

*Title:* **Report for Deliverables 2.2  
"Guidelines, benefits and  
limitations"**

*Synopsis:* This document summarises the findings from this project, including benefits and limitations, as well as the specific considerations and challenges in order to implement coordinated control of voltage regulation devices, specifically OLTC-fitted transformers and capacitor banks.

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## Executive Summary

This report corresponds to Deliverable 2.2 "Guidelines, benefits and limitations" 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.

This document summarises the findings from this project, including benefits and limitations, as well as the specific considerations and challenges in order to implement coordinated control of voltage regulation devices, specifically OLTC-fitted transformers and capacitor banks.

The studies carried out have demonstrated the effectiveness and flexibility of the LoVIA architecture for voltage management in LV networks with high penetrations of PV systems. A summary of the main recommendations of this report is presented below.

- **OLTC Control Strategies.** This project has devised three different OLTC control strategies (without capacitors), including constant set-point (CSC), time-based (TC) and LoVIA control. Based on seasonal week-long Monte Carlo simulations, the TC strategy results in a better mitigation of voltage issues than CSC and is comparable with the LoVIA control. However, this is mostly done at the expense of more tap operations. Overall, the LoVIA control strategy resulted in a much better mitigation of voltage issues than TC and CSC and with only a fifth of the tap operations. Consequently, the LoVIA control strategy is recommended if remote monitoring is possible. Otherwise, the TC control is recommended.
- **Control Cycles / Sampling Intervals.** It was found that for all the studied PV penetration levels, the LoVIA control strategy using a 30-minute control cycle provided a good compromise between voltage management and number of tap changes. Strictly speaking, the best performance was found with a 5-minute control cycle. However, given that longer control cycles enable longer sampling intervals from the monitoring devices, a trade-off has to be found by the DNOs considering the corresponding financial and ICT aspects.
- **Coordinated Voltage Control using Capacitors.** In coordination with the LoVIA control strategy, the recommended switch-on and switch-off voltages of the capacitor bank in *Leicester Ave* (one capacitor bank) were found to be 230.9 and 238V, respectively. For the capacitor banks in *Landgate* (three capacitor banks), the recommended values are 228.6 and 246V. These ranges, however, are site specific and produced based on the capacitor banks used in the trial (150kVAR three phase). Further studies are required to generalise values for different capacitor sizes and locations.
- **Capacitor Banks.** The voltage gains brought by the 150 kVAR capacitor banks are bigger than those actually needed by the networks. This affects busbar voltages and results in further tap changes. Therefore, small capacitor banks are recommended, e.g., 50kVAR.
- **Loss of Communications.** The LoVIA control strategy has adopted a fall back setting of sending the set-point to 1.04 p.u. (i.e., 240.2V) when the centralised controller loses up to 25% of the remote phase voltage measurements (either mid or end point). This setting was defined based on the characteristics of the networks and the current PV penetrations (~30% of the households almost evenly among feeders). However, when higher PV penetrations and/or dissimilar penetrations among feeders are present, more intelligent fall back settings should be used.

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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 low voltage (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 is 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 Deliverable 2.2

This document summarises the main findings and recommendations from this project. These findings and recommendations are mainly based on report Deliverables 1.2 and 1.3 and Deliverable 2.1.

This report is structured as follows. First, the performances of three different OLTC control strategies are presented to show the benefits of using these control strategies, particularly in comparison with the off-load tap changer. This leads to the analysis of the use of the control cycles / sample intervals for the LoVIA control. Then the assessment of the coordination between the OLTC-fitted transformer and capacitor banks, including the recommended settings for the capacitor banks used in the trial and the recommended size, are presented. In the sequence, recommendations are provided for the loss of communications. The conclusions are drawn in the final section.

## 2 Main Findings and Recommendations

The studies carried out for this project have demonstrated the effectiveness and flexibility of the LoVIA architecture for voltage management in LV networks with high penetrations of PV systems. The main findings and recommendations are presented as follows.

### 2.1 OLTC Control Strategies

This section presents the assessment of different OLTC control strategies (based on Deliverable 2.1 "Scenario-based analysis of the potential benefits from adopting OLTC-fitted transformers").

This project has devised three different OLTC-based control strategies, including constant set-point, time-based and LoVIA control. The benefits of adopting OLTC-fitted transformers, particularly in comparison with the off-load tap changer, are assessed through week-long Monte Carlo-based analyses considering all PV penetrations and seasonality (i.e., summer, spring/autumn and winter).

These voltage control strategies are:

- **Off-Load Tap Changer.** To cope with PV systems, the off-load tap changer is set to tap position 4, i.e., +2.5%.
- **Constant Set-Point Control (CSC).** The set-point is kept a fixed value of 1.04p.u. (i.e., 240.2V line-to-neutral) throughout the year.
- **Time-Based Control (TC).** The set-point is changed according to the time of the day. During minimum demand a set-point voltage of 1.03p.u. (237.9V) is considered whereas during peak this value is set to 1.05p.u. (242.5V). Daily schedules are slightly modified per season to account for daylight hours.
- **LoVIA Control.** The set-point is changed according to the measured voltages at the busbar as well as mid and end points. Three voltage zones, red (>253 and <216V), orange (248 to 253V and 216 to 221V) and green (221 to 248V) are defined, as shown in Table 1. By determining how far the monitoring voltages, in particular the maximum and minimum values, are from the ideal range (i.e., the green zone), this control strategy estimates the needed compensation, and provides the corresponding set-point voltage. Details of this control strategy are presented in Deliverable 2.1 Section 2.

Table 1 Voltage zones

		Maximum				
		Red	Orange	Green	Orange	Red
		>253V	253V≥. ≥248V	248V>. ≥221V	221V>. ≥216V	<216V
Minimum	Red >253V	+3				
	Orange 253V≥. ≥248V	+2	+2			
	Green 248V>. ≥221V	+2	+1	0		
	Orange 221V>. ≥216V	+1	0	-1	-2	
	Red <216V	0	-1	-2	-2	-3

Figure 1 and Figure 2, extracted from Deliverable 2.1 Section 3.3.4, present the season-weighted average (i.e., annual average) performance metrics, i.e., voltage compliance with the standard BS EN50160 and the number of tap operations, respectively. As seen in Figure 1, with the off-load tap changer customers present voltage issues from 30% of PV penetration. With a 70% penetration, one in four customers in the network is non-compliant with BS EN50160. However, with the OLTC, disregarding the control strategy, it is only until 50% of PV penetration that customers might experience voltage problems. Although the TC strategy results in a better mitigation of voltage issues than CSC and comparable with the LoVIA control, this is mostly done at the expense of more tap

operations. Overall, the LoVIA control strategy resulted in a much better mitigation of voltage issues than TC and CSC and with only a fifth of the tap operations.

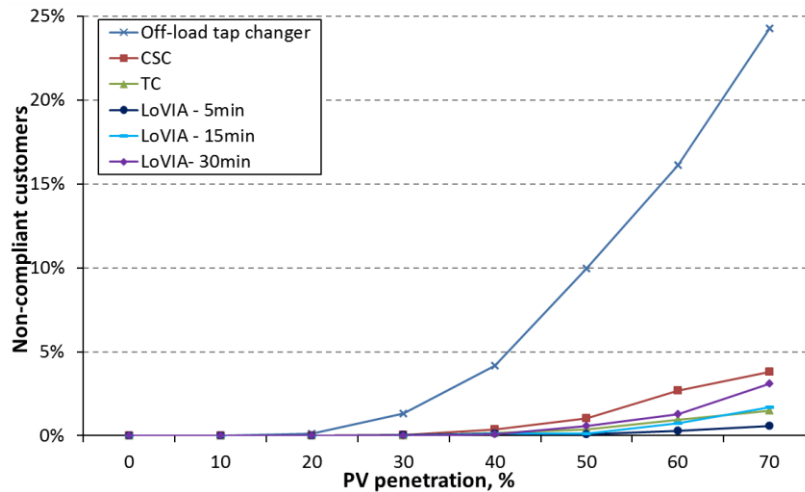


Figure 1 Customers with voltage problems – comparison (annual average)

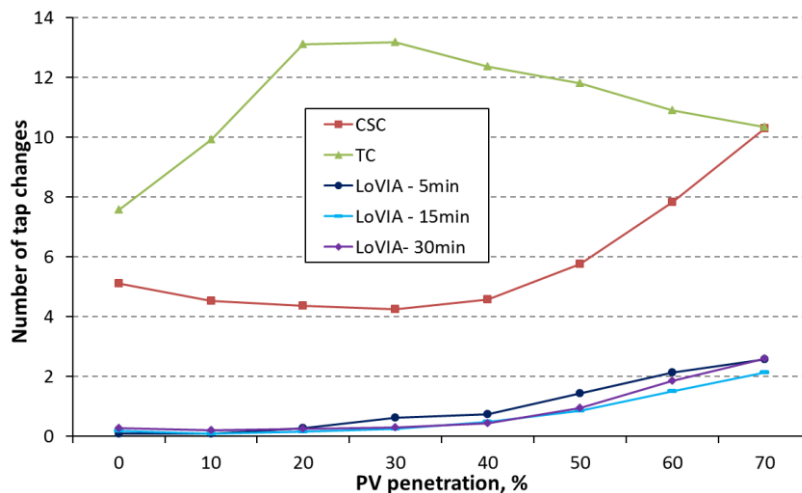


Figure 2 Daily average number of tap changes – comparison (annual average)

It is concluded that the LoVIA is the best OLTC control strategy among the three. However, for networks without available remote monitoring, CSC and TC can be used. DNOs can choose the most suitable control strategy depending on the characteristics of their networks and the focus of the operation, e.g., targeting voltage compliance or fewer tap operations.

To effectively manage voltages in LV networks with high PV penetrations, the LoVIA control strategy is recommended if remote monitoring is possible. Otherwise, the TC control is recommended.

## 2.2 Control Cycles / Sampling Intervals

For the LoVIA control strategy, 5, 15 and 30-min control cycles were investigated. 5-min is considered as the shortest control cycle so as to cater for the communication and tap operation delay times.

As seen from Figure 1 and Figure 2, for all the studied PV penetration levels, the LoVIA control strategy using a 30-min control cycle provided a good compromise between voltage management and number of tap changes. Strictly speaking, the best performance was found with a 5-minute control cycle. However, given that longer control cycles enable longer sampling intervals from the monitoring devices, a trade-off has to be found by the DNOs considering the corresponding financial and ICT aspects.

For the LoVIA control strategy, using a control cycle length of 30-min is recommended. However, if shorter control cycle length, e.g., 15-min, 5-min, is considered, a trade-off has to be found by the DNOs considering the corresponding financial and ICT aspects.

### 2.3 Coordinated Voltage Control using Capacitors

This section presents the assessment of the coordination between the OLTC-fitted transformer and capacitor banks (based on Deliverables 1.2 and 1.3 “Control logic considering different voltage regulation devices”).

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 PV systems, result in even lower voltages in other feeders. Although, the two trial LV networks, *Landgate* and *Leicester Ave*, 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 project investigates a coordinated voltage control between the OLTC-fitted transformers and capacitor banks adopting suitable scenarios.

In coordination with the LoVIA control, capacitor banks are connected to feeders having larger loads and less, or no, PV installations. In *Landgate*, three 150 kVAr three-phase capacitor banks are placed approximately in the mid points of three different feeders. In *Leicester Ave*, a 150 kVAr three-phase capacitor bank is also connected somewhere in one feeder. According to the power-flow analyses adopting a case-by-case approach, i.e., one-cap and multiple-cap cases, the following findings have been obtained.

- **Coordinated Voltage Control: One-cap Case.** The recommended switch-on and switch-off voltages of the capacitor in *Leicester Ave* were found to be 230.9 and 238V, respectively.
- **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. For the capacitor banks in *Landgate* (three capacitor banks), the recommended switch-on and switch-off voltages are 228.6 and 246V. 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.

Table 2 presents the recommended settings for *Landgate* (three-cap case) and *Leicester Ave* (one-cap case).

**Table 2 Recommended settings for the capacitor banks**

Capacitor connecting feeder	Location	Voltage (V)		Delays (s)	
		Switch-on	Switch-off	Switch-on	Switch-off
63057172 ( <i>Landgate</i> )	Opposite 50 Patterdale Rd, Ashton-in-Makerfield	228.6	246	60	100
63057173 ( <i>Landgate</i> )	Side of 2 Dovedale Road, Ashton- in-Makerfield	228.6	246	80	80
63057174 ( <i>Landgate</i> )	Opposite 41 Yewdale Rd, Ashton- in-Makerfield	228.6	246	100	60
69051565 ( <i>Leicester Ave</i> )	Opposite 1 Belmont Rd, Hindley, Wigan	230.9	238	60	60

These recommended settings are site specific and produced based on the capacitor banks used in the trial (150kVAr three-phase). Further studies are required to generalise values for different capacitor sizes and locations.



## 2.4 Capacitor Banks

The ideal case of using capacitor banks is to have voltage gains in the feeders that have larger loads and less, or no, PV installations and small, or no, voltage gains at the busbar and other feeders that do not have voltage issues.

In this project, one 150 kVAr capacitor bank resulted in 5 to 8V voltage gains at the feeder in which capacitor banks are placed, and 3 to 4V in the other feeders in the network. Three banks of capacitor as of *Landgate* will result in ~17V voltage gains in the connection feeders and ~10V at busbar and other feeders. These voltage gains are bigger than those actually needed by the networks. This affects busbar voltages and results in further tap changes.

Therefore, for a more adequate management of voltages in LV networks, smaller capacitor banks are recommended, e.g., 50kVAr.

## 2.5 Loss of Communications

For the LoVIA control strategy, the set-point voltage is changed according to the measured voltages at the busbar as well as mid and end points. The voltages at the mid and end points are received by the centralised controller (located at the substation) via wireless communications. Therefore, loss of the communications means some measurements are not able to be taken into account in the control logic and consequently would affect the performance of this control strategy.

A Monte Carlo-based analysis was carried out to assess the performances of the LoVIA control strategy in *Landgate* with different monitoring conditions. Table 3 presents the EN50160 voltage non-compliant customers and the daily number of tap changers under these monitoring conditions. It is found that even the centralised controller loses 50% of all monitoring points, the LoVIA control still could result in a better performance than the CSC with a set-point of 1.04 p.u. This means that the LoVIA control allows losing up to 50% of all the remote monitoring for networks as of *Landgate* that have similar PV penetrations between feeders.

**Table 3 Performance of the LoVIA control in *Landgate* with different monitoring conditions**

Monitoring condition	30% PV penetration		60% PV penetration	
	EN50160 non-compliant customers, %	Daily no. of tap changes	EN50160 non-compliant customers, %	Daily no. of tap changes
1 All mid and end points	0.81	1.8	1.46	14.7
2 Losing the most critical feeder	0.83	1.2	1.61	11.1
3 Losing 50% of all monitoring (the most critical feeder is not monitored)	0.83	1.1	1.81	9.5
4 Losing 50% of all monitoring (the most critical feeder is monitored)	0.83	1.2	1.52	10.9
5 Losing randomly 50% of all monitoring	0.83	1.2	1.63	10.4
6 No monitoring, CSC with set-point 1.04 p.u.	0.87	3.9	1.74	27.8

For the two trial networks, the LoVIA control strategy has adopted a fall back setting of sending the set-point to 1.04 p.u. (i.e., 240.2V) when the centralised controller loses up to 25% of the remote phase voltage measurements (either mid or end point). This setting was defined based on the characteristics of the networks and the current PV penetrations (~30% of the households almost evenly among feeders).

When higher PV penetrations and/or dissimilar penetrations among feeders are present in LV networks, instead of a defined percentage of loss of monitoring units, more intelligent fall back settings should be used.



### 3 Conclusions

Based on the study of this project, the following conclusions have been drawn:

- **OLTC Control Strategies.** This project has devised three different OLTC control strategies (without capacitors), including constant set-point (CSC), time-based (TC) and LoVIA control. Based on seasonal week-long Monte Carlo simulations, the TC strategy results in a better mitigation of voltage issues than CSC and is comparable with the LoVIA control. However, this is mostly done at the expense of more tap operations. Overall, the LoVIA control strategy resulted in a much better mitigation of voltage issues than TC and CSC and with only a fifth of the tap operations. Consequently, the LoVIA control strategy is recommended if remote monitoring is possible. Otherwise, the TC control is recommended.
- **Control Cycles / Sampling Intervals.** It was found for all the studied PV penetration levels that the LoVIA control strategy using a 30-minute control cycle provided a good compromise between voltage management and number of tap changes. Strictly speaking, the best performance was found with a 5-minute control cycle. However, given that longer control cycles enable longer sampling intervals from the monitoring devices, a trade-off has to be found by the DNOs considering the corresponding financial and ICT aspects.
- **Coordinated Voltage Control using Capacitors.** In coordination with the LoVIA control strategy, the recommended switch-on and switch-off voltages of the capacitor bank in *Leicester Ave* (one capacitor bank) were found to be 230.9 and 238V, respectively. For the capacitor banks in *Landgate* (three capacitor banks), the recommended values are 228.6 and 246V. These ranges, however, are site specific and produced based on the capacitor banks used in the trial (150kVAr three phase). Further studies are required to generalise values for different capacitor sizes and locations.
- **Capacitor Banks.** The voltage gains brought by the 150 kVAr capacitor banks are bigger than actually needed by the networks. This affects busbar voltages and results in further tap changes. Therefore, small capacitor banks are recommended, e.g., 50kVAr.
- **Loss of Communications.** The LoVIA control strategy has adopted a fall back setting of sending the set-point to 1.04 p.u. (i.e., 240.2V) when the centralised controller loses up to 25% of the remote phase voltage measurements (either mid or end point). This setting was defined based on the characteristics of the networks and the current PV penetrations (~30% of the households almost evenly among feeders). However, when higher PV penetrations and/or dissimilar penetrations among feeders are present, more intelligent fall back settings should be used.