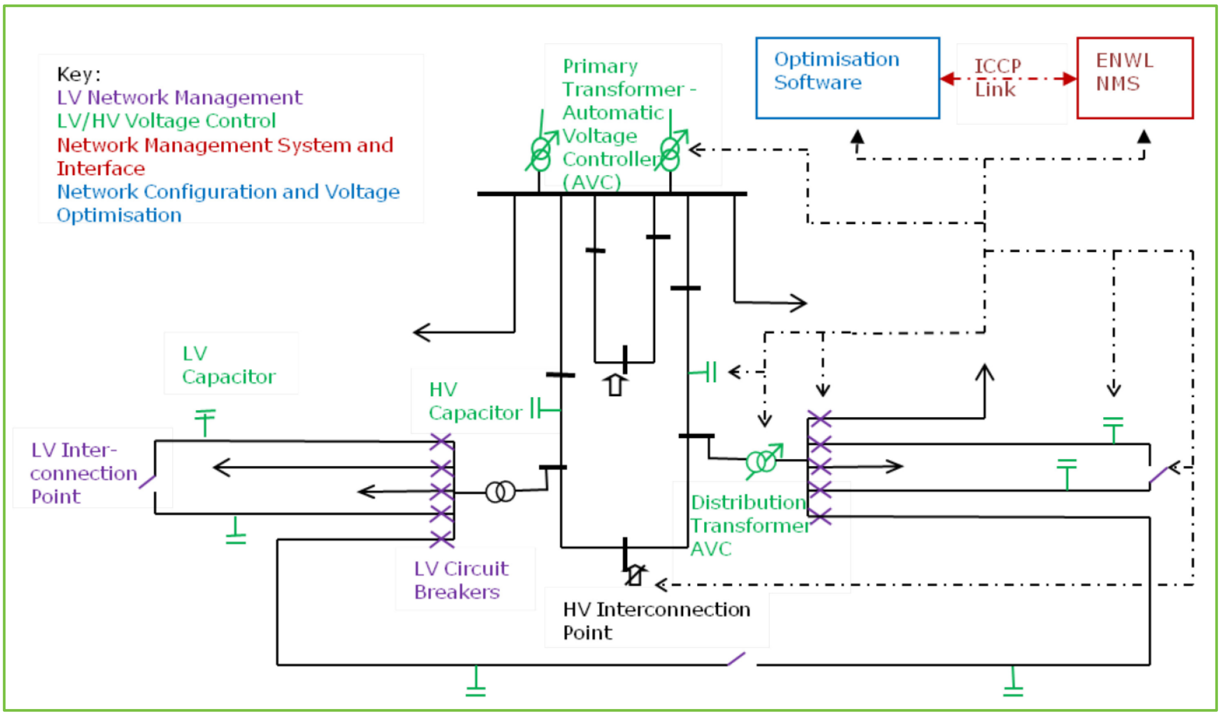
Our project partner, Kelvatek, has developed new controllable retrofit vacuum switching devices especially for this project. These devices are to be utilised at the existing distribution boards and in link boxes across the LV trial circuits. The devices will have the capability to be remotely controlled allowing both sensing of feeder flows and reconfiguration of the LV network.

1.5 Control systems

Figure 1 shows an example of how the various Smart Street technologies will be installed across the trial networks. The optimisation will include the ability to optimise for violations, losses and to minimise load as a single VVC function. The opportunity to mesh the trial networks will also be included in this function, but radial configurations will be the preferred running arrangement. This is specified to minimise customer outages during electrical faults. Therefore the switching equipment shall be closed (create loop or mesh networks) if the objective-function results in positive changes to the network above a set threshold.

The optimisation application calculates the optimal procedures to reach the optimisation objectives, which may be different for HV and LV depending on the chosen function. The user can select if the switching equipment shall be included or inhibited in the optimisation scheme and only specified remote controlled switches will be included in the optimisation.

Figure 1: Smart Street network management



1.6 Overview of the Smart Street test regimes

A summary of the Smart Street trials is shown in Table 1 below.

Table 1: List of Smart Street Trials

Smart Street Trial	Test Regime
Trial 1: LV voltage control	T1.1 On-load tap changing distribution transformer only
	T1.2 On-load tap changing distribution transformer and capacitor(s) on LV circuits
	T1.3 Capacitors at distribution substation only
	T1.4 Capacitors at distribution substation and on LV circuits
	T1.5 Capacitor(s) on LV circuits only
Trial 2: LV network management & interconnection	T2.1 LV radial circuits
	T2.2 LV interconnected circuits
Trial 3: HV voltage control	T3.1 Voltage controllers at primary substation only
	T3.2 Voltage controllers at primary substation and capacitors on HV circuits
Trial 4: HV network management & interconnection	T4.1 HV radial circuits
	T4.2 HV interconnected circuits
Trial 5: Network configuration & voltage optimisation	T5.1 Losses reduction
	T5.2 Energy consumption reduction.

The Smart Street trials will take place over a two year period using an off/on test regime which will result in one year's worth of data for both network normal running configurations and for Smart Street operation. This will allow for the two scenarios to be compared and analysed enabling the overall benefits of Smart Street to be calculated.

2 MODEL DEVELOPMENT

The network data for the trial areas was extracted from the Electricity North West Control Room Management System and GIS and presented to the university in extensible markup language (XML). These files contained connectivity and technical data such as, ratings, impedances, line lengths, etc. From this data the University of Manchester converted the relevant data from these files to a readable OpenDSS format. OpenDSS is the software selected to model the networks as it will allow representation of unbalanced three phase plus neutral and time-series power flows. Following the input into OpenDSS a series of checks are carried out to ensure that all the data is correct and complete, to ensure all the elements are connected and no isolated zone exists and to ensure the models match the network diagrams.

The Smart Street assets were added to the model as well as the relevant one minute resolution load profiles of the connected customers. The load profiles were created using the ELEXON profile classes and a modified version of the CREST tool.

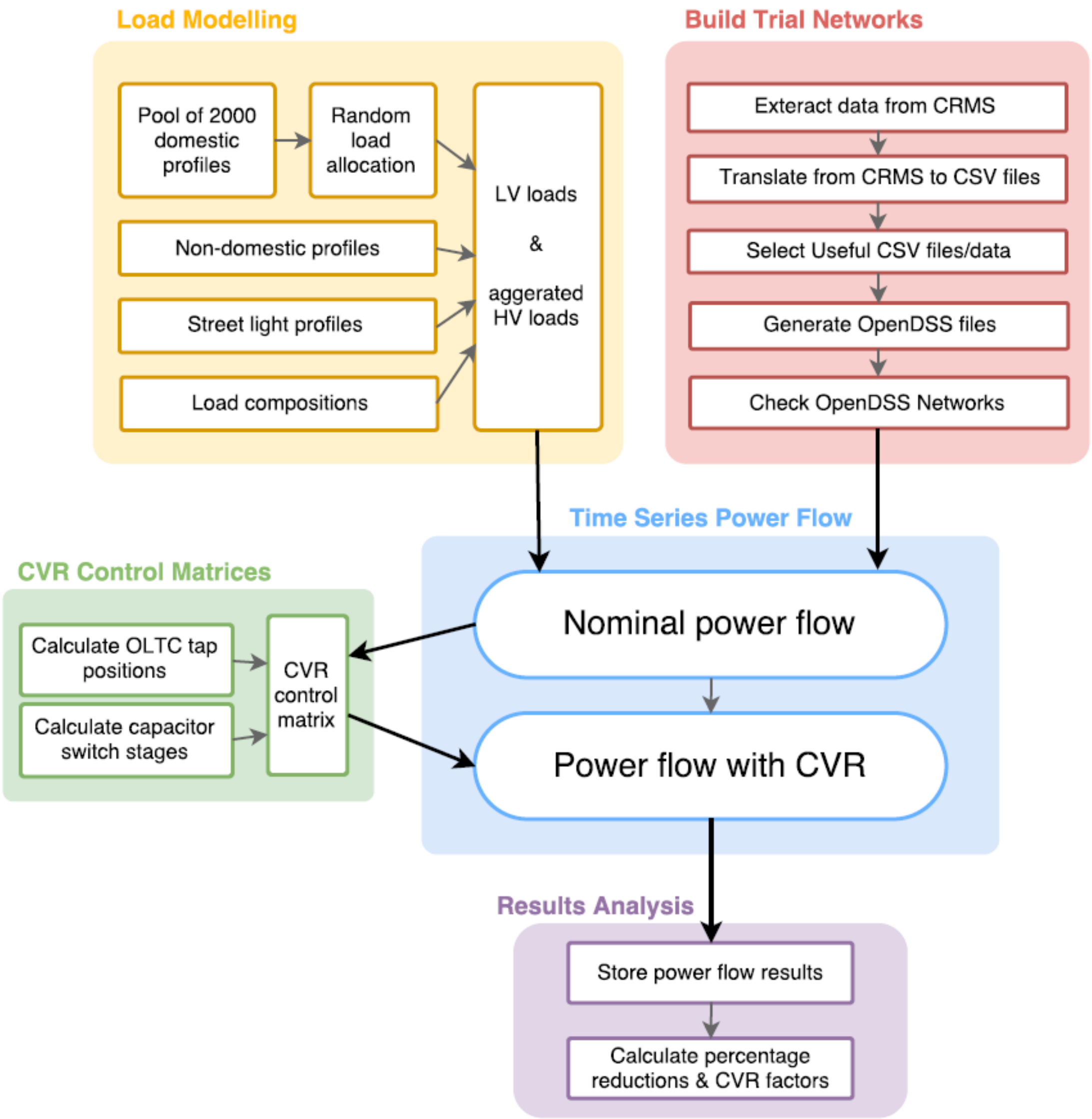
These models will then be used for all research work packages at the University of Manchester and Queen's University, Belfast.

3 CVR IMPLEMENTATION

3.1 University of Manchester Method

The approach used by the University of Manchester for CVR modelling is shown in Figure 2. Section 2 and the UoM reports for Deliverables 1.1.2, 1.1.3, 1.1.4 and 2.1 describe in more detail the building of the trial networks, the load modelling and simulation work.

Figure 2: Flow chart of CVR modelling



The simulation results from the nominal power flow are used to calculate the CVR control matrices – one for the HV network and one for the LV network.

The CVR control matrix of LV networks is calculated as follows:

i. Run the nominal power flow and record results;
ii. Calculate the optimal tap positions for the distribution transformer tap changers
iii. Run the power flow with the calculated tap positions.
iv. Calculate the capacitance stage required to be switched in,

v. Run the power flow with the calculated capacitor stages and the tap positions from ii;
vi. Calculate the optimal tap positions again using the results from v as adding capacitance may provide more headroom for voltage reduction
vii. Run the power flow with the re-calculated tap positions and the capacitor stages from vi;
viii. Compare the power consumption obtained from vi and iii. For each control interval, the calculated settings which provide less power consumption is selected and recorded in the control matrix.
ix. Compare the results obtained from the nominal model (ie nominal power flow) and the CVR model (ie power flow using the control matrix) and analysis the CVR benefits.

The CVR control matrix of HV networks is calculated as follows:

i. Run nominal power flow and record the results;
ii. Calculate the optimal tap positions of the HV tapchangers.
iii. Run the power flow with the calculated tap positions.
iv. Calculate the optimal tap position of the LV tap changers.
v. Run the power flow with the calculated LV tap positions and the HV tap positions from ii.
vi. Repeat ii - v with different HV capacitor combinations.
vii. Determine the optimal HV capacitor switch stages for each control interval and the corresponding HV and LV tap positions, record the settings of control devices in the control matrix.
viii. Compare the results obtained from the nominal model (ie nominal power flow) and the CVR model (ie power flow using the control matrix) and analysis the CVR benefits.

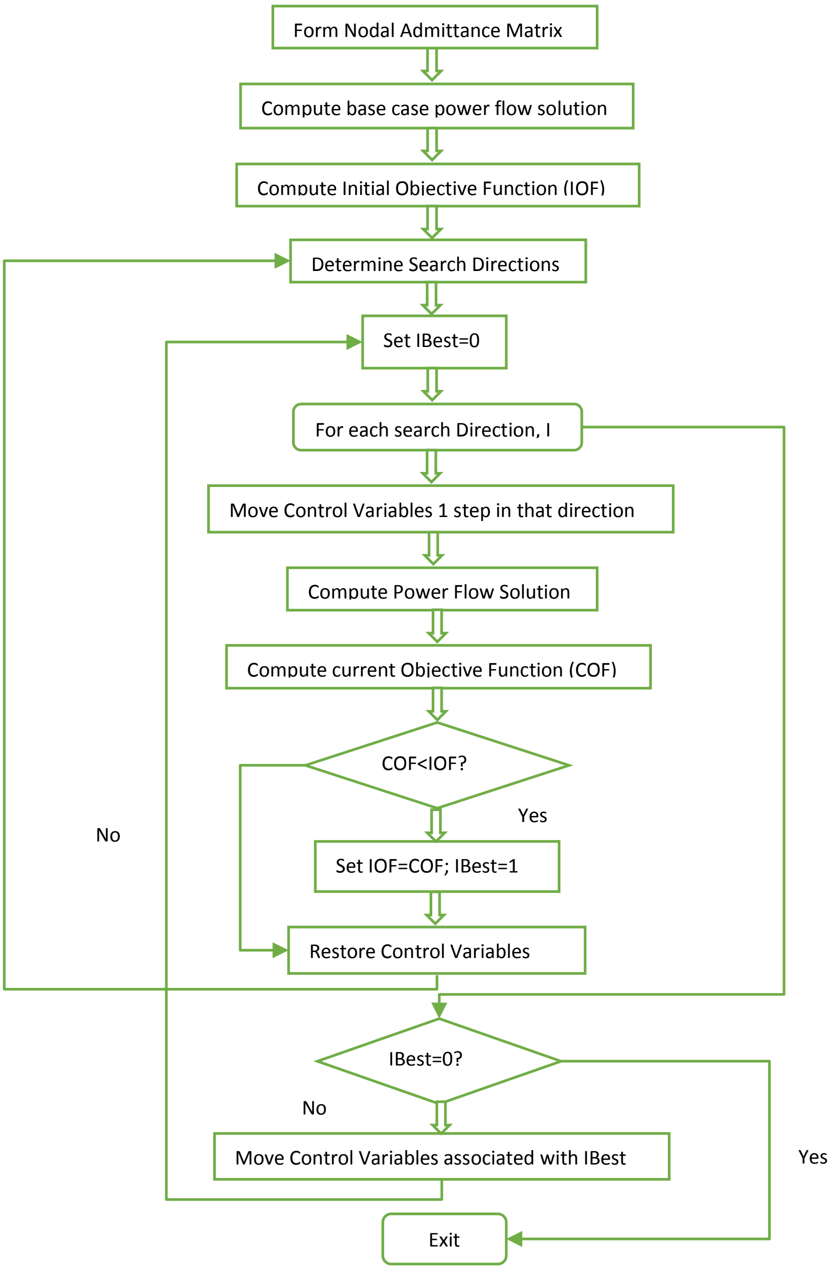
3.2 Queen’s University Belfast method

The modelling and simulation work carried out by Queens University Belfast is explained in more detail in Deliverable 1.2.

Selection of the optimisation methodology and algorithms for CVR optimisation is not a trivial task. The main factors which need to be considered are the nature and number of objectives to be optimised, the nature of the control variables (discrete or continuous), and the constraints that must be adhered to. The technical specifications for Spectrum Power 5 specify that the optimisation is performed using the ‘reduced dynamic gradient’ method and it is believed that this method may be the ‘oriented discrete coordinate decent’ method (ODCD), which is introduced in a paper published by Siemens in 1995. This algorithm is widely used as a low complexity iterative combinatorial unconstrained optimisation technique, and is appropriate for large-scale nonlinear minimization problems with discrete (integer) variables. While CVR is a constrained combinatorial optimisation problem (with linear inequality constraints), a standard approach to handling constraints is to convert them into additional penalty terms in the cost function to give an unconstrained optimisation problem. The technical specifications for Spectrum 5 suggest that their software handles constraints in this way. As such, ODCD is well suited to the problem at hand, and hereafter is assumed to be representative of the optimisation algorithm employed in Spectrum Power 5.

The basic ODCD algorithm is not guaranteed to find the global optimum due to the dependency of the final solution on the initial conditions. To achieve stable results, particularly in the absence of information on good initial device settings, a ***warm start*** implementation is used, where the optimum control settings from the previous time period, are chosen as the initial conditions for the current optimisation step. For the first iteration, where previous settings are not available, the optimisation is repeated three times with three randomly selected initial conditions and the best solution retained. Figure 3 details the process for CVR implementation.

Figure 3: Flow chart for ODCD CVR implementation



In this context the methodology used to validate ODCD was as follows. Firstly, CVR simulation studies were conducted using openDSS models of two of the Smart Street LV networks to compare the quality of solutions generated by ODCD and other CVR methods to verify that ODCD was an effective optimisation strategy. Then, more comprehensive simulation studies were undertaken using ODCD to quantify the energy reduction achievable with dynamically optimised CVR. Finally, Smart Street trial data was analysed to determine the actual energy reduction being achieved by Spectrum Power 5's implementation of CVR, to check if these were consistent with the findings of the simulation studies.

Eleven different LV networks were selected as a representative sample for analysis. The objective function for the optimisation process was minimisation of the energy used by consumers for a typical winter day profile. Optimisation was performed on a half hourly basis and only considered capacitor banks and transformer tap positions as control variables.

Finally, a detailed comparison of the simulated and real optimised network control sequences for a single network was conducted for a 24 hour period where the weather conditions were similar to the winter day scenario implemented in the OpenDSS simulations.

4 RESULTS

4.1 University of Manchester simulation

UoM carried out four case studies using the CVR model detailed in section 3.1. The case studies were for a rural LV network, an urban LV network, a rural HV network and an urban HV network. The detailed results are in Deliverable 1.1.4 but are summarised in Table 2 and Figures 4 and 5.

Table 2: CVR results by network type

Network	Parameter	Nominal Model	CVR Model	% Reduction
Rural LV	Substation voltage	1.09 pu	1.00 pu	7.41%
	Energy consumption	1922.83 kWh	1766.23 kWh	8.14%
	Energy losses	19.36 kWh	18.58 kWh	4.05%
Urban LV	Substation voltage	1.09 pu	1.04 pu	3.54%
	Energy consumption	3518.59 kWh	3402.48 kWh	3.30%
	Energy losses	80.28 kWh	79.24 kWh	1.3%
Rural HV	Primary substation voltage	1.0 pu	0.98 pu	1.57%
	Average customer voltage	1.05 pu	0.989 pu	5.92%
	Energy consumption	156.11 MWh	146.56 MWh	6.12%
	Energy losses	3.209 MWh	3.107 MWh	3.18%
Urban HV	Primary substation voltage	1.0 pu	0.98 pu	1.85%
	Average customer voltage	1.05 pu	0.98 pu	6.03%
	Energy consumption	155.93 MWh	145.87 MWh	6.45%
	Energy losses	2.91 MWh	2.79 MWh	3.95%

The CVR model was then applied to all HV and LV networks and the benefit in energy saving and loss saving of the trial networks analysed.

Figure 4: Energy and loss reduction on LV networks using CVR model

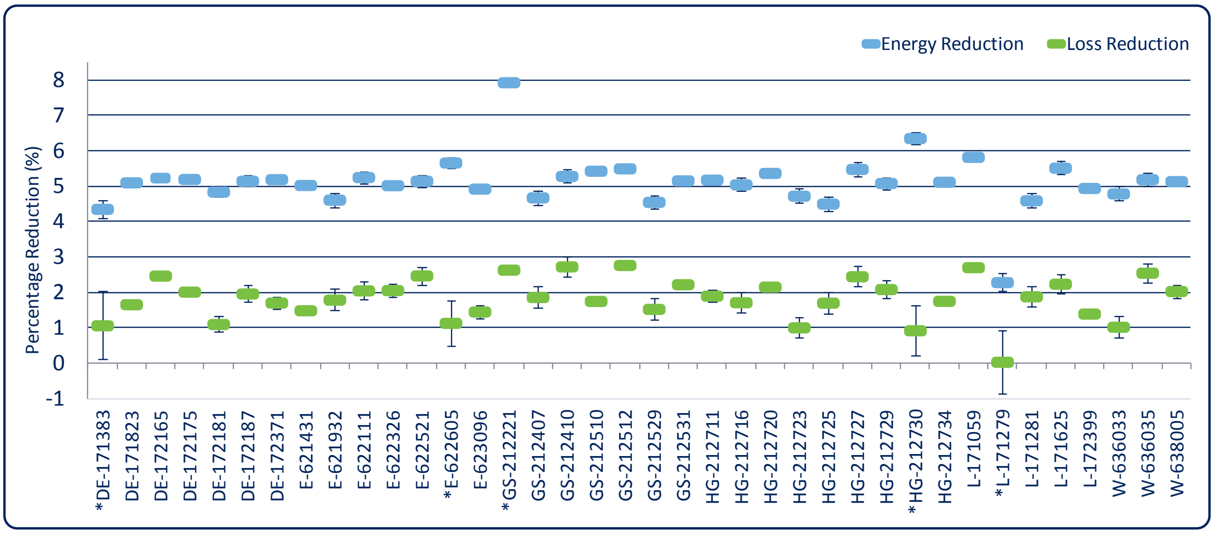
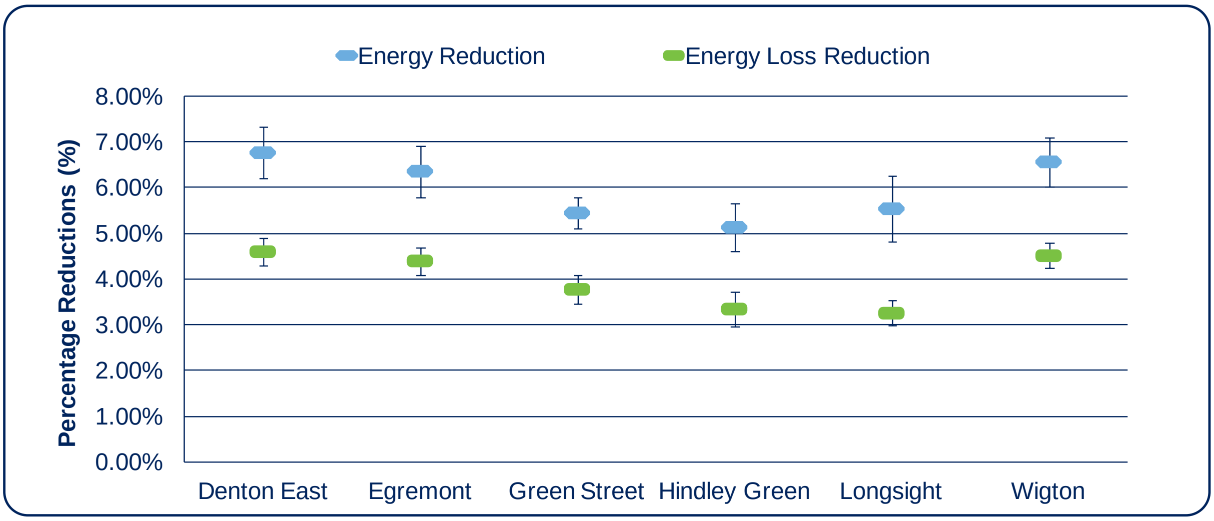


Figure 5: Energy and loss reduction on HV networks using CVR model



According to the simulation results the CVR model is capable of providing energy and loss savings to all LV and HV networks.

On the LV network the energy consumption and energy losses can be reduced by up to 8% and 2.8% respectively. On the HV network these reductions can be up to 7% in energy consumption and 5% in energy losses.

The average values across each voltage network is summarised in Table 3. The CVR factors presented are the ratio of energy or loss reduction to the voltage reduction.

Table 3: Summary of the results of the CVR modelling

	Voltage Reduction	Energy Reduction	Losses Reduction	CVRf (energy)	CVRf (loss)
HV	5.50%	5.97%	3.98%	1.08	0.72
LV	4.88%	5.12%	1.83%	1.05	0.38

It indicates that for each 1% voltage reduction about 1.05% energy savings and 0.38% energy loss savings can be achieved on the LV network with 1.09% energy savings and 0.72% energy loss savings on the HV network. This demonstrates that the relationship between voltage reduction and energy saving is roughly linear which correlates with findings from the CLASS project.

4.2 Queen's University Belfast simulation

QUB carried out some analysis using the CVR model detailed in section 3.2. The detailed results are in Deliverable 1.2 but are summarised here.

In this study CVR is applied to 11 LV networks with 'warm start' ODCD used to perform the optimisation. Five of the networks are the trial networks equipped with on-load tap changing (OLTC) transformers. The other six networks have no-load tap changing (NLTC) transformers, and were selected as representative of heavily loaded LV networks.

The voltage control devices considered were the LV network capacitor banks and transformer tap positions. The OLTC transformers have 9 distinct tap positions which can be updated on a half hourly basis, while capacitors were assumed to be switchable in blocks 50 kVAr, also on a half hourly basis. In contrast, the NTLC transformers, which have 5 tap positions, were fixed in a single position for the full day.

The CVR objective function was defined to be minimisation of the active power consumption of each LV network over the 24 hour winter day scenario, subject to line voltages being maintained within regulatory limits.

In all simulations the CVR optimised networks are compared against a **base case** of nominal operation where all the network devices are at nominal settings (transformer tap positions corresponding to nominal voltage and all capacitors switched off).

Figures 6 and 7 shows the percentage reduction in total energy consumption and percentage reduction in LV network losses achieved for each network using ODCD optimised CVR. As can be seen an average energy reduction of 8% is achieved, with a minimum of 4% and a maximum of 16%. The application of CVR also yields a significant reduction in LV network losses for most networks, except network 3 where losses increase by 3%.

Figure 6: Percentage reduction in energy consumption

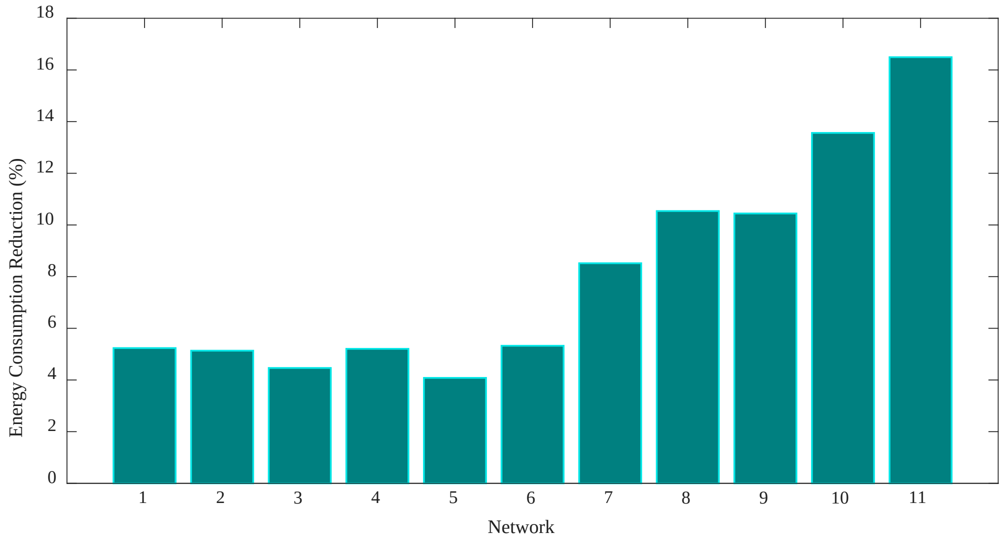
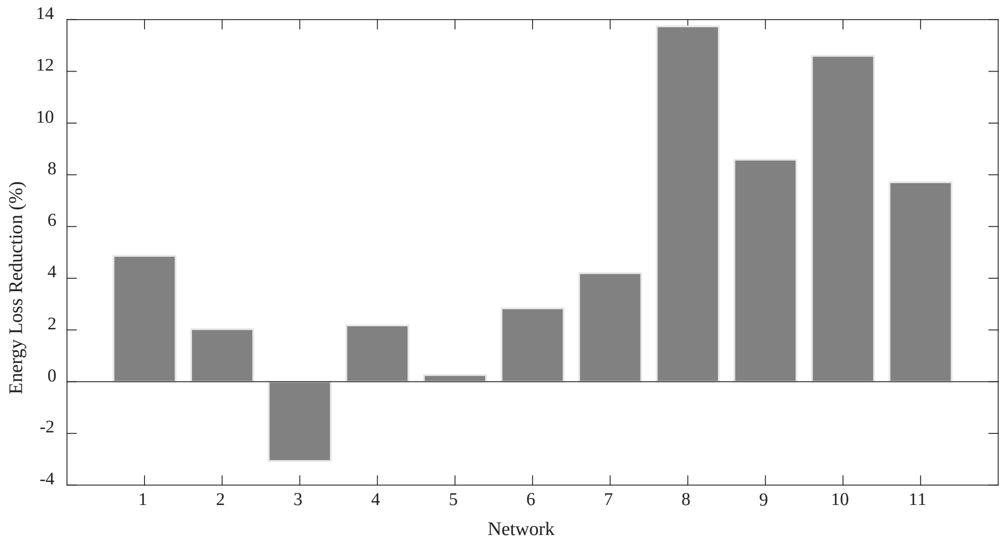


Figure 7: Percentage reduction in LV network energy losses



To provide more insight into the operation of CVR, plots of the voltage, transformer taps settings, capacitor values and real power consumption are presented in the figures 8 – 14 for networks 3 and 9. Networks 3 and 9 are both urban networks but 3 is selected as representative of a network with an OLTC installed and 9 is selected as representative of a heavily loaded network with a NTLC installed.

The OLTC network has a more stable voltage profile than the NTLC network, but this is a feature of the load on network 9, and not a consequence of OLTC operation.

Figure 8: Voltage profile network 3 with NTLC

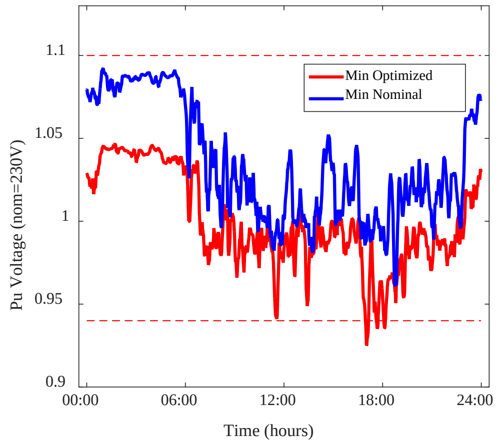


Figure 9: Voltage profile network 9 with OTLC

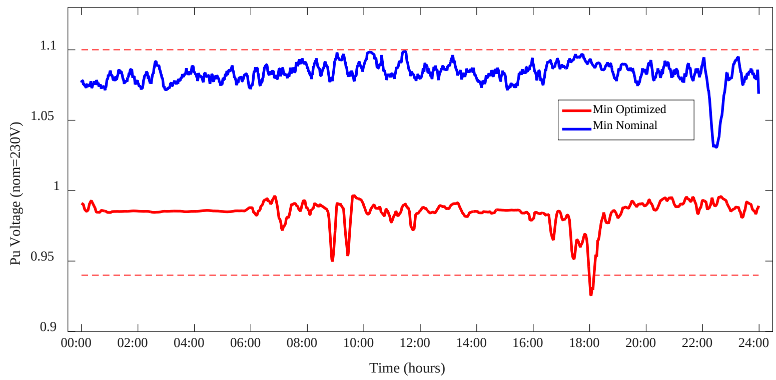


Figure 10: OLTC position network 9

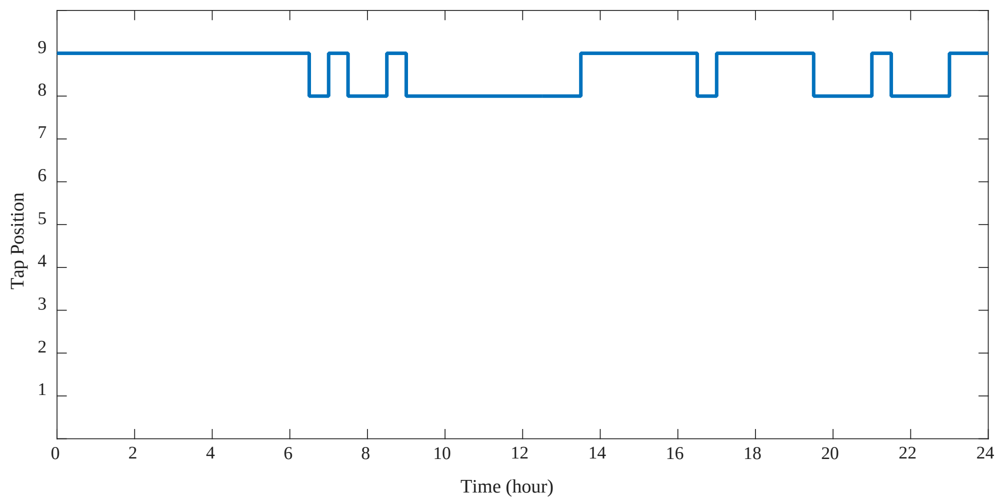


Figure 11: Capacitor values network 3 with NLTC

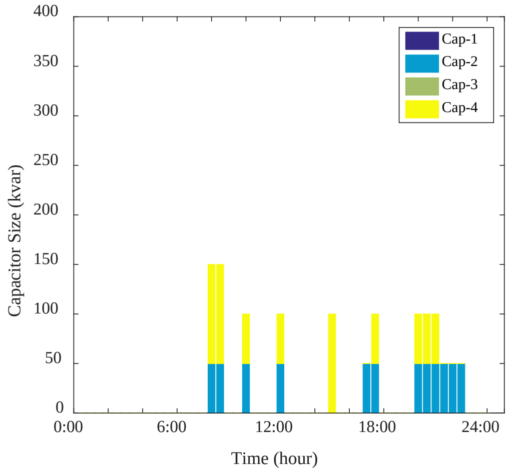


Figure 12: Capacitor values network 9 with OLTC

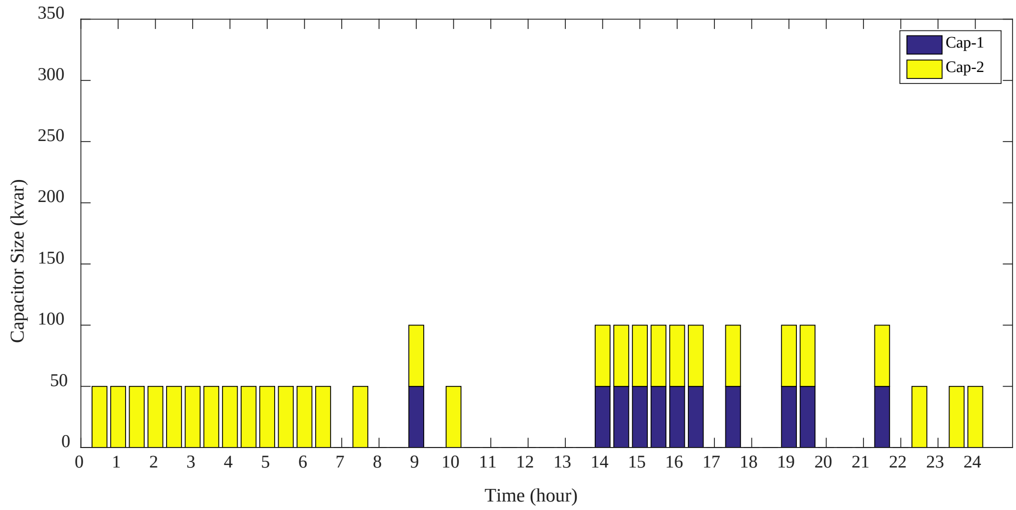


Figure 13: Power consumption network 3 with NLTC

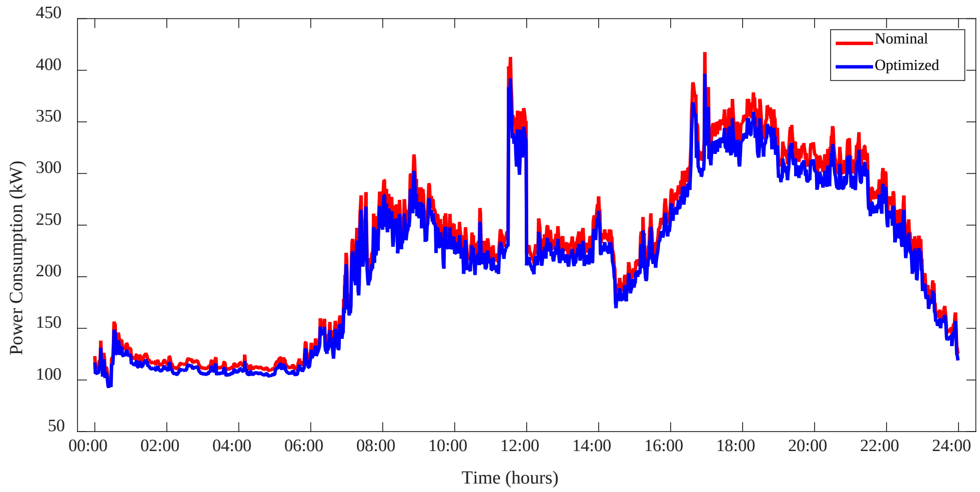
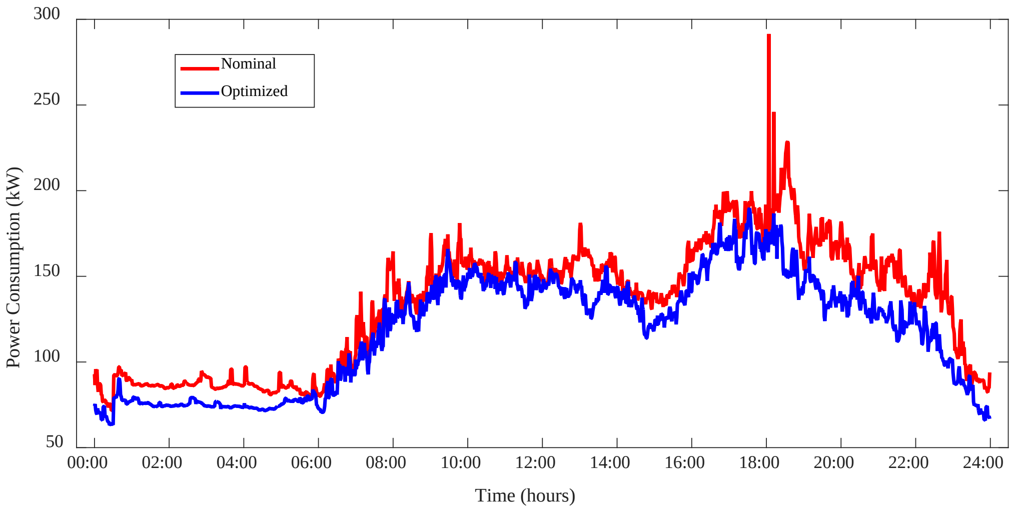


Figure 14: Power consumption network 9 with OLTC



To evaluate the benefit of having OLTC enabled transformers over NTLC transformers the CVR simulation study was repeated with the NTLC transformers in six of the networks replaced with OLTC transformers. The percentage reduction in energy consumed under both scenarios is shown in Table 4. As expected, more energy reduction can be achieved when using OLTC, the improvement is a factor of two for the networks considered

Table 4: Percentage reduction in energy consumption

Network	1	2	3	4	5	6	Average
with NLTC	5.1	5	4.2	5	4	5.1	4.7
with OLTC	12.1	11.5	9.5	8.5	8	10	9.9

The CVR plots of the voltage, transformer tap positions, capacitor values and real power are plotted in figures 15 - 18 for Network 3 when operating with an OTLC transformer.

Figure 15: Voltage profile network 3 with an OLTC.

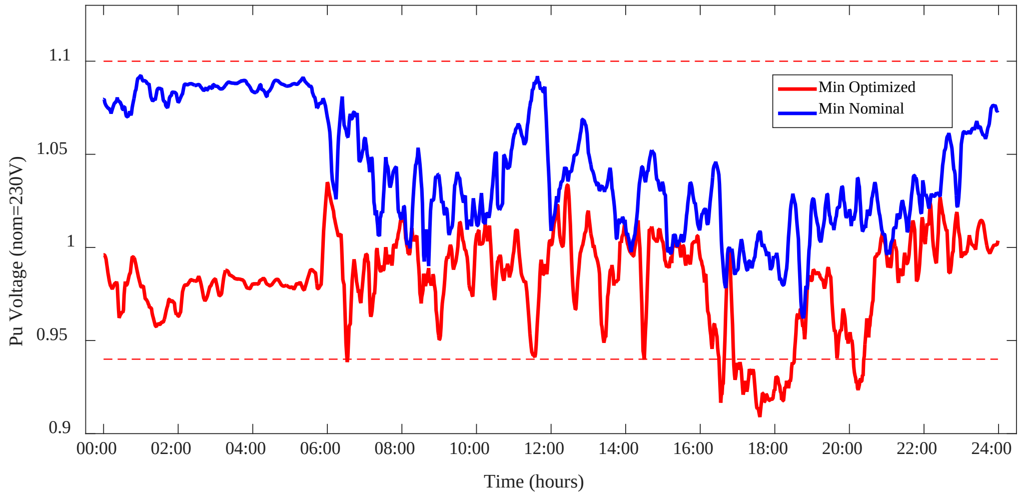


Figure 16 : CVR tap settings network 3 with an OLTC

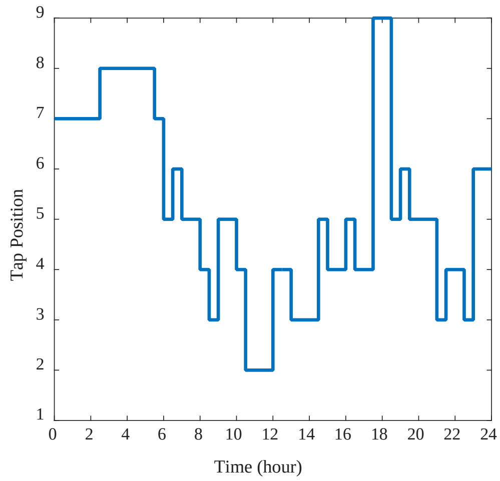


Figure 17: Capacitor settings network 3 with an OLTC

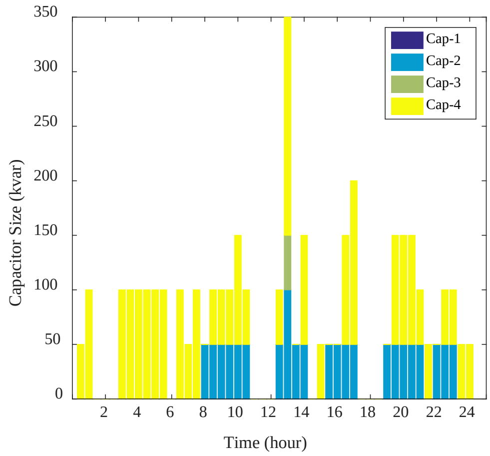
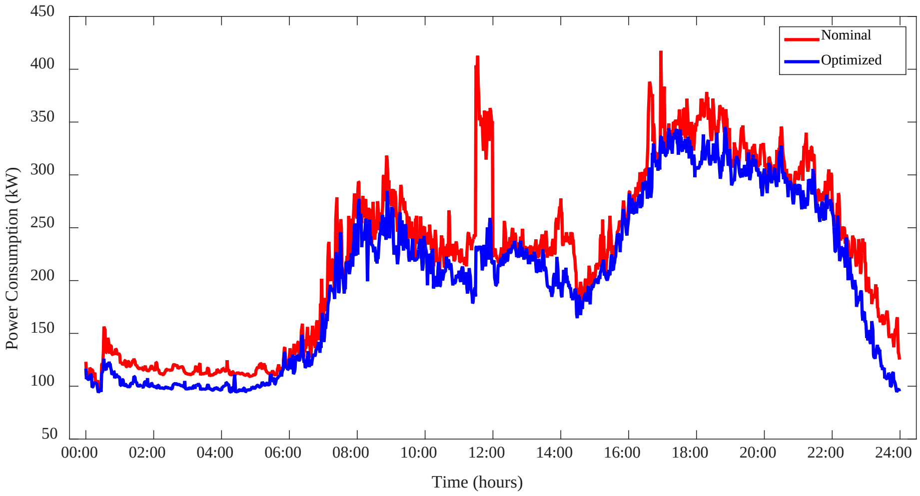


Figure 18: Real power consumption Nnetwork 3 with an OLTC



4.3 Analysis of trial data

The standard approach to quantifying the performance of CVR in field trials is to compare network characteristics during periods where CVR is active to periods where it is inactive, while taking into account other factors that cause variation such as weather conditions, day of the week, and time of the year. In practise, this is very challenging as the variation due to other factors can be substantial. A preliminary analysis of the energy reduction performance of CVR was conducted with the available data for the 11 test networks considered in the simulation studies. This was done by matching periods where CVR was in operation to the closest matching periods of non-operation in terms of climate conditions (average daily temperature and time of the year) and days of the week considered.

Four CVR periods were selected for evaluation and table 5 describes the selected CVR periods, the matching non-CVR reference periods, and the average percentage reduction in energy consumed across the 11 test networks due to CVR. As can be seen from the results, the percentage reduction in energy consumption with CVR varies between 4% and 11.9% with the overall average reduction being 8.7%. These results are in agreement with the 8% reduction predicted by simulation studies. This indicates that, as expected, CVR has a substantial positive impact on energy reduction, and the CVR optimisation being performed by Spectrum power 5 is effective.

Table 5: CVR periods selected for analysis

CVR on	CVR off	Percentage Reduction in Consumed Energy (%)
14/3/16 – 20/3/16	5/3/16 – 11/3/16	8.4
26/7/16 – 31/7/16	6/7/16 – 11/7/16	8.6
28/11/16 – 30/11/16	21/11/16 – 23/11/16	4.0
2/12/16 – 4/12/16 and 6/12/16 – 9/12/16	12/12/16 – 14/12/16, 21/12/16 and 23/12/16 – 25/12/16	11.9

A comparison of the daily profiles for a simulated OLTC LV network and the corresponding trial network during CVR operation was carried out.

Figures 18 - 21 provides a comparison of the traces of the CVR plots for transformer tap positions, capacitor values, real and reactive power and end of line voltages

Significant differences exist in the reactive power profile due to the deviations caused by the capacitors switching in and out at different times. It is also evident from the tap position sequences and end-of-line voltage plots that CVR is performing differently in the real and simulated networks.

It is noticeable that the voltage in the real network is substantially higher than the allowable lower limit of 0.94 PU (216.2V), suggesting that CVR is not operating as intended. On investigation, it was discovered that the voltage constraints had been conservatively set to be 0.98 of nominal voltage in Spectrum Power 5 during the time when this data was being collected. Accounting for this constraint it can be seen that CVR is operating correctly in that it maintains the end-of-line voltage at or around 245V (equivalent to 0.98pu).

Figure 18: Simulated vs real measurement tap positions

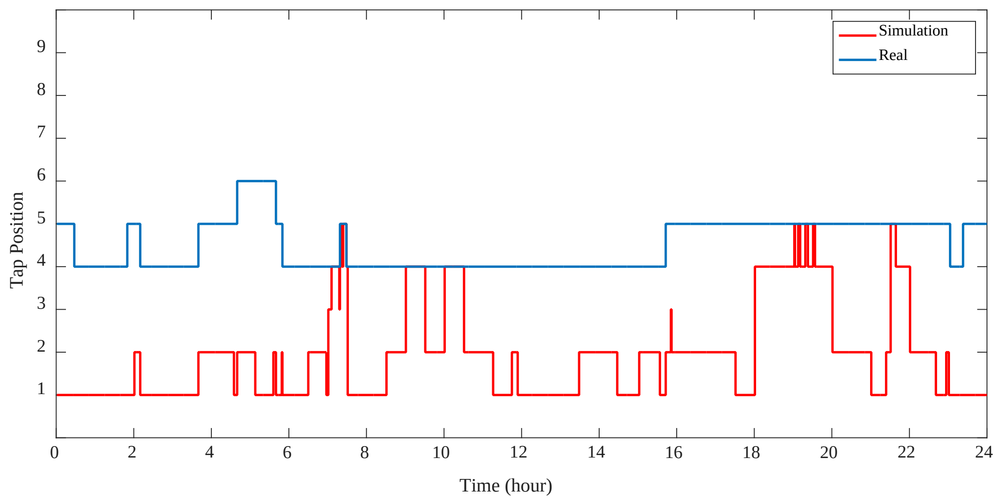


Figure 19: Simulated vs real measurement capacitance connected

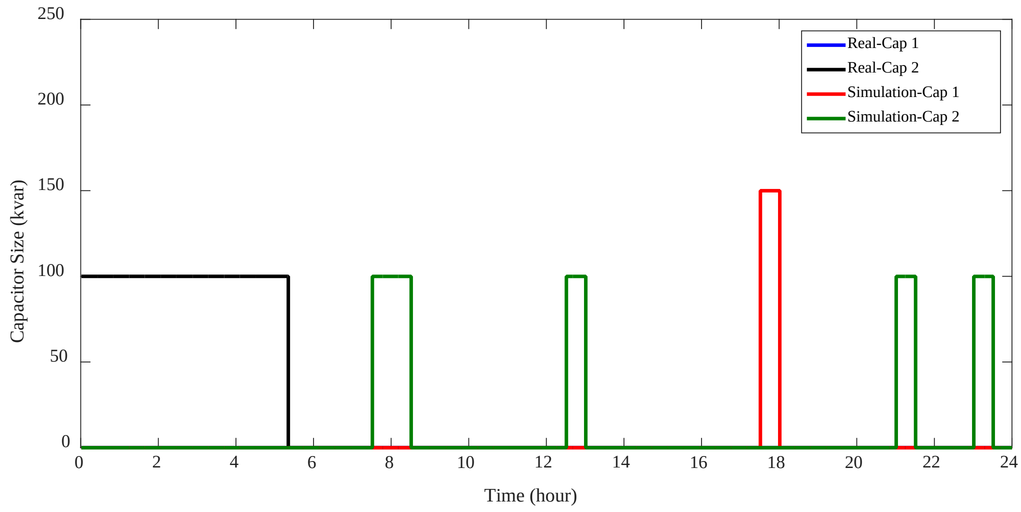


Figure 20: Simulated vs real measurement real and reactive power traces

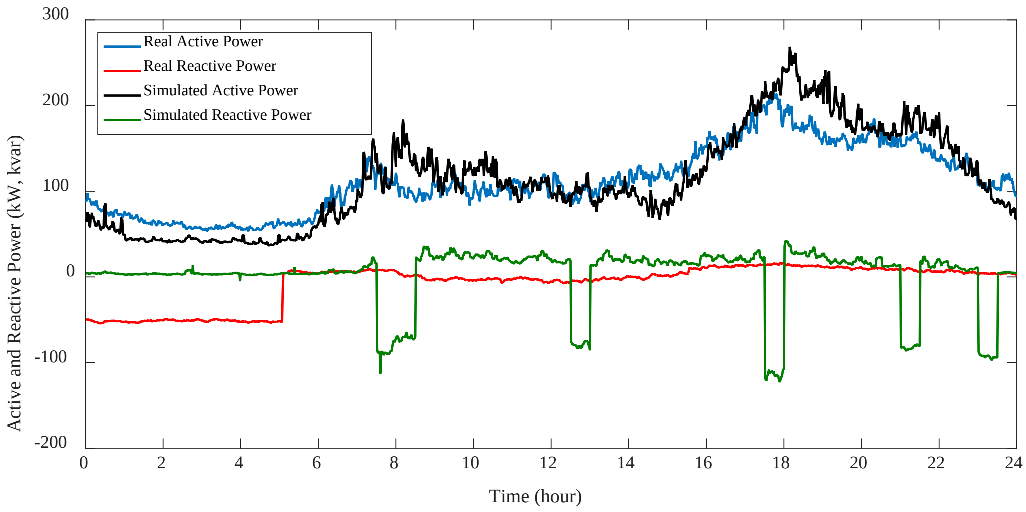
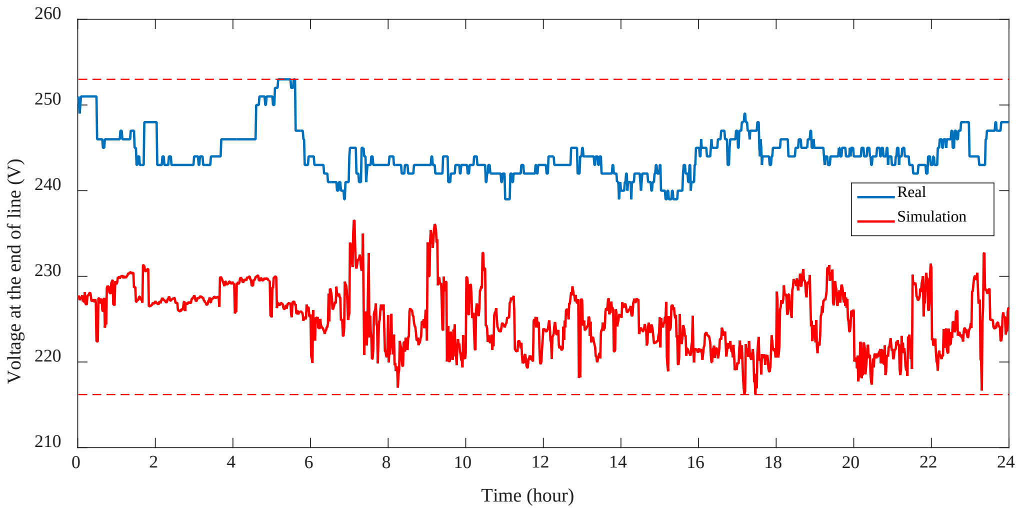


Figure 21: Simulated vs real measurement end of line voltage traces



5 CONCLUSIONS

This report has presented the initial findings from the simulation and analysis work carried out by University of Manchester and Queens University Belfast.

From the work carried out it is clear that the use of CVR has the potential to reduce the energy consumption on the network by up to 12%.

The results from the simulation work differ between the two universities: UoM calculated an average energy reduction of 5.12% whereas QUB calculated 8%. This difference can be attributed to a number of reasons:

i. The universities have used different methodologies to apply CVR
ii. UoM is an average across all the LV networks
iii. QUB is an average across 11 networks
iv. The 11 networks selected by QUB are all heavily loaded.

QUB carried out analysis of the trial data and compared the results to the simulation for the 11 selected networks. This comparison showed a strong correlation between the actual energy consumption reduction and the simulated reduction.

The analysis of the trial data highlighted that Spectrum Power 5 was set up to optimise for a higher LV voltage than intended. Investigations revealed settings on some of the tolerances had caused this. The tolerance settings have now been adjusted.

As a result of this adjustment we are now reviewing the trials regime to ensure we get the most out of the rest of the trial period.