

*Title:* **Report for Deliverables 1.2 and 1.3  
"Control logic considering different  
voltage regulation devices"**

*Synopsis:* This document presents a coordinated voltage control between the on-load tap changer and capacitor banks in the substations *Landgate* and *Leicester Avenue*. The modelling and settings of capacitor banks are presented. Power flow analyses are carried out to assess the performance of the proposed coordinated control logic considering different number of capacitors.

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## Executive Summary

This report corresponds to Deliverables 1.2 and 1.3 "Control logic considering different voltage regulation devices" part of the Low Carbon Networks Fund Tier 1 project "Low Voltage Integrated Automation (LoVIA)" run by Electricity North West Limited (ENWL).

The aim of the LoVIA project is to demonstrate, through the deployment of two trial systems, a suitable coordinated voltage control of the LV networks by the successful integration of new distribution system equipment such as on-load tap changer (OLTC)-fitted transformers and capacitor banks.

The further flexibility provided by capacitor banks to manage voltages is needed when low target voltages at the substation, required to cope with voltage rise in feeders with photovoltaic (PV) systems, result in even lower voltages in other feeders. Although, the two trial LV networks, *Landgate* and *Leicester Avenue*, do not present any feeder with potential voltage drop issues that could be further worsened by low target voltages at the busbar, and, consequently, capacitor banks are not truly needed, this document investigates a coordinated voltage control between the on-load tap changer and capacitor banks adopting suitable scenarios.

A summary of the main aspects of this report is presented below.

- **Capacitor Banks.** Three banks of capacitors were installed in *Landgate* and one bank of capacitors was placed in *Leicester Avenue*. All the four capacitor banks are three-phase with a rating of 150 kVar. The three capacitor banks in *Landgate* are located approximately in the mid points of three different LV feeders. The one in *Leicester Avenue* is also connected somewhere in one feeder but close to the substation.
- **Capacitor Bank Modelling.** Models for capacitor banks are readily available considering different operational characteristics (e.g., current-based control, voltage-based control, kVar-based control, power factor-based control, and time-based control). In this project, voltage-based control is used. The three phases of each of the four capacitor banks can only be operated in an all-in or all-out mode. A local control of the capacitor banks is considered, i.e., the capacitor banks are operated based on the voltage at the capacitor's connection point.
- **Coordinated Voltage Control: One-cap Case.** The most suitable switch-on and switch-off voltage values for the capacitor bank in *Leicester Avenue* were found to be 230.9 and 238V, respectively. In *Landgate* (with only one capacitor bank), the switch-on and switch-off voltages should be 228.6 and 238V, respectively. Despite the low X/R ratio found in LV networks, the simulations did show an increase in voltages when the capacitor was used (5 to 8V). This voltage gain also affected the other feeders in the network (3 to 4V). In addition, the simulations showed that the use of the capacitor resulted in a reduced number of tap changes.
- **Coordinated Voltage Control: Multiple-cap Case.** To control multiple capacitor banks simultaneously whilst avoiding the hunting effect, a larger difference between the switch-on and switch-off voltages should be adopted. In *Landgate* (three capacitor banks), the most suitable values were found to be 228.6 and 246V, respectively. This control also considered a specific switch-on/switch-off sequence based on the loading of the feeders, as well as delays among each capacitor bank within the tap delay of the OLTC. The simulations showed that these 150 kVar capacitor banks resulted in high voltage gains (~17V) suggesting that smaller devices should be used. The number of tap changes was also found to be reduced.

The above recommendations and conclusions are based on load and generation scenarios produced to create significant voltage drop issues in certain feeders within the two trial LV networks so the use of capacitor banks can be justified. Although these scenarios do not mimic the actual behaviour of these particular networks, the proposed methodology to find the most adequate settings and control logic can be applied to any LV network that requires similar voltage management schemes.

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# 1 Introduction

As part of the transition towards a low carbon economy, Electricity North West Limited (ENWL), the Distribution Network Operator (DNO) of the North West of England, is involved in different projects funded by the Low Carbon Networks Fund. The University of Manchester is part of the Tier 1 project "Low Voltage Integrated Automation (LoVIA)".

The objective of this project is to demonstrate, through the deployment of two trial systems, a suitable coordinated voltage control of the LV networks by the successful integration of new distribution system equipment such as on-load tap changing transformers and capacitor banks. The coordinated voltage control approach will be implemented based on the analysis of data gathered by appropriate monitoring of the two trial LV networks and the assessment of the corresponding computer-based network models in current and future scenarios.

## 1.1 Deliverables 1.2 and 1.3

In Deliverable 1.1<sup>1</sup>, the modelling and performance of the independent (i.e., stand-alone) control of the on-load tap changer (OLTC) fitted transformer was presented. The objective of Deliverables 1.2 and 1.3 is to investigate the coordination required between the OLTC and capacitor banks so the most suitable control logic can be found. This will require a case-by-case approach in which the following cases have to be considered:

- **One-cap case.** One voltage regulation device (i.e., capacitor banks) is deployed in the LV network
- **Multiple-cap case.** More than one bank of capacitors are deployed in the LV network

This report is structured as follows. First, the location and size of the capacitor banks installed in the two trial networks, i.e., *Landgate* and *Leicester Avenue*, are introduced. Then these capacitor banks are modelled in OpenDSS. The voltage gains in the network when fixed capacitor banks are placed (connected all the time without any control) in the network are then quantified. These gains are used to define the most suitable settings for the capacitor banks (i.e., switch-on and switch-off voltage values and coordination aspects). In the sequence, time-series power flow analyses are carried out to assess the performance of the proposed logic for each of the two cases (one-cap and multiple-cap). Finally, the recommended settings and conclusions for the capacitor banks, including switch-on and switch-off voltages and delays, are presented.

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<sup>1</sup> Creation of initial models and AVC control logic, UoM-ENWL\_LoVIA\_Deliverable1.1 v08, 3<sup>rd</sup> March 2014.

## 2 Capacitor Banks in Landgate and Leicester Avenue

### 2.1 Location and Size

The two trial LV networks, *Landgate* and *Leicester Avenue*, have already installed OLTC fitted transformers and capacitor banks. As shown in Figure 1, the triangles represent distribution transformers. The five-point stars represent capacitor banks. Three capacitor banks are installed in *Landgate* and one is installed in *Leicester Avenue*. All the four capacitor banks are three-phase with a rating of 150 kVar (50 kVar per phase). The location details are presented in Table 1.

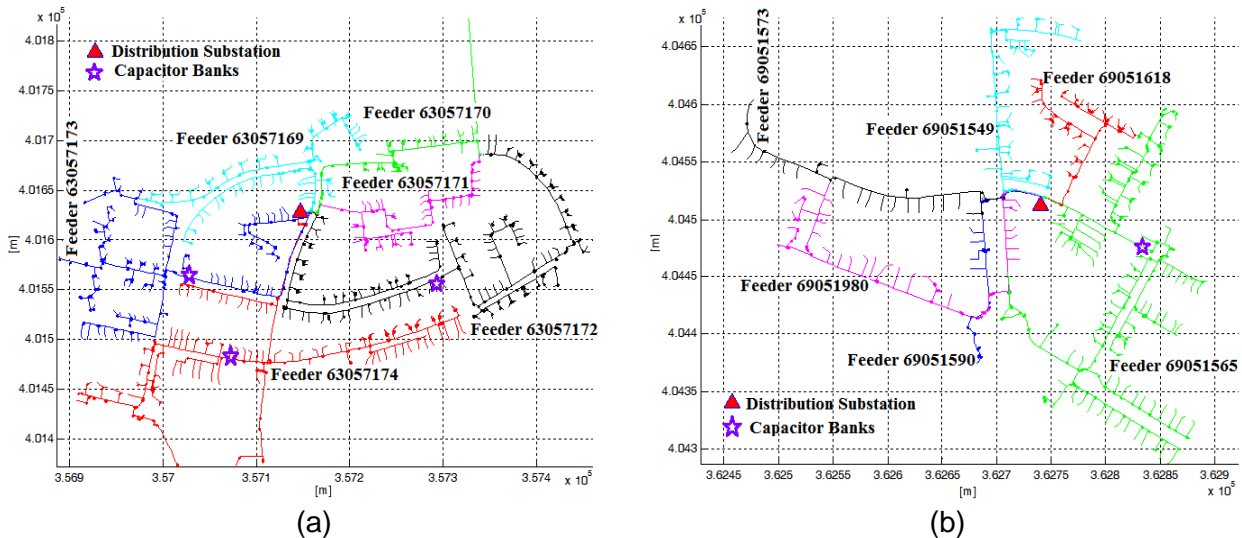


Figure 1 Capacitors in the two LV networks: (a) *Landgate* (b) *Leicester Avenue*

Table 1 Location and size of capacitor banks in the two LV networks

Substation	Size (kVar)	Location	Connected feeder ID
<i>Landgate</i>	150	Opposite 50 Patterdale Rd, Ashton-in-Makerfield	63057172
<i>Landgate</i>	150	Opposite 4 Patterdale Rd, Ashton-in-Makerfield	63057173
<i>Landgate</i>	150	Opposite 41 Yewdale Rd, Ashton-in-Makerfield	63057174
<i>Leicester Ave.</i>	150	Opposite 1 Belmont Rd, Hindley, Wigan	69051565

All the four capacitor banks are “delta” connected to the LV feeders through controllable switches. These switches are operated by the capacitor controller. For illustration purposes, the bank of capacitors installed in *Leicester Avenue* is shown in Figure 2.

### 2.2 Capacitor Bank Modelling

Models for embedded capacitor banks are readily available in OpenDSS. OpenDSS contains many control features for capacitor banks, including voltage-based control, kVar-based control, current-based control, power factor-based control and time-based control. For instance, the capacitor can be controlled to switch ON when the voltage is lower than a pre-set value, e.g., 225V and to switch OFF when at a certain fixed value, e.g., 235V. The capacitor can also be controlled to switch ON when the

reactive power flow in the line is at a pre-set percentage, e.g., 50%, of the capacitor size and to switch OFF when the flow is 75% of the capacitor size in the reverse direction.



**Figure 2 Capacitor bank in Leicester Avenue in feeder 69051565**

According to the manufacturer's specification<sup>2</sup>, the installed capacitors can be operated in one of the following five modes: voltage-based control, kVar-based control, current-based control, temperature-based control and time-based control. In this report, the voltage-based control has been investigated in detail. Section 3 also considers fixed capacitor banks (i.e., connected all the time without any control) in order to quantify the corresponding voltage gains.

In OpenDSS, both single and three-phase capacitors can be modelled. This allows for capacitor banks being connected to a single-phase at the connection points when necessary. In this project, the three phases of each of the four capacitor banks can only be operated in an "all-in" or "all-out" mode. Therefore, connecting a single-phase capacitor into the LV network is not considered in this report.

According to the manufacturer's specification, the capacitor controller is able to communicate and be controlled remotely over either a wireless or wired SCADA network using the DNP3.0 protocol. However, at the time of writing of this report, a remote control scheme for the capacitor banks in either network was not available. Therefore, this report only considers local control of the capacitor banks, i.e., they are operated based on the voltages at the point of connection.

### 2.3 Summary

- **Capacitor Banks.** Three banks of capacitors were installed in *Landgate* and one was placed in *Leicester Avenue*. All the four capacitor banks are three-phase (delta connected) with a rating of 150 kVar. The three capacitor banks in *Landgate* are located approximately in the mid points of three different LV feeders. The one in *Leicester Avenue* is connected in one of the feeders but relatively close to the substation.
- **Capacitor Bank Modelling.** Models for capacitor banks are readily available considering different operational characteristics (e.g., current-based control, voltage-based control, kVar-based control, power factor-based control, and time-based control). In this project, voltage-based control is used. The three phases of each of the four capacitor banks can only be operated in an all-in or all-out mode. A local control of the capacitor banks is considered, i.e., the capacitor banks are operated based on the voltage at the capacitor's connection point.

<sup>2</sup> ABB CQ900 Capacitor controller installation and operation manual, Available: [http://www05.abb.com/global/scot/scot245.nsf/veritydisplay/55fcd932334f07c12578fd004b8022/\\$file/CQ900%20Capacitor%20Controller%20Manual%20\(rev%201.6%20-%2000612\).pdf](http://www05.abb.com/global/scot/scot245.nsf/veritydisplay/55fcd932334f07c12578fd004b8022/$file/CQ900%20Capacitor%20Controller%20Manual%20(rev%201.6%20-%2000612).pdf) (accessed 28/04/2014).

### 3 Performance of Coordinated Voltage Control

To adequately control voltage in LV networks using on-load tap changer (OLTC)-fitted transformers, the maximum and minimum voltages of all LV feeders (mid and end points) are taken into account (see Deliverable 1.1<sup>1</sup>). This voltage control will attempt to take tap changing actions to achieve the target busbar voltage based on the needs of the critical feeder. This control action will however influence all the other feeders. While this approach performs well in a network where all feeders behave similarly due to the distribution of photovoltaic (PV) systems and/or load among them, it would not be able to effectively manage voltages when feeders have contrasting voltages issues (e.g., significant voltage rise in one feeder and significant voltage drop in another).

To cope with voltage rise due to PV systems, the OLTC-fitted transformer finds lower target voltages at the busbar. These lower voltages can have a negative effect in feeders already experiencing significant voltage drops. If capacitor banks are installed in these particular feeders and its operation coordinated with the OLTC-fitted transformer, then it would be possible to have a much more effective voltage management scheme.

Although, the two trial LV networks, *Landgate* and *Leicester Avenue*, do not present any feeder with potential voltage drop issues that could be further worsened by low target voltages at the busbar, and, consequently, capacitor banks are not truly needed, this document investigates a coordinated voltage control between the on-load tap changer and capacitor banks adopting suitable scenarios. The modelling and most suitable settings of capacitor banks are presented. Power flow analyses are carried out to assess the performance of the proposed coordinated control logic considering different number of capacitors.

Feeders with capacitor banks are considered to have larger loads and less, or no, PV installations. The control of these capacitor banks should be coordinated with the OLTC in a centralised fashion by the RTU. However, this report only considers a local control of the capacitor banks. The performance of the coordination between the OLTC and capacitor banks still needs to be assessed.

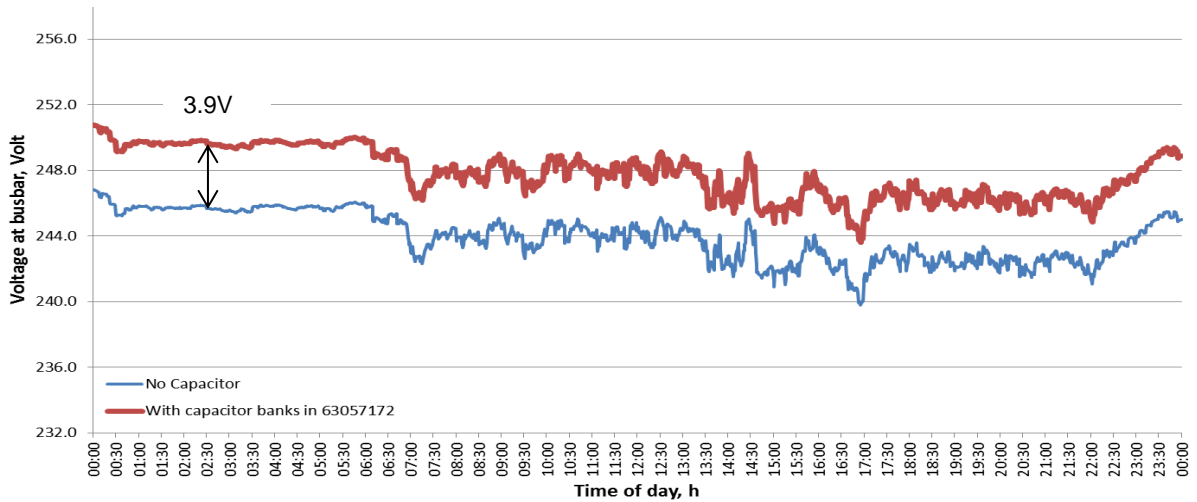
The study on the coordination requires a case-by-case approach, in which two cases have to be considered: one-cap and multiple-cap cases.

#### 3.1 One Bank of Capacitor (One-cap Case)

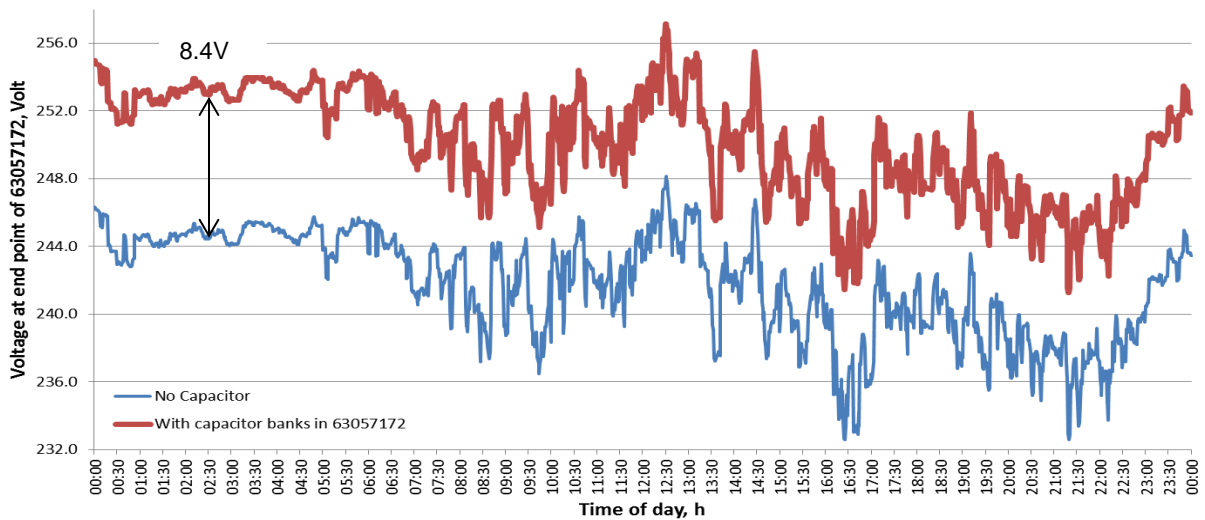
##### 3.1.1 Voltage Gains by One Fixed Capacitor Bank

Power flow analyses were first carried out to quantify the voltage gains caused by a fixed capacitor bank (i.e., connected to a network all the time without any control). Daily power-flow simulations for the two networks were implemented. For this purpose, the taps of the OLTC were considered to be in a fixed position (position 5) and no tap change was made throughout the day.

For a one-day (weekday, July) simulation, voltage gains at busbar (Phase A) of network *Landgate* when placed the bank of capacitors in the middle of feeder *63057172* are shown in Figure 3. At each time instant of the day, an approximate 3.9V voltage increase was seen. At the end point of feeder *63057172*, more than 8V voltage gains were found, as shown in Figure 4.



**Figure 3 Voltage increases at busbar (Phase A) of network *Landgate* when placed the bank of capacitors in feeder 63057172**



**Figure 4 Voltage increases at end point (Phase A) feeder 63057172 of network *Landgate* when placed the bank of capacitors in feeder 63057172**

Voltages at the busbar and mid and end points of all LV feeders were examined for the two networks. In *Landgate*, there are three capacitor banks installed. The voltage gains were found by comparing these voltages with and without the capacitor banks one at a time. Table 2 shows the daily average voltage gain at the busbar as well as mid and end points of all LV feeders in *Landgate* (voltages at each time step are the average of the three phases). In *Leicester Avenue*, only one capacitor bank is installed. The daily average voltage gains at the busbar, mid and end points are illustrated in Table 3.

**Table 2 Voltage gains in *Landgate* with current PV penetration (29.3%)**

	Capacitor connecting feeder			Busbar	63057169		63057170		63057171		63057172		63057173		63057174		
	63057172	63057173	63057174		Mid	End	Mid	End	Mid	End	Mid	End	Mid	End	Mid	End	
One bank of capacitors	Yes			3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	8.4	8.4	3.9	3.9	3.9	3.9
		Yes		3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	7.2	7.2	3.9	3.9
			Yes	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	7.1	7.1



**Table 3 Voltage gains in Leicester Avenue with current PV penetration (22.3%)**

Capacitor connecting feeder	Busbar	69051549		69051565		69051573		69051590		69051618		69051980	
69051565		Mid	End	Mid	End	Mid	End	Mid	End	Mid	End	Mid	End
Yes	3.4	3.4	3.4	5.2	5.2	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4

As seen from above tables, in *Landgate*, one capacitor bank increases the mid and end points of the feeder, to which the capacitor bank is connected, by 7.1 to 8.4V and increases the busbar and the other feeders by approximately 4V.

In *Leicester Avenue*, the capacitor bank increases the mid and end points of the feeder, to which the capacitor bank is placed, by 5.2V and increases the busbar and the other feeders by 3.4V.

It is important to highlight that the above calculations could be expanded to consider different seasons and types of day to capture the most likely range of potential gains from the capacitors. However, these values are likely to be similar given that one of the main factors is the network itself. On the other hand, by considering the scenario above (weekday, July) it will be possible to validate the findings with monitoring data.

### 3.1.2 Creating Network Scenarios for the Coordinated Voltage Control

Capacitor banks are proposed to switch on when low target voltages at the substation, required to cope with voltage rise in feeders with PV systems, result in even lower voltages in these heavily loaded feeders (where the capacitor banks are placed).

In *Landgate*, all the 6 LV feeders have similar PV penetration levels (from 20% to 38.8%). Because the network is in a small-scale area, all PV systems are assumed to have the same PV profile. Therefore, at the same instant of a day, similar voltage rises/drops were found in these LV feeders. The available real monitoring data shows the maximum voltage rise/drop along a feeder in *Landgate* and *Leicester Avenue* is approximately 5V, i.e., there is no voltage drop issue. The OLTC will be able to manage well the voltages in the two networks. In other words, capacitor banks are not truly needed.

To assess the benefits of using capacitor banks, the PV penetration in *Landgate* was modified. Table 4 shows the modified PV penetrations in each of the 6 feeders in *Landgate*. Feeders 63057172 and 63057174 were put relatively high levels of PV penetration, i.e., 80% and 60%, respectively. Feeder 63057173 was set to zero PV penetration. The other feeders were given twice the current PV penetrations.

**Table 4 Modified PV penetrations in each of the 6 feeders in Landgate for one-cap case**

<i>Landgate</i>	Feeder ID	63057169	63057170	63057171	63057172	63057173	63057174
	Total feeder length (km)	1.22	0.67	0.78	2.32	1.83	2.48
	Customers	49	21	30	100	68	83
	Current penetration (%)	38.8	38.1	20	28	35.3	21.7
	Modified penetration (%)	77.6	76.2	40	80	0	60

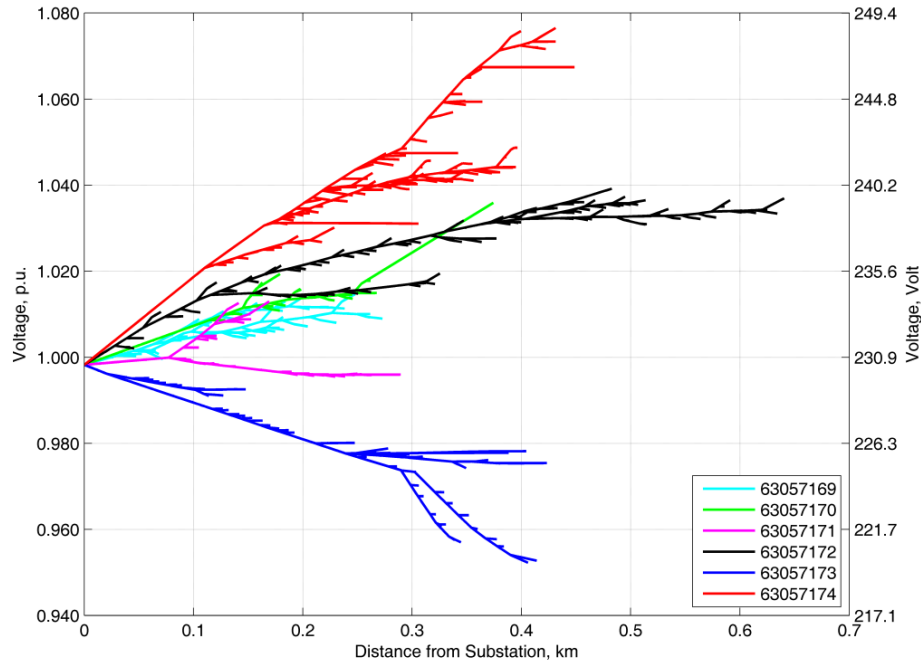


Figure 5 Voltage snapshot (12:48) for the 6 feeders in *Landgate*

A snapshot of the voltages of the 6 feeders in *Landgate* at 12:48 of a day (weekday, July), is shown in Figure 5. With the modified PV penetration (Table 4), feeders 63057174 and 63057172 had significant voltage rises (up to 8% of the nominal) at this instant. The OLTC had been tapped to the lowest tap position, i.e., position 1. Feeder 63057173, however, had a voltage drop of approximate 5% of nominal voltage. This has created a network scenario that requires at some instants of the day the capacitor bank in feeder 63057173 to switch on. The following sections will simulate this network with or without the connection the capacitor bank in feeder 63057173.

### 3.1.3 Capacitor Bank “Switch-on” and “Switch-off” Voltages

For a voltage-based control, capacitor banks should be switched on when the voltage at the capacitor’s connection point is lower than the pre-set “switch-on” voltage. Similarly, they should be switched off when the voltage is higher than the pre-set “switch-off” voltage. These switch-on and switch-off voltages have to be set properly to avoid frequent switching operation or hunting effect.

**“Switch-on” Voltage.** It is assumed that the use of capacitor banks could keep voltages at the feeder far ends higher than the lower limit of the green zone (see Deliverable 1.1<sup>1</sup>), i.e., L-N 221.7V or 0.96 p.u. Consequently, if the capacitor is placed at the end point of the feeder, a potential suitable “switch-on” voltage would be 0.96p.u.

In *Landgate*, the capacitor banks are placed approximately in the mid-point of the feeders. Given that (and according to the ENWL Code of Practice 370<sup>3</sup>) there is a 6% voltage drop along an LV feeder during peak load, it can be considered that for an end-point voltage of 0.96p.u., the mid-point voltage would be 0.99p.u. Therefore the switch-on voltage for the capacitor banks in *Landgate* can be calculated as follows.

$$(0.96 + 0.03) * 230.94V = 228.6V$$

In *Leicester Avenue*, the capacitor banks are placed closer to the substation. Assuming that there is a 4% (of nominal) voltage drop between the capacitor bank and the feeder far end, the switch-on voltage for the capacitor bank in *Leicester Avenue* can be calculated as follows.

$$(0.96 + 0.04) * 230.94V = 230.9V$$

<sup>3</sup> Code of Practice 370, “Voltage control for 132kV, 33kV and 11/6.6kV systems”, Issue 1, August 2009.

**“Switch-off” Voltage.** For a single capacitor bank, the difference between the switch-off and switch-on voltages has to be larger than the voltage gain (at the capacitor’s connection point) provided by the capacitor bank.

In *Leicester Avenue*, only one capacitor bank is installed. The voltage gain at the capacitor’s connection point provided by the capacitor bank is 5.2V (Table 3). Hence, the pre-set value of the switch-off voltage should be higher than 236.1V, e.g., taking it as 238V.

In *Landgate*, one-cap case is first considered. The voltage gain at the capacitor’s connection point provided by one capacitor bank is at the range of 7.1 to 8.4V (Table 2). Hence, the switch-off voltage should be higher than 237V, e.g., taking it as 238V.

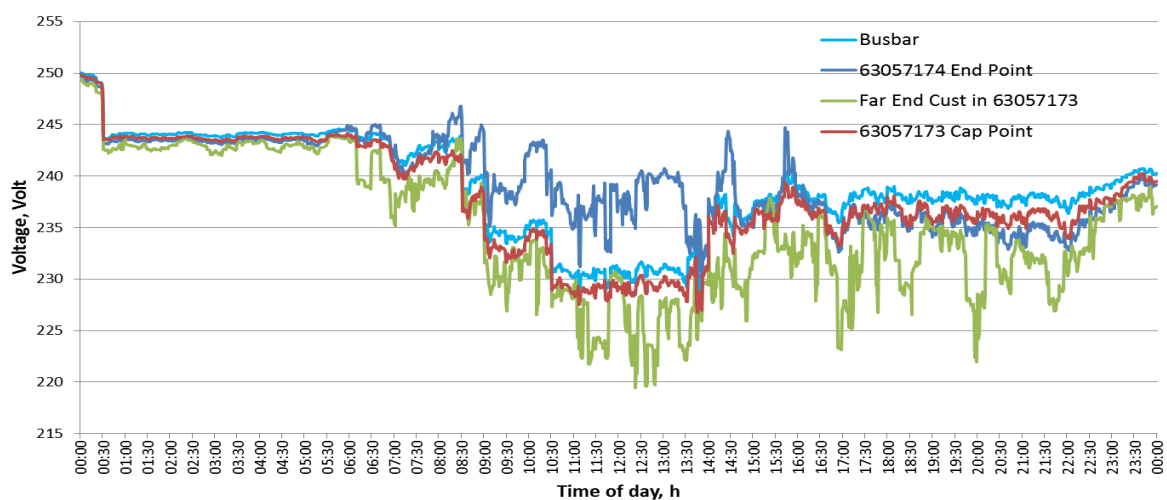
Delays for switch-on and switch-off operation for the one-cap case are proposed to be 30 seconds, which is within the tap delay of the OLTC (120 seconds).

### 3.1.4 Coordination between OLTC and One Capacitor Bank

A coordinated voltage control was carried out through power flow simulations of the modified *Landgate* network model created in section 3.1.2. In particular, it was considered that only the capacitor bank in 63057173 is installed. For comparison purposes, the results of the power flow simulation of the network without capacitor banks are also presented.

Figure 6 shows daily (weekday, July) voltage profiles in *Landgate* without capacitor banks. Figure 7 depicts the corresponding OLTC tap positions. As seen from Figure 7, the OLTC taps were in the lowest position (position 1) from 10:30 to 13:30. During this period, the far end customer in 63057173 had relatively low voltages, which were, from time to time, in the lower orange zone (from 216 to 221V). 10 tap changes were made throughout the day.

Figure 8 shows voltage profiles in *Landgate* with the capacitor bank in 63057173 in a voltage-based control mode setting operation delay 30 seconds and switch-on and switch-off voltages 228.6 and 238V, respectively. Figure 9 depicts the corresponding OLTC tap positions and the capacitor switching operations. As seen from Figure 8, the capacitor bank was switched on from 11:00 to 14:00. During this period, the voltages at the far end customer in 63057173 were higher than 225V. 7 tap changes were made throughout the day.



**Figure 6 Daily voltage profiles (weekday, July) for *Landgate* without capacitor bank**

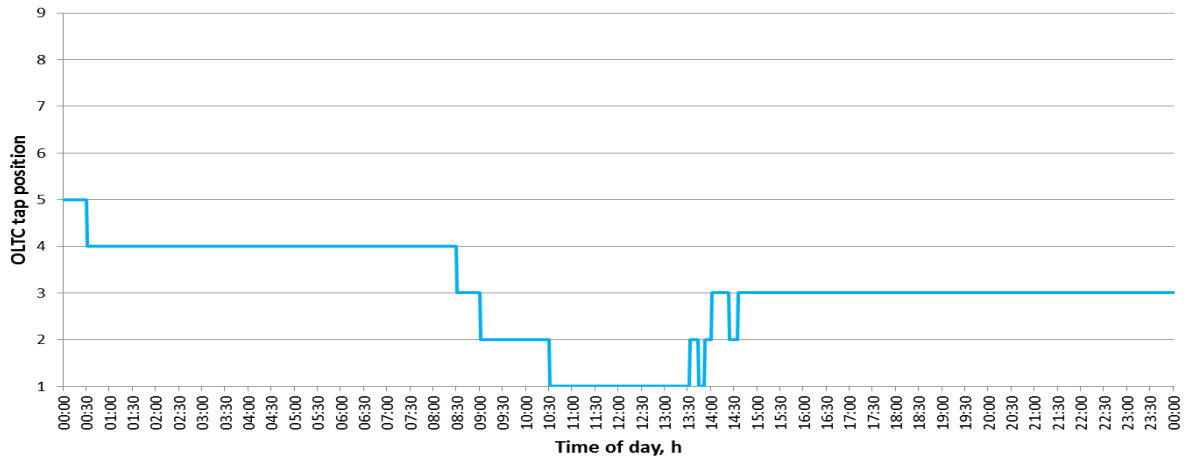


Figure 7 Daily tap positions (weekday, July) for *Landgate* without capacitor bank

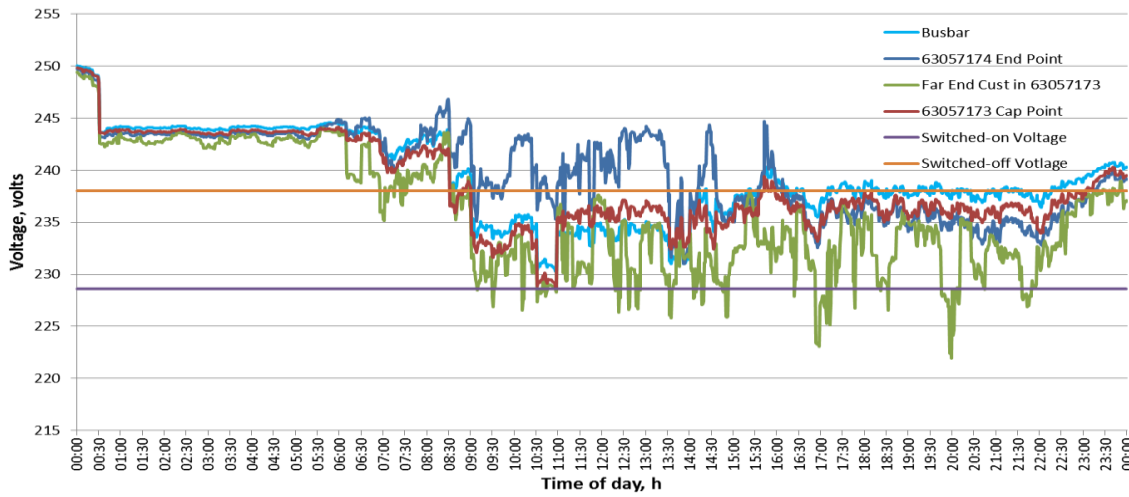


Figure 8 Daily voltage profiles (weekday, July) for *Landgate* with the capacitor bank in 63057173 (Switch-off voltage 238V)

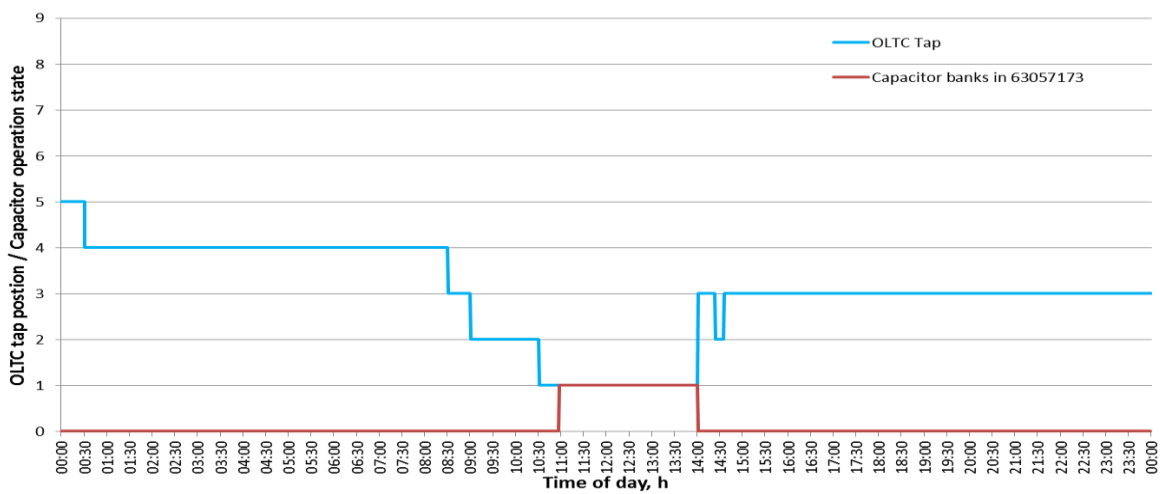


Figure 9 Daily tap positions and capacitor switching (weekday, July) for *Landgate* with the capacitor bank in 63057173 (Switch-off voltage 238V)

In *Leicester Avenue*, the feeder that has the largest number of customers and the highest PV penetration level is the same feeder, i.e., *69051565*. The capacitor bank is also placed in this feeder. Even with 100% PV penetrations in the other 5 feeders, the lowest tap position seen from a one-day (weekday, July) simulation was position 3 (corresponding to busbar voltage 240V). With the proposed switch-on and switch-off voltages, the voltages in feeder *69051565* possibly would never be so low as to operate the capacitor to switch on. However, assuming there is a case that the tap is in position 1 required to cope with feeder *69051565*'s voltage rise, a sudden reduction of the PV generation (i.e., caused by cloud transients) could possibly make feeder *69051565* have relatively low voltage. Therefore, by setting the bank of capacitors with the proposed switch-on and switch-off voltages can prevent the feeder from low voltage under the above scenario.

### 3.2 Multiple Banks of Capacitors (Multiple-cap Case)

#### 3.2.1 Voltage Gains by Multiple Fixed Capacitor Banks

The voltage gains when multiple fixed capacitor banks are placed (connected all the time without any control) in *Landgate* were also quantified. Daily power-flow simulations for *Landgate* with two or three banks of capacitors were implemented. The taps of the OLTC were considered to be in a fixed position (position 5) and no tap change was made throughout the day.

**Table 5 Voltage gains provided by multiple fixed capacitor banks in *Landgate* with current PV penetration (29.3%)**

Scenario	Capacitor connecting feeder			Busbar	63057169		63057170		63057171		63057172		63057173		63057174	
	63057172	63057173	63057174		Mid	End	Mid	End	Mid	End	Mid	End	Mid	End	Mid	End
Two banks of capacitors	Yes	Yes		7.9	7.8	7.8	7.9	7.8	7.8	7.8	12.5	12.4	11.2	11.2	7.8	7.8
	Yes		Yes	7.8	7.8	7.8	7.8	7.8	7.8	7.8	12.5	12.4	7.8	7.8	11.1	11.1
		Yes	Yes	7.9	7.8	7.8	7.9	7.9	7.9	7.8	7.8	7.8	11.2	11.2	11.1	11.1
Three banks of capacitors	Yes	Yes	Yes	12.0	11.9	11.9	12.0	12.0	11.9	11.9	16.6	16.6	15.3	15.3	15.3	15.3

Table 5 depicts the daily average voltage gain at the busbar, mid and end point of all LV feeders (voltages at each time step are the average of the three phases). Using this table and Table 2, it is possible to conclude that multiple capacitors have linear mutual influences in terms of the voltage gains. For instance, when two capacitor banks, e.g., those in *63057172* and *63057173*, are connected, the voltage gain at the busbar (7.8 or 7.9V) is equal to the sum of voltage gains caused by each single capacitor bank (3.9V).

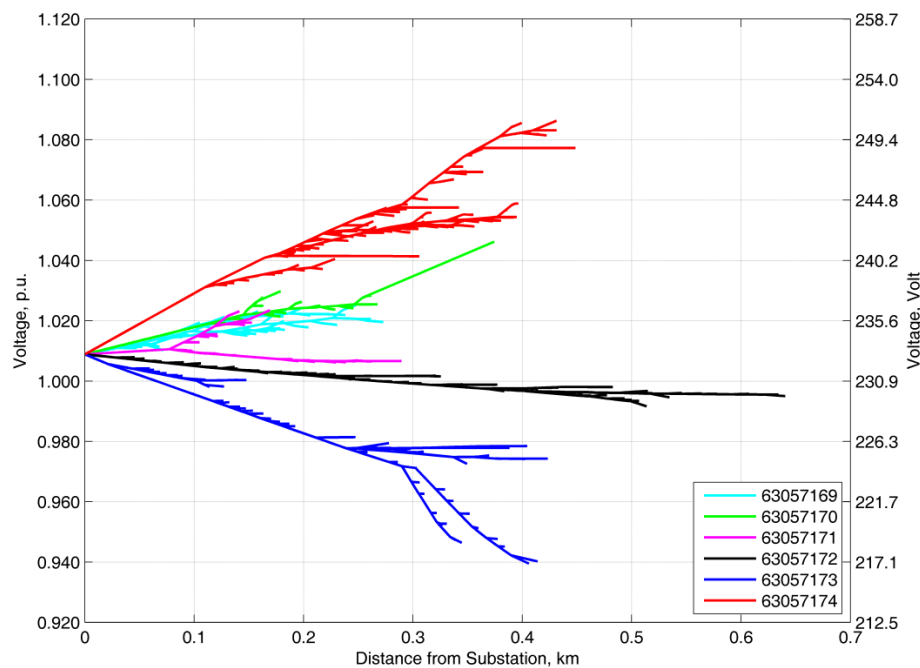
#### 3.2.2 Creating Network Scenarios for the Coordinated Voltage Control

The original PV penetration of *Landgate* was modified to assess the benefits of using multiple capacitor banks. Table 6 shows the modified PV penetrations in each of the 6 feeders. Feeder *63057174* was put an 80% PV penetration. Feeders *63057172* and *63057173* were set zero PV penetration. The other feeders were twice of current PV penetrations.

**Table 6 Modified PV penetrations in *Landgate* for multiple-cap case**

	Feeder ID	63057169	63057170	63057171	63057172	63057173	63057174
<b>Landgate</b>	Total feeder length (km)	1.22	0.67	0.78	2.32	1.83	2.48
	Customers	49	21	30	100	68	83
	Current penetration (%)	38.8	38.1	20	28	35.3	21.7
	Modified penetration (%)	77.6	76.2	40	0	0	60

A snapshot of the voltages of the 6 feeders in *Landgate* at 12:48 of a day (weekday, July), is shown in Figure 10. With the modified PV penetration (Table 6), feeders 63057174 had significant voltage rises (8% of the nominal) at this instant. The OLTC tap was in position 2. Feeders 63057172 and 63057173, however, had voltage drops (approximately 5% of nominal in 63057173). This has created a network scenario that requires at some instants of the day both of the capacitor banks in feeders 63057172 and 63057173 to be switched on. The following sections will simulate this network with multiple capacitor banks.



**Figure 10 Voltage snapshot (12:48) for the 6 feeders in *Landgate***

### 3.2.3 Capacitor Bank “Switch-on” and “Switch-off” Voltages

In the multiple-cap case, the switch-on voltage is the same as that used for the one-cap case. However, for the switch-off voltage, the mutual influences between the capacitor banks have to be taken into account.

Different settings of the switch-off voltage will allow different numbers of banks of capacitors being on simultaneously. For instance, if all three capacitor banks are set to a switch-off voltage of 238V (9.4V higher than the switch-on voltage), then only one capacitor can be on at any given time. This is because the gain from one capacitor bank (8.4V, Table 2) does not exceed the 9.4V margin but a

second one would do (aggregated gain of 12.5V, Table 5), resulting in the disconnection of the first capacitor bank. Thus, this setting does not allow more than one capacitor bank to be on at a given time.

Table 7 shows the possible settings for the three capacitor banks in *Landgate* when allowing different numbers of capacitor banks to be on simultaneously.

**Table 7 Voltage settings for multiple capacitor banks in *Landgate***

	Voltage (V)	
	Switch-on	Switch-off
ONE bank of capacitors on	228.6	238
TWO banks of capacitors on simultaneously	228.6	242
THREE banks of capacitors on simultaneously	228.6	246

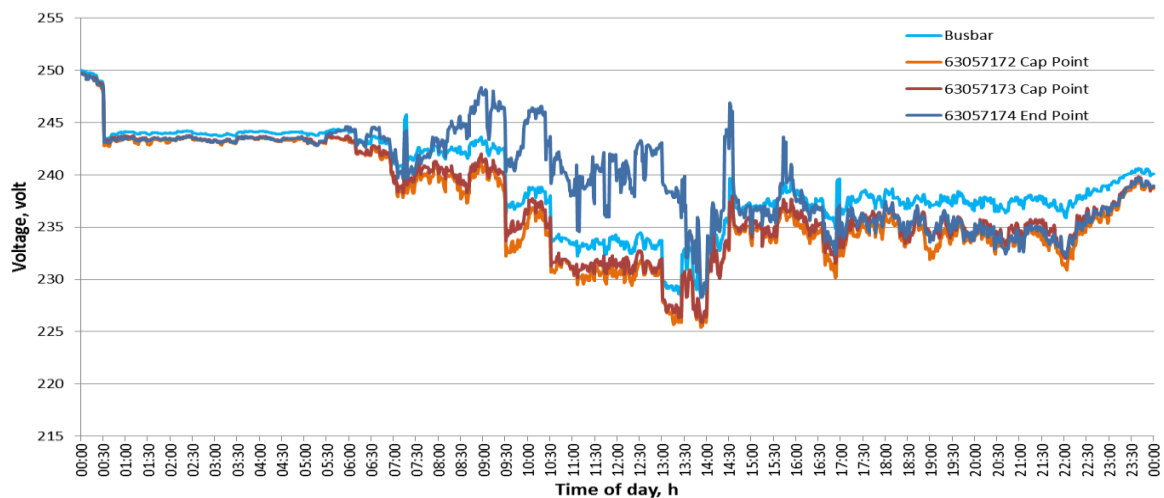
### 3.2.4 Coordination between OLTC and Multiple Banks of Capacitors

A coordinated voltage control was implemented through power flow simulations with the modified *Landgate* model (different PV penetration) created in section 3.2.2. For the multiple-cap case, the three capacitor banks were connected in the network.

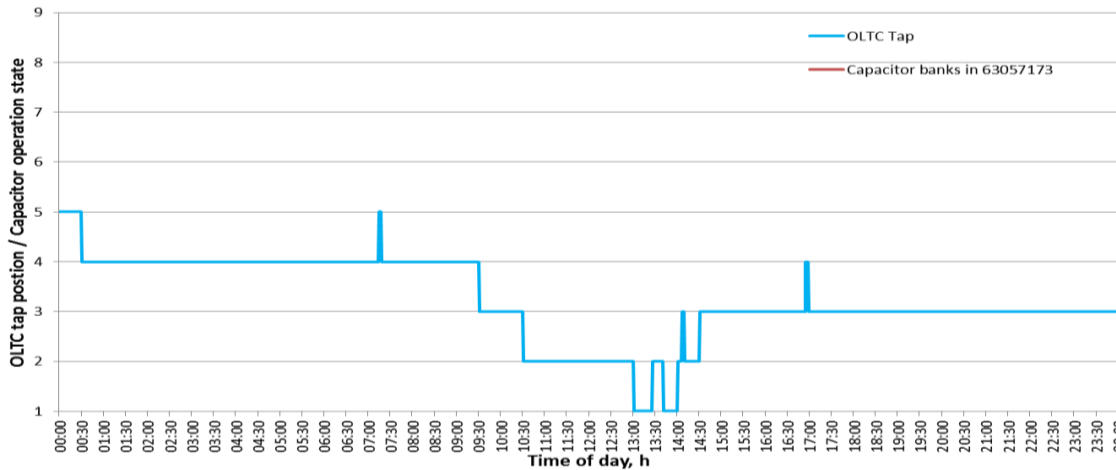
The proposed delays for the three capacitor banks are shown in Table 8. A specific switch-on/switch-off sequence based on the loading of the feeders is considered. Feeder 63057172 has the heaviest load among the three feeders, therefore the corresponding capacitor banks is set as "first on" and "last off". Feeder 63057174 has the lightest load and thus its capacitor bank is set as "last on" and "first off". These delays ensure the best utilisation of the capacitor banks as it avoids unnecessary simultaneous responses to a voltage drop issue. These delays are also within the tap delay (120 seconds).

**Table 8 Proposed delays of the three capacitor banks in *Landgate***

Capacitor connecting feeder	Delays (s)	
	Switching on	Switching off
63057172	30	90
63057173	60	60
63057174	90	30



**Figure 11 Daily voltage profiles (weekday, July) for *Landgate* without capacitor banks**

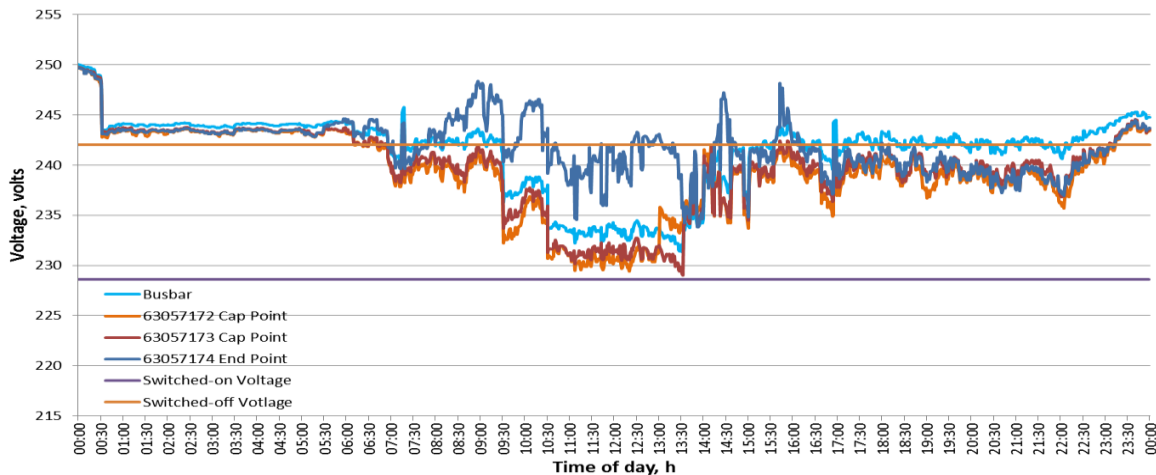


**Figure 12 Daily tap positions (weekday, July) for Landgate without capacitor banks**

Figure 11 shows daily (weekday, July) voltage profiles for *Landgate* without capacitor banks. Figure 12 depicts the corresponding OLTC tap positions. In this network, the two feeders 63057172 and 63057173 have relatively low voltage, particularly during the period from 13:00 to 14:00. 14 tap changes were made throughout the day.

The capacitor banks set with different "switch-off" voltages were investigated. When the switch-off voltage for the three capacitor banks was set to 238V, the hunting effect was seen. This is because the simulation tried to switch on both capacitor banks in 63057172 and 63057173. The mutual influence (12.5V gain) of the two capacitor banks does not allow this to happen.

Figure 13 and Figure 16 show voltage profiles for *Landgate* with all the three capacitor banks set to the "switch-off" voltage of 242 and 246V, respectively. Figure 14 and Figure 17 show the corresponding OLTC tap positions. Figure 15 and Figure 18 illustrate the capacitor switching operations.



**Figure 13 Daily voltage profiles (weekday, July) for *Landgate* with capacitor banks in 63057172 and 63057173 (Switch-off voltage 242V)**



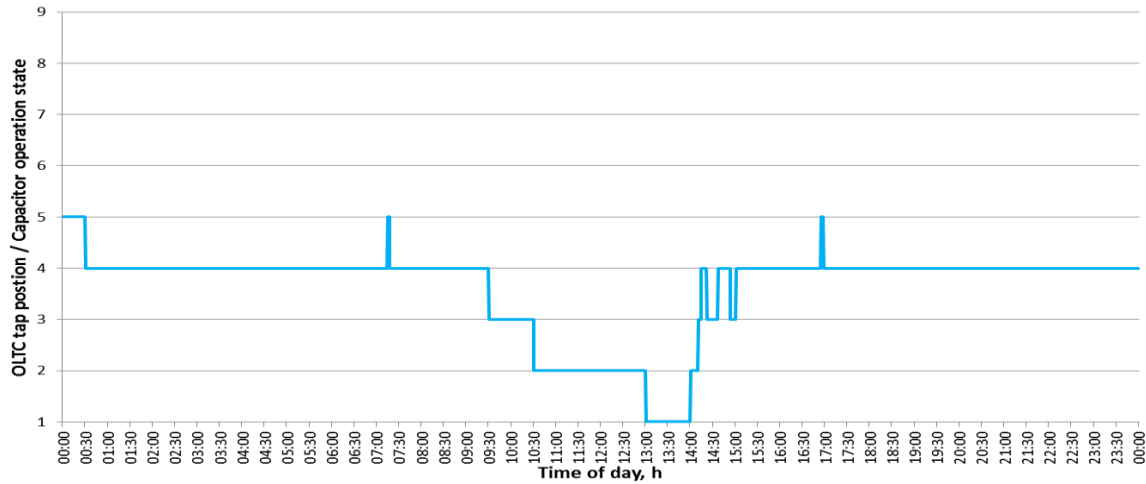


Figure 14 Daily tap position (weekday, July) for *Landgate* with capacitor banks in 63057172 and 63057173 (Switch-off voltage 242V)

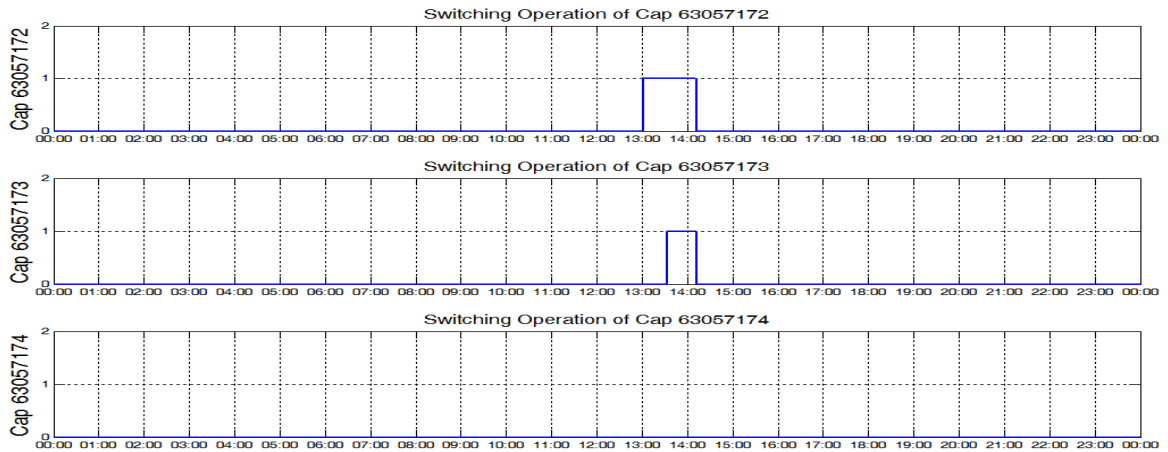


Figure 15 Daily capacitor bank operation (weekday, July) for *Landgate* with capacitor banks in 63057172 and 63057173 (Switch-off voltage 242V)

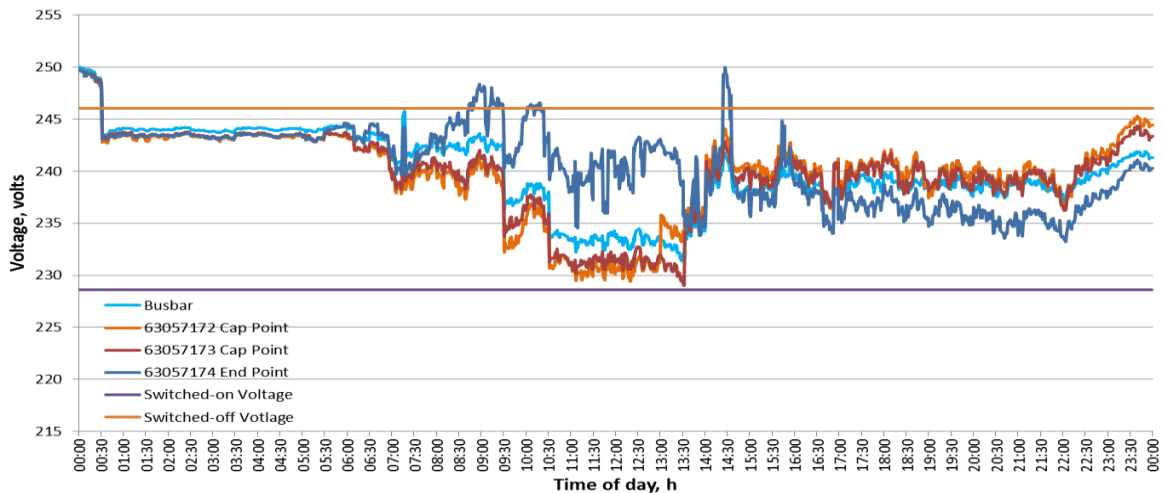
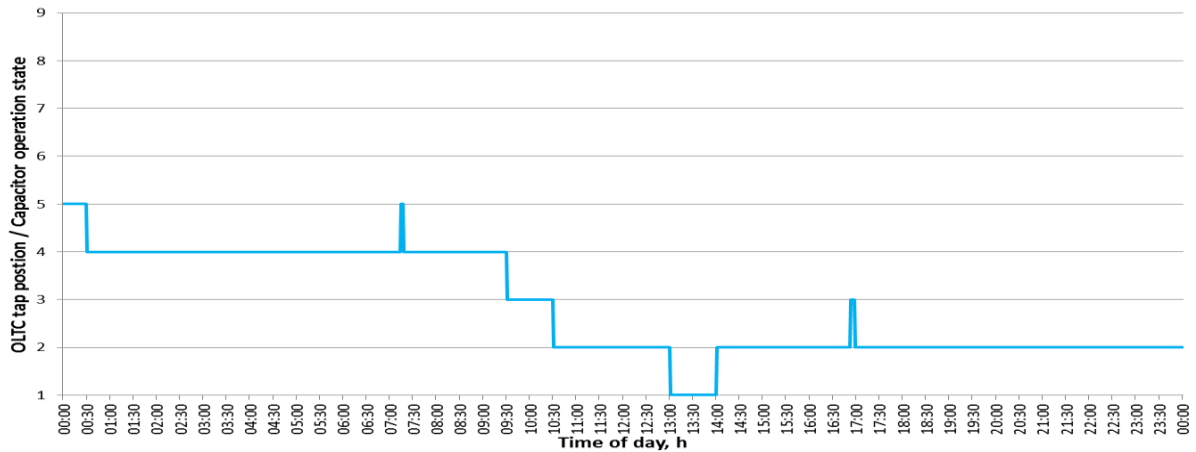
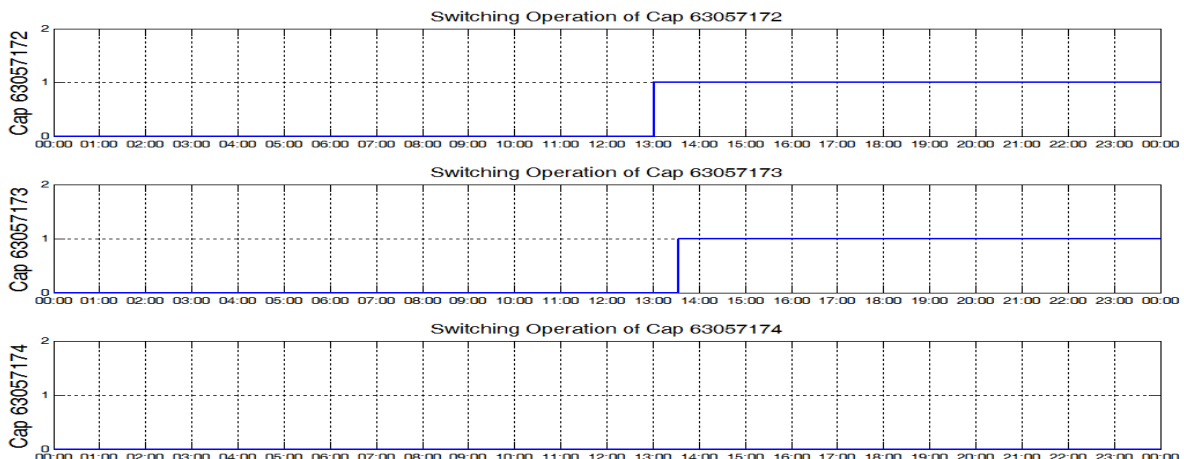


Figure 16 Daily voltage profiles (weekday, July) for *Landgate* with capacitor banks in 63057172 and 63057173 (Switch-off voltage 246V)



**Figure 17 Daily tap positions (weekday, July) for *Landgate* with capacitor banks in 63057172 and 63057173 (Switch-off voltage 246V)**



**Figure 18 Daily capacitor bank operation (weekday, July) for *Landgate* with capacitor banks in 63057172 and 63057173 (Switch-off voltage 246V)**

As seen from these figures, when a higher switch-off voltage is set, the capacitor banks had a longer period of time being on. In Figure 15, the capacitor bank in 63057172 was switched on at 13:00 and kept on for more than one hour. The capacitor bank in 63057173 was switched on from approximately 13:30 and switched off simultaneously with the former. 15 tap changes were made throughout the day in Figure 14.

When the switch-off voltage was set 246V, the two capacitor banks in 63057172 and 63057173 were turned on in mid-day (Figure 18) and kept on for the rest of the day. In Figure 17, 9 tap changes were made throughout the day.

To allow all the three capacitor banks being able to switch on simultaneously, the difference between switch-off and switch-on voltages has to be larger than 16.6V (which is the aggregated gain, Table 5). After two of the capacitors were switched on, throughout the rest of the day there was no voltage exceeding the 246V setting, hence they continued to be on (Figure 18) until this is exceeded the next days (due to changes in load and/or PV generation).

### 3.3 Discussion

The following discussion points are presented to complement the findings from this report:

- Although the scenarios adopted in the analysis do not mimic the actual behaviour of the trial LV networks (scenarios were produced to justify the use of capacitor banks), the proposed methodology to find the most adequate settings and control logic can be applied to any LV network that requires similar voltage management schemes.
- The implementation of the proposed settings in the trial networks is likely not to trigger any capacitor action given that significant voltage drops do not currently exist (based on monitoring data).
- The proposed logic has been produced having as the main objective the effective management of voltages across the feeders. It has not yet been optimised to also reduce the number of control actions in specific elements (e.g., tap changes, capacitor switching, etc.).
- The voltage gain at the busbar produced by one or multiple capacitor banks is likely to affect the number of tap changes (although this has not been quantified in this report). Therefore, when deploying capacitor banks smaller sizes than those used in the trials (150 kVar) are recommended.
- The voltage gains provided by capacitor banks were obtained by power flow simulations. The results of the power flow simulations were related to the load and PV models. Therefore, voltage gains should be validated with actual data (such as voltage, current or the actual voltage gain, etc.) once made available. The settings of the capacitor banks, particularly the "switch-off" voltage, should be revised accordingly.
- A centralised approach to control voltages was not considered in this report. Once the remote control infrastructure for the capacitor banks in *Landgate* and/or *Leicester Avenue* is made available, the algorithm can be adapted accordingly and implemented in the RTU.

## 4 Recommended Settings and Conclusions

### 4.1 Recommended Settings

According to the modelling of the two networks and power-flow analyses considering the OLTC-fitted transformer and the capacitor banks, Table 9 presents the most suitable settings.

- Leicester Avenue. Only one capacitor bank is installed in this network, hence it is recommended to use the one-cap case settings.
- Landgate. From the multiple-cap case, the recommended settings are those when three capacitor banks are present (as is the case of this network).

**Table 9 Recommended settings for the capacitor banks**

Capacitor connecting feeder	Voltage (V)		Delays (s)	
	Switched on	Switched off	Switched on	Switched off
63057172 ( <i>Landgate</i> )	228.6	246	30	90
63057173 ( <i>Landgate</i> )	228.6	246	60	60
63057174 ( <i>Landgate</i> )	228.6	246	90	30
69051565 ( <i>Leicester Av</i> )	230.9	238	30	30

### 4.2 Conclusions

Based on the voltage gains found in this report and the most suitable settings for the capacitor banks defined, power flow analyses were carried out to assess the performance of the coordinated voltage control. The following conclusions have been drawn:

- **Coordinated Voltage Control: One-cap Case.** The most suitable switch-on and switch-off voltage values for the capacitor bank in *Leicester Avenue* were found to be 230.9 and 238V, respectively. In *Landgate* (with only one capacitor bank), the switch-on and switch-off voltages should be 228.6 and 238V, respectively. Despite the low X/R ratio found in LV networks, the simulations did show an increase in voltages when the capacitor was used (5 to 8V). This voltage gain also affected the other feeders in the network (3 to 4V). In addition, the simulations showed that the use of the capacitor resulted in a reduced number of tap changes.
- **Coordinated Voltage Control: Multiple-cap Case.** To control multiple capacitor banks simultaneously whilst avoiding the hunting effect, a larger difference between the switch-on and switch-off voltages should be adopted. In *Landgate* (three capacitor banks), the most suitable values were found to be 228.6 and 246V, respectively. This control also considered a specific switch-on/switch-off sequence based on the loading of the feeders, as well as delays among each capacitor bank within the tap delay of the OLTC. The simulations showed that these 150kVar capacitor banks resulted in high voltage gains (~17V) suggesting that smaller devices should be used. The number of tap changes was also found to be reduced.

The above recommendations and conclusions are based on load and generation scenarios produced to create significant voltage drop issues in certain feeders within the two trial LV networks so the use of capacitor banks can be justified. Although these scenarios do not mimic the actual behaviour of these particular networks, the proposed methodology to find the most adequate settings and control logic can be applied to any LV network that requires similar voltage management schemes.

## 5 Next Steps

The next steps to be carried out by The University of Manchester for the LoVIA project include:

- Performance assessment of the algorithm considering improvements and also a multi-season horizon. This will focus primarily on the OLTC-only case.
- Deliverable 2.1. Quantification of New Hosting Capabilities. Different PV penetration scenarios will be considered in order to investigate the extent to which (i.e., penetration level) the coordinated control between OLTC and capacitor banks is capable of coping with voltages satisfactorily. In addition, cases with significant disparity among feeders (heavily loaded no generation and lightly load with generation) will also be investigated.
- Deliverable 2.2. Findings and Recommendations. This deliverable will conclude the initial findings and recommendations obtained from this project.