The University of Manchester

Title: **Report for Deliverable 2.1 “Scenario-based analysis of the potential benefits from adopting OLTC-fitted transformers”**

Synopsis: This document presents a performance analysis of different OLTC control strategies: constant set-point, time-based and LoVIA logic. A Monte Carlo-based time-series analysis is carried out considering different PV penetrations and seasonality. The number of tap operations and voltage compliance with the standard BS EN50160 are used as key performance metrics. A performance analysis of the deployed LoVIA logic control in *Landgate* and *Leicester Ave* is also presented.

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Executive Summary

This report corresponds to Deliverable 2.1 “Scenario-based analysis of the potential benefits from adopting OLTC-fitted transformers” 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 presents a performance analysis of different OLTC control strategies: constant set-point, time-based and LoVIA logic. A Monte Carlo-based weekly time-series analysis is carried out considering different PV penetrations and seasonality (i.e., summer, spring/autumn and winter). The number of tap operations and voltage compliance with the standard BS EN50160 are used as key performance metrics. A performance analysis of the deployed LoVIA logic control in *Landgate* and *Leicester Ave* is also presented

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

- **Off-Load Tap Changer**. The season-weighted average (i.e., annual average) shows that with the off-load tap changer (tap position 4, i.e., +2.5%) customers in *Landgate* 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.

- **Constant Set-Point Control (CSC).** By keeping a fixed value of 1.04p.u. (i.e., 240.2V line-to-neutral) throughout the year, this strategy allows up to 40% of PV penetration.

- **Time-Based Control (TC)**. Here, the set-point voltage 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. This strategy also allows up to 40% of PV penetration but results in a better mitigation of voltage issues. Nonetheless, on a daily basis, it requires a slightly higher number of tap changes than CSC.

- **LoVIA**. This strategy changes the set-point voltage 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. 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 at the busbar voltage, and provides the corresponding set-point voltage. This strategy allows up to 50% of PV penetration with only a fifth of the tap operations needed by CSC or TC.

- **Deployed LoVIA Control in *Landgate* and *Leicester Ave* Networks**. These two networks have an approximate PV penetration of 30%. According to the monitoring data during the summer and autumn of 2014 (5 weeks and 2 days for *Landgate* and 10 weeks and 3 days for *Leicester Ave*), voltages at all mid and end points of the LV feeders were within the statutory limits. There were 50 tap operations (1.4 per day on average) in *Landgate* and 136 in *Leicester Ave* (1.9 per day on average). These values are aligned with those find through simulations. Therefore, it can be concluded that the LoVIA control strategy has performed as expected in the two networks.

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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 Deliverable 2.1

In Deliverable 1.1 [1], the modelling and performance of the independent (i.e., stand-alone) control of the on-load tap changer (OLTC) fitted transformer was presented. In Deliverables 1.2 and 1.3 [2], the coordination between the OLTC and capacitor banks was reported. In this document, the OLTC-based voltage control strategies are quantified considering all PV penetrations and also seasonality so as to fully understand the benefits brought by the OLTC-fitted transformers. These control strategies include constant set-point control, time-based control and the LoVIA logic control.

The objective of the voltage management is to keep customer voltages within the statutory limits. However, depending on the corresponding voltage control strategy, tap operations can be significant, leading to the wear and tear of the OLTC. Therefore, an adequate OLTC control strategy should be used to ensure customer voltages are within the statutory limits whilst minimizing tap operations. In this report, the number of tap operations and voltage compliance with the standard BS EN50160 are used as key performance metrics. A Monte Carlo methodology considering 1-minute resolution throughout a week (per season) is used to assess the control performances.

This report is structured as follows. First, the basic OLTC control concepts and the three OLTC-based voltage control strategies are presented. The corresponding performances are analysed considering weekly simulations for three seasonal categories, i.e., summer, spring/autumn and winter. In addition, to understand the importance of the stochastic behaviour of load and generation, a deterministic analysis is carried out and compared with the more thorough Monte Carlo-based analysis. In the sequence, the performance analysis of the deployed LoVIA control strategy on the two trial networks *Landgate* and *Leicester Ave* is presented. The conclusions are drawn in the final section.

2 OLTC-based Control Strategies

In this section, first the basic OLTC control concepts are presented. Then, three control strategies are investigated in order to maximise the benefits brought by OLTC-fitted transformers: constant set-point control, time-based control and LoVIA logic control.

2.1 Basic OLTC Control Concepts

The OLTC keeps the secondary bus (busbar) voltage within a bandwidth, as shown in (1).

$$V_{LB} \le V_{busbar} \le \mathrm{V_{UB}} \quad (1)$$

where, V_{busbar} is the transformer secondary bus (busbar) voltage; V_{LB} is the lower boundary voltage ($V_{set} - 0.5BW$); V_{UB} is the upper boundary voltage ($V_{set} + 0.5BW$); V_{set} is the set-point voltage; and, BW is the bandwidth.

The set-point voltage, also known as voltage target, is either a constant or varying value depending on the control strategy. Once the set-point voltage and bandwidth are set, the OLTC will adjust its tap position accordingly. The busbar voltage is checked frequently (e.g., 1 second). However, the actual tap change occurs if the bandwidth has been exceeded for longer than a pre-defined delay (e.g., 2 minutes).

Assuming that the magnitude of the voltage change at the busbar for a single tap operation (one step) is $V_{one-tap}$, the chosen bandwidth has to be larger as shown in (2).

$$BW > V_{one-tap} \quad (2)$$

2.2 Constant Set-Point Control (CSC)

The principle for this control strategy is that the set-point voltage keeps a fixed value all the time (disregarding the season). However, there will still be tap operations as the OLTC will change the position to maintain the busbar voltage at, or close to, the set-point voltage. For this control strategy, 240.2V line-to-neutral, i.e., 1.04 p.u., was taken as the set-point voltage. This value provides extra headroom for PV generation compared to the business as usual approach (~250V using the off-load tap changer set to the nominal tap position) whilst coping with potential voltage drops during peak demand.

2.3 Time-Based Control (TC)

In the UK, voltage rise due to PV systems happens because of its coincidence with minimum demand. This PV generation does not extend considerably to hours of peak demand (e.g., 17:00 to 20:00). Hence, by changing the set-point voltage according to the time it is possible to adopt a less conservative value during minimum demand and a more conservative one during peak. The set-point voltages for different periods of the day adopted for the TC strategy are shown in Table 1. This also considers the duration of daylight for the different seasons in the North West of England.

Table 1 Set-point voltages for different seasons

Season	Time	Set-point Voltage
Summer	6:00 to 16:59	237.9V (1.03 p.u.)
	00:00 to 5:59 and 17:00 to 23:59	242.5V (1.05 p.u.)
Spring/Autumn	7:00 to 16:59	237.9V (1.03 p.u.)
	00:00 to 6:59 and 17:00 to 23:59	242.5V (1.05 p.u.)
Winter	8:30 to 15:59	237.9V (1.03 p.u.)
	00:00 to 8:29 and 16:00 to 23:59	242.5V (1.05 p.u.)

2.4 LoVIA Logic Control

The LoVIA logic control was presented in Deliverable 1.1 [1]. The logic has been improved to further minimise the number of tap changes, particularly at high penetration levels (more than 50%). The detailed control logic and corresponding improvements are presented in this section.

2.4.1 Architecture

The architecture of the LoVIA logic was illustrated in Section 3.1 in report Deliverable 1.1 [1]. The remote voltage monitoring devices, i.e., metrology and communications units (MCUs), are installed at the mid and end points of the LV feeders. These MCUs send the voltage values to a remote terminal unit (RTU) located at the substation. In this case, the RTU is a physical device in which the control logic is coded. Based on this logic, the RTU can then send to the tap changer controller a command to produce a set-point voltage that ultimately alleviates any potential issue.

2.4.2 Control Logic

For the LoVIA the set-point voltage is changed according to the measured voltages at the busbar as well as mid and end points. Consequently, if needed, this set-point is changed as frequently as the control cycles.

Considering the busbar voltage as a reference, a compensating voltage (ΔV_i) for the control cycle i is calculated taking into account the monitoring voltages. The new set-point voltage ($V_{set\ i+1}$) is then obtained by the difference between the monitoring busbar voltage ($V_{busbar\ i}$, average of the control cycle) and the compensating voltage (ΔV_i), as shown in (3). This process takes place every control cycle (e.g., every 5 minutes, every 15 minutes, etc.).

$$V_{set\ i+1} = V_{busbar\ i} - \Delta V_i \quad (3)$$

To calculate the compensating voltage, three voltage zones have been defined as presented in Table 2. If voltages at the mid and end points breach the statutory limits, i.e., either higher than 253V or lower than 216V, they are in the red zone. When voltages are up to 2% close to the boundary, i.e., from 248 to 253V and from 216 to 221V, then they are considered to be in the orange zone. Finally, voltages between 221 and 248V correspond to the green zone. The latter is the ideal zone.

Table 2 Compensating voltage factor according to the voltage zones

Minimum \ Maximum	Red >253V	Orange 253V≥. ≥248V	Green 248V>. ≥221V	Orange 221V>. ≥216V	Red <216V
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

By determining how far the monitoring voltages, in particular the maximum and minimum values, are from the ideal range (i.e., the green zone) it is possible to estimate the needed compensation at the busbar voltage. The latter, however, has to be estimated considering the tap steps that the OLTC might require. This estimation is presented in Table 2 where each value corresponds to a factor that should be multiplied by $V_{one-tap}$.

Therefore, for a given control cycle i, first the voltage zones of the maximum and minimum of all the mid and end point voltages are determined. The compensating voltage (ΔV_i) is then obtained by multiplying the corresponding factor in Table 2 and $V_{one-tap}$ equal to 4.6V (2% tap step [3]).

The main difference of the above logic with that presented in Deliverable 1.1, is that here any voltage within the green zone is an ideal voltage, i.e., no set-point changes are required. The previous logic required voltages within the green zone to be brought to a value much closer to a ‘typical’ voltage (e.g., 240V). This previous requirement led to a higher number of tap changes particularly for high PV penetrations (more than 50%). For lower penetrations, both logics had almost the same performance.

2.5 Summary

Three OLTC-based control strategies are presented in this section.

- **Constant Set-point Control (CSC)**. The set-point voltage keeps a fixed value, i.e., 240.2V, line-to-neutral, 1.04 p.u., all the time throughout the year.

- **Time-based Control (TC).** The set-point voltage is changed according to the time of the day. A lower set-point voltage, 237.9V, 1.03 p.u., is set during minimum demand and a higher set-point voltage, 242.5V, 1.05 p.u. during the peak. Daily schedules are slightly modified per season to account for daylight hours.

- **LoVIA Logic Control.** The set-point voltage 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) have been defined. 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 at the busbar voltage, and provides the corresponding set-point voltage.

3 Performance of the OLTC-based Control Strategies

3.1 Case Study

The control strategies Constant Set-Point Control (CSC), Time-Based Control (TC), and LoVIA are applied to the trial network *Landgate* to assess the corresponding performances.

The network *Landgate* is modelled in the distribution system analysis software package OpenDSS [4] and the CREST tool [5] is used to generate the load and PV profiles. Details of the network models, the load and PV profiles and the real OLTC data used in the trial network can be found in Deliverable 1.1 [1]. Three-phase time-series (1-minute resolution) power flow simulations are carried out to simulate the network and the corresponding control strategies.

Different PV penetrations (from 0 to 70%) are studied. In this report, the PV penetration is calculated by the number of houses having PV systems installed in relation to the total number of houses. For a certain penetration, PV systems are randomly allocated assuming all feeders have the same penetration level. Due to the area of LV networks, for a given day, all PV systems are considered to have the same generation profile.

The aggregated daily load profiles (weekday, July) of the network with 0, 30, and 70% PV penetrations are illustrated in Figure 1. A negative power consumption means reverse power flows upstream. 70% was considered as the highest PV penetration as the peak reverse power reaches the transformer rating (i.e., 500kVA).

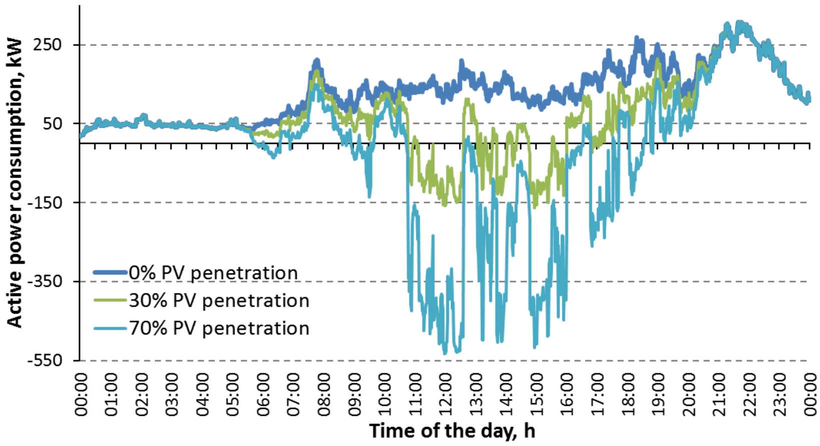

Figure 1 The aggregated daily load profiles (weekday, July) of the network

To assess the performance of the voltage control strategies, power flow simulations are carried out on a weekly basis using the deterministic and Monte Carlo-based analysis methods, respectively. In addition, the performances in three seasonal categories, i.e., summer, spring/autumn and winter, are also investigated. For comparison purposes, the network equipped with off-load tap changer is also analysed considering a suitable tap position to cope with PV systems (+2.5%, i.e., 244V, corresponding to tap position 4).

It is important to highlight that the bandwidth used in the simulations for all the control strategies is 2.2% (i.e., +/- 1.1%). This is more conservative than the one used in the trial, but it is deemed necessary in order to analyse the performance of different OLTC control strategies. Note that this total bandwidth, i.e., 2.2% in the simulation case, is –as required– larger than $V_{one-tap}$, (2%). The tap operation delay is 120 seconds. These values are used in all simulations in this report.

3.2 Deterministic Analysis

In each of the three seasonal categories, a week-long deterministic power flow simulation is carried out to show the performance of the corresponding control strategies.

3.2.1 Summer

Figure 2, Figure 3 and Figure 4 show the profiles for a week in July (representing the summer) with a 70% PV penetration for the CSC, TC and LoVIA strategies, respectively. The set-point voltage, the corresponding tap position and the busbar voltage profiles are plotted.

For the LoVIA, 5, 15 and 30-min control cycles are investigated. 5-min is considered as the shortest control cycle so as to cater for the communication and tap operation delay times. Detailed results for the 30-min control cycle are presented in Figure 4. Note that this control cycle length was adopted in the trial networks.

For the studied summer week, the CSC, TC and LoVIA strategies resulted in 8.3, 7.7 and 5.4% of the 351 customers with BS EN50160 non-compliant voltages. This shows a clear improvement when adopting the remote control, particularly in comparison with the off-load tap changer (41.5%). In terms of the usage of the OLTC, for this week each of the control strategies required 114, 80 and 19 tap changes, respectively. In this case, the LoVIA resulted in just a fraction of the tap changes needed by other two strategies.

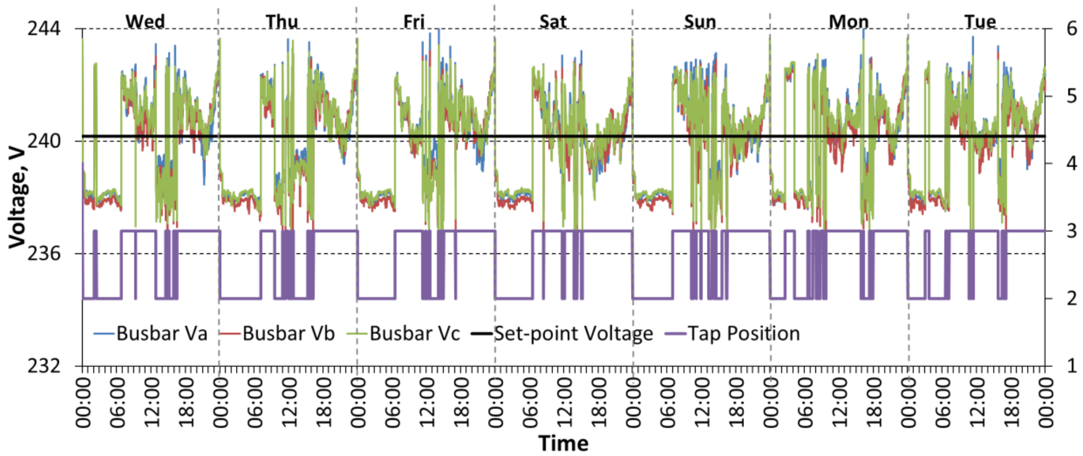

Figure 2 Summer week busbar voltage profiles and tap position by CSC

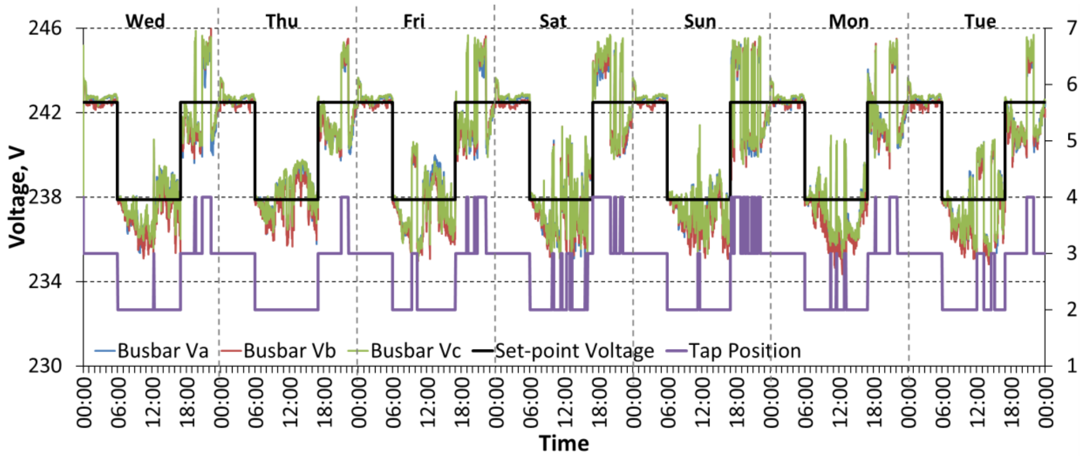

Figure 3 Summer week busbar voltage profiles and tap position by TC

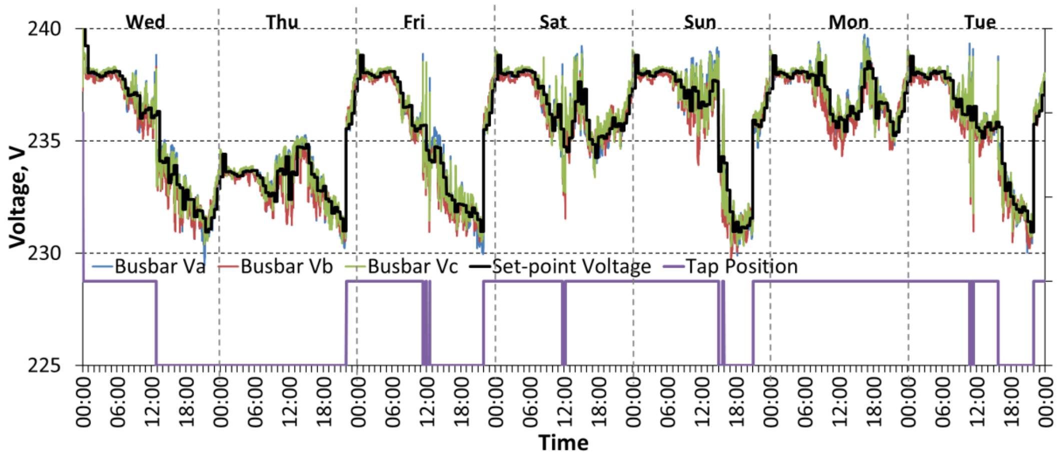

Figure 4 Summer week busbar voltage profiles and tap position by LoVIA, 30-min control cycle

3.2.2 Spring/Autumn

Figure 5, Figure 6 and Figure 7 show the profiles for a week in October (representing the spring/autumn) with a 70% PV penetration for the CSC, TC and LoVIA strategies, respectively. The set-point voltage, the corresponding tap position and the busbar voltage profiles are plotted.

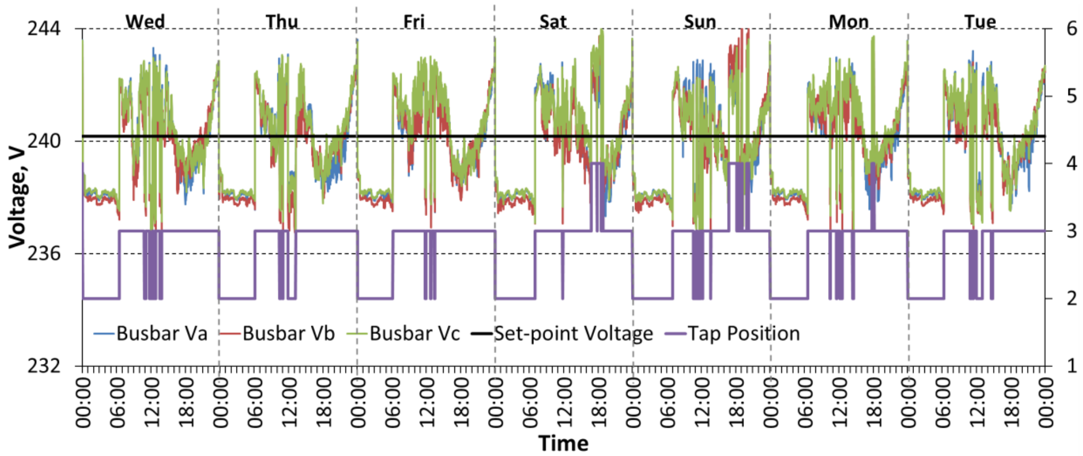

Figure 5 Spring/autumn week busbar voltage profiles and tap position by CSC

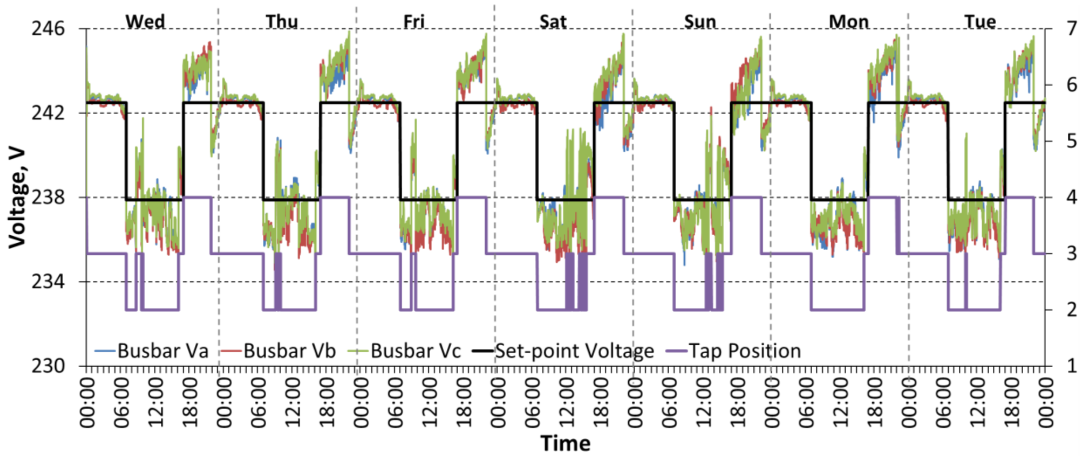

Figure 6 Spring/autumn week busbar voltage profiles and tap position by TC

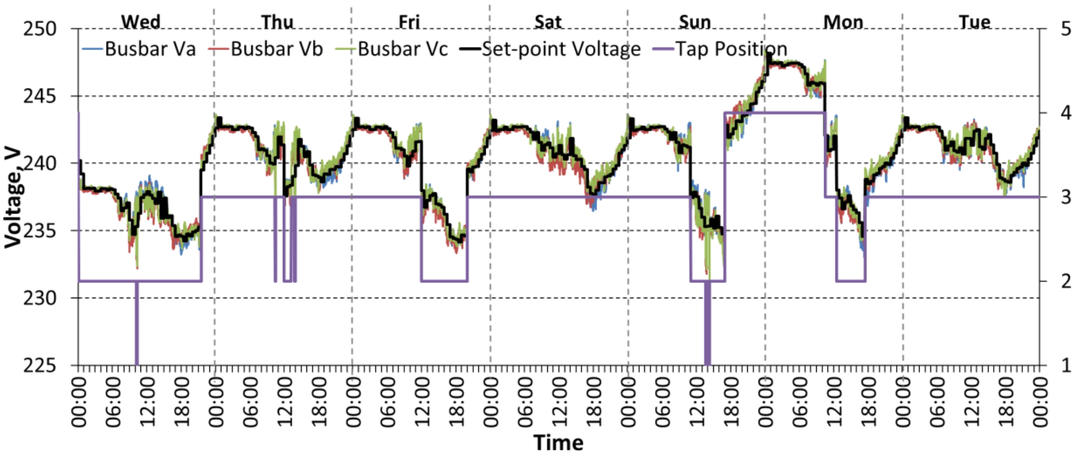

Figure 7 Spring/autumn week voltage profiles and tap position by LoVIA, 30-min control cycle

For the studied autumn week, the CSC, TC and LoVIA strategies resulted in 0.9, 0 and 4.3% of the 351 customers with BS EN50160 non-compliant voltages. While the off-load tap changer resulted in 25.4% non-compliant customers. In terms of the usage of the OLTC, for this week each of the control strategies required 86, 64 and 24 tap changes, respectively. The LoVIA also required the fewest number of the tap changes.

3.2.3 Winter

Figure 5, Figure 6 and Figure 7 show the profiles for a week in January (representing the winter) with a 70% PV penetration for the CSC, TC and LoVIA strategies, respectively. The set-point voltage, the corresponding tap position and the busbar voltage profiles are plotted.

For the studied winter week, the CSC, TC and LoVIA strategies resulted in 0, 0 and 0.3% of the 351 customers with BS EN50160 non-compliant voltages. While the off-load tap changer resulted in 8.0% non-compliant customers. In terms of the usage of the OLTC, for this week each of the control strategies required 34, 72 and 10 tap changes, respectively. The LoVIA also required the fewest number of the tap changes.

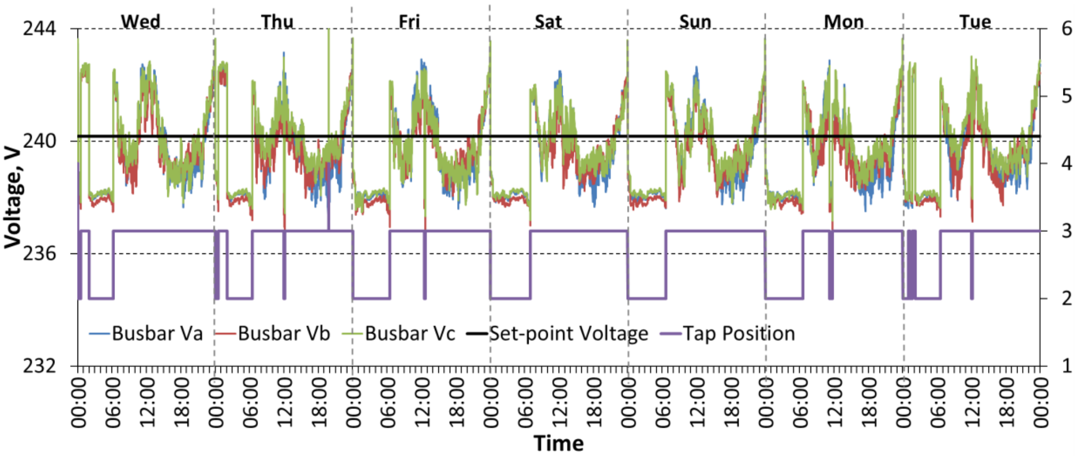

Figure 8 Winter week voltage profiles and tap position by CSC

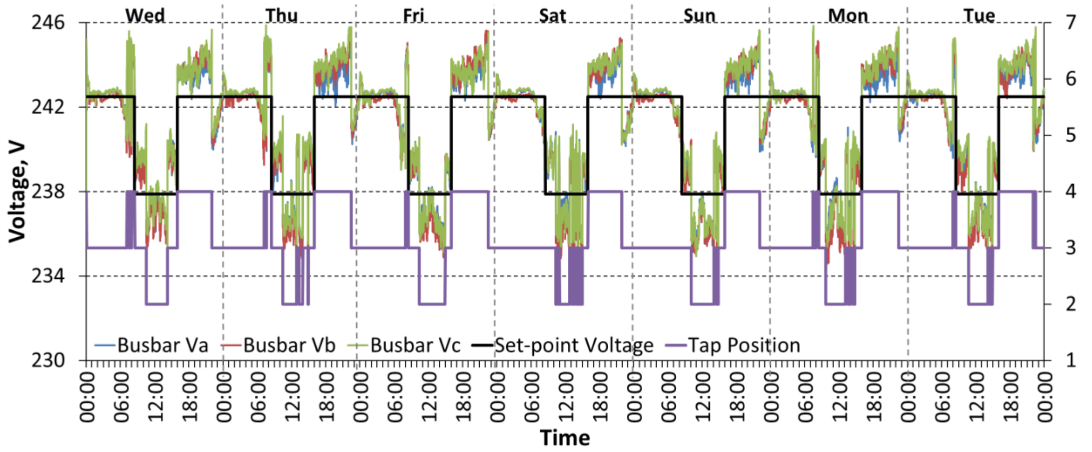

Figure 9 Winter week voltage profiles and tap position by TC

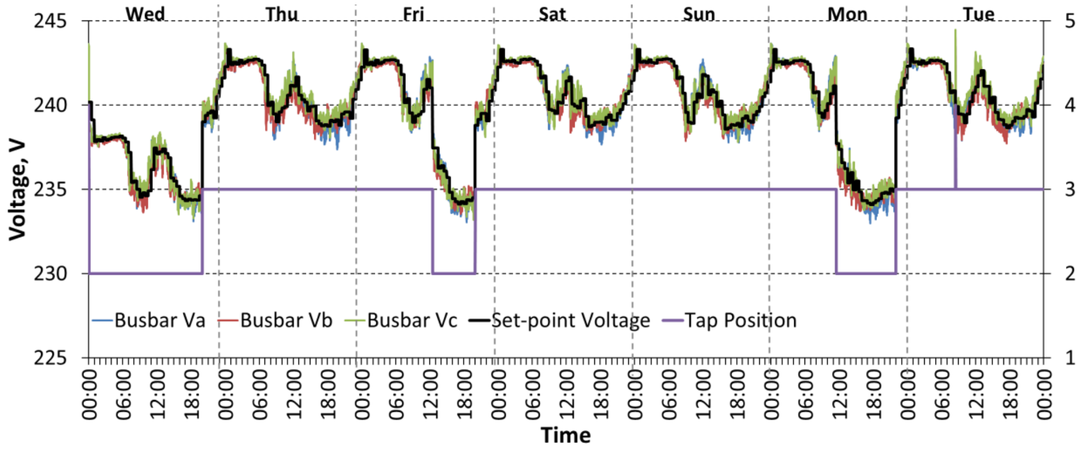

Figure 10 Winter week voltage profiles and tap position by LoVIA, 30-min control cycle

3.2.4 Season-Weighted Average

The performance metrics of the week-long deterministic analysis for the three seasonal categories are shown in Table 3. The season-weighted average, i.e., annual average, is calculated by adopting a weight of 1 for summer, 2 for spring/autumn, and 1 for winter. The results show a significant improvement in voltages when adopting the OLTC, in comparison with the off-load tap changer. For the analysed PV penetration of 70%, the TC strategy resulted in a better mitigation of voltage issues and also a smaller number of tap changes than CSC. However, the LoVIA strategy (using 5 and 15-min control cycle) resulted in the best performance for mitigating voltage issues and with only 30% of the tap operations needed by CSC or TC.

Table 3 Seasonal and annual performance of the week-long deterministic analysis

Metric	Control strategies	Summer	Spring/Autumn	Winter	Season weighted average
Non-compliant customers, % (in a week)	Off-load tap changer	41.5	25.4	8.0	25.1
	CSC	8.3	0.9	0	2.5
	TC	7.7	0	0	1.9
	LoVIA (5-min)	1.4	0	0	0.4
	LoVIA (15-min)	0.85	3.1	0.85	2.0
	LoVIA (30-min)	5.4	4.3	0.3	3.6
Daily average number of tap changes	CSC	16.3	12.3	4.9	11.5
	TC	11.4	9.1	10.3	10.0
	LoVIA (5-min)	4.4	4.6	2	3.9
	LoVIA (15-min)	3.3	2.7	1.3	2.5
	LoVIA (30-min)	2.7	3.4	1.4	2.8

3.3 Monte Carlo Analysis

In each of the three seasonal categories, fifty simulations (each representing a week in that corresponding season) are carried out to extend the potential diversity in PV generation and household demand.

3.3.1 Summer

The average and standard deviation of the percentage of non-compliant customers for different control strategies in July (representing the summer) are shown in Figure 11. The daily average number of tap changes and the corresponding standard deviation are shown in Figure 12.

As seen in Figure 11, with the off-load tap changer customers present voltage issues from 20% of PV penetration. With a 70% penetration, nearly half of the customers are non-compliant with BS EN50160. On the other hand, with the OLTC, disregarding the control strategy, it is only until 40% of PV penetration that customers might experience voltage problems. The three control cycles (5, 15 and 30-min) investigated for the LoVIA strategy outperformed the CSC and TC in terms of voltages. The LoVIA also resulted in the fewest tap operations in all PV penetrations. Interestingly, although the TC has a better performance than CSC in terms of voltages, this is mostly done at the expense of more tap operations.

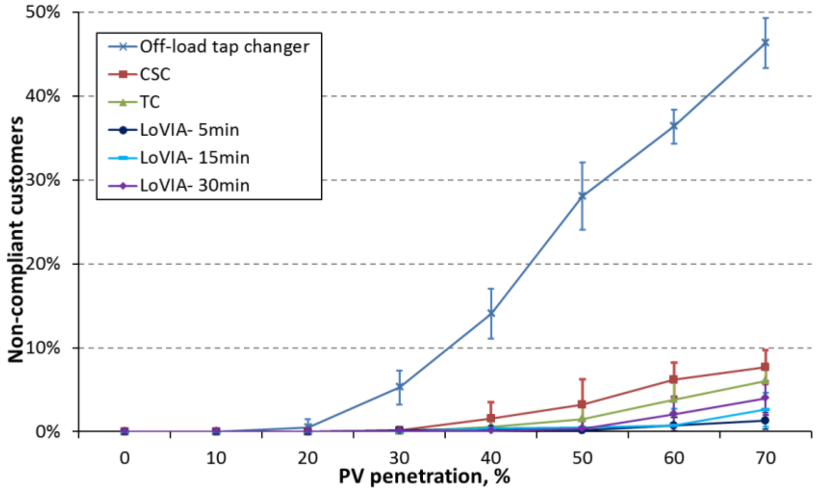

Figure 11 Customers with voltage problems – comparison (summer)

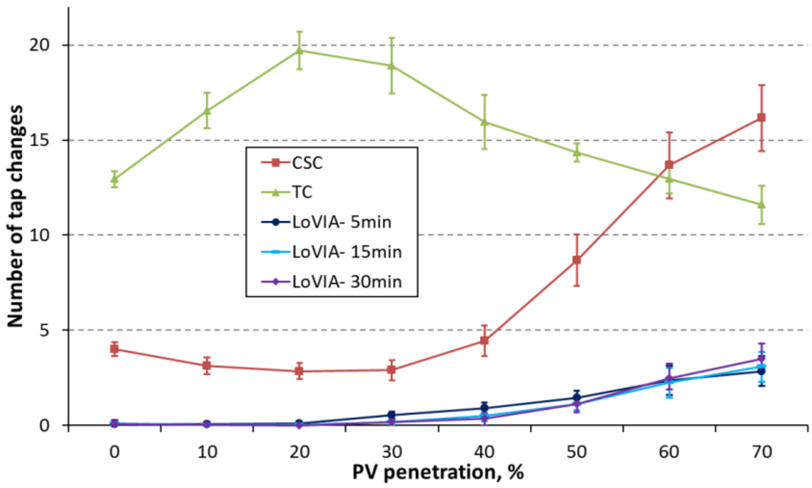

Figure 12 Daily average number of tap changes – comparison (summer)

3.3.2 Spring/Autumn

The average and standard deviation of the percentage of non-compliant customers for different control strategies in October (representing the spring/autumn) are shown in Figure 13. The daily average number of tap changes and the corresponding standard deviation are shown in Figure 14.

As seen in Figure 13, with the off-load tap changer customers present voltage issues from 40% of PV penetration. With a 70% penetration, a fourth of the customers are non-compliant with BS EN50160. On the other hand, with the OLTC, disregarding the control strategy, it is only until 50% of PV penetration that customers might experience voltage problems. The TC strategy, which resulted in zero non-compliant customers in all PV penetrations, outperformed the CSC and LoVIA in terms of voltages, but this is mostly done at the expense of more tap operations than the other strategies.

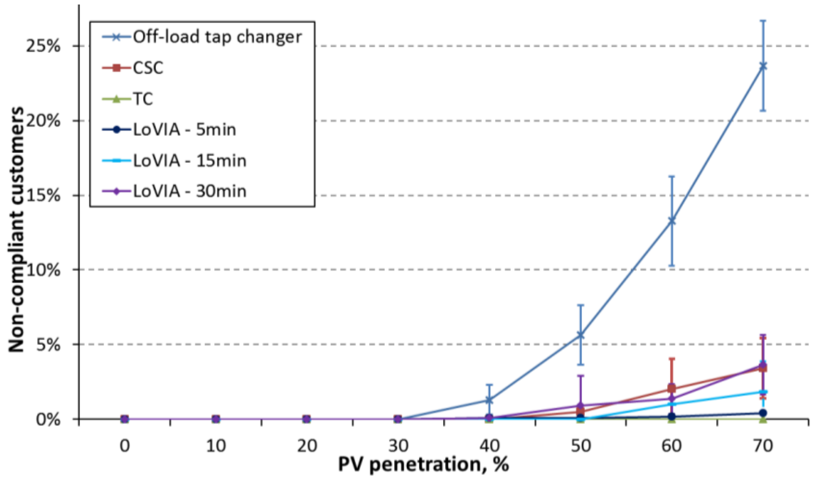

Figure 13 Customers with voltage problems – comparison (spring/autumn)

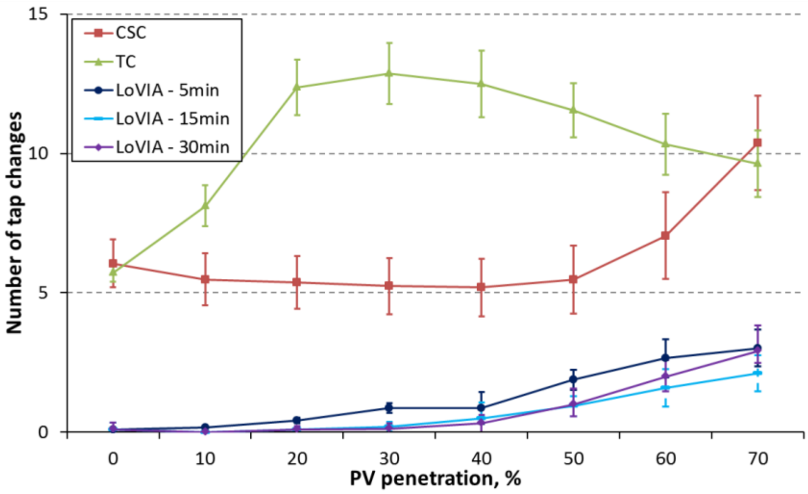

Figure 14 Daily average number of tap changes – comparison (spring/autumn)

3.3.3 Winter

The average and standard deviation of the percentage of non-compliant customers for different control strategies in January (representing the winter), are shown in Figure 15. The daily average number of tap changes and the corresponding standard deviation are shown in Figure 16.

As seen in Figure 15, with the off-load tap changer customers present voltage issues from 50% of PV penetration. With a 70% penetration, less than 6% of the customers are non-compliant with BS EN50160. On the other hand, with the OLTC, disregarding the control strategy, it is only until 60% of PV penetration that customers might experience voltage problems. The TC strategy, which resulted in zero non-compliant customers in all PV penetrations, outperformed the CSC and LoVIA in terms of voltages, but this is mostly done at the expense of more tap operations than the other strategies.

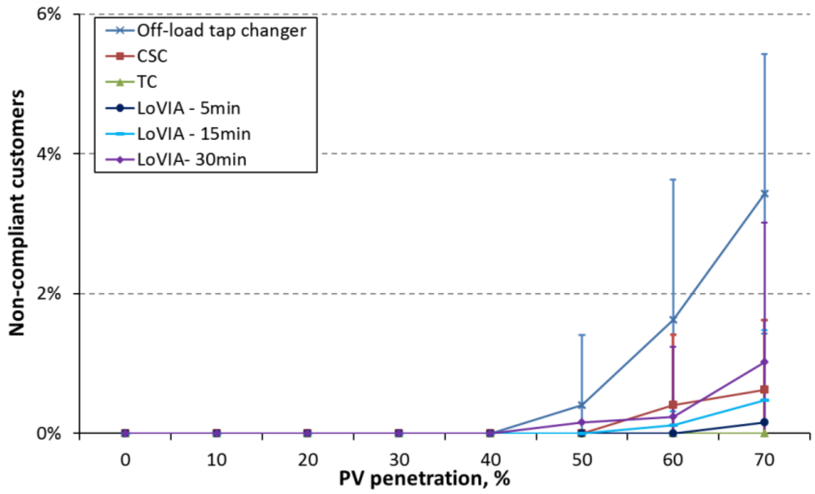

Figure 15 Customers with voltage problems – comparison (winter)

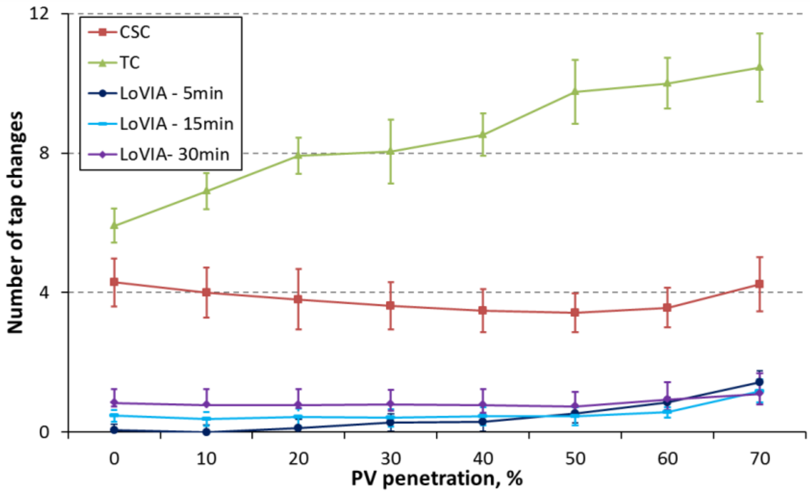

Figure 16 Daily average number of tap changes – comparison (winter)

3.3.4 Season-Weighted Average

The season-weighted average (i.e., annual average) performance metrics for the Monte Carlo analysis are shown in Figure 17 and Figure 18. As seen in Figure 17, 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. On the other hand, with the OLTC, disregarding the control strategy, it is only until 50% of PV penetration that customers might experience voltage problems. Considering the voltages as well as the use of the OLTC, the LoVIA strategy outperformed the CSC and TC. In terms of control cycles, the 5-min control cycle resulted in fewer non-compliant customers, but more tap changes than the other two control cycles. Although the TC has a good performance in terms of voltages, this is mostly done at the expense of more tap operations.

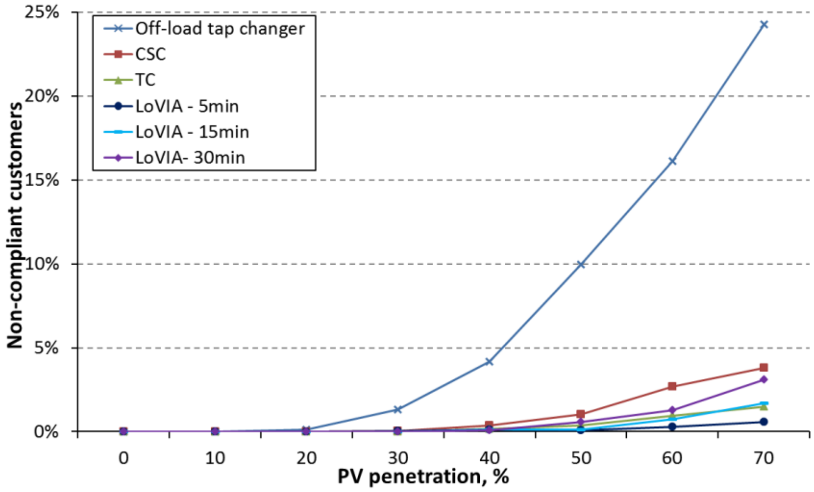

Figure 17 Customers with voltage problems – comparison (season-weighted average)

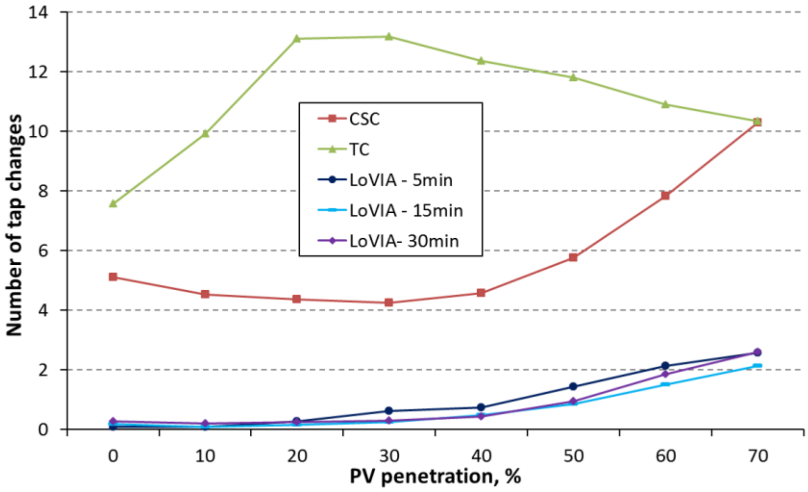

Figure 18 Daily average number of tap changes – comparison (season-weighted average)

3.4 Monte Carlo Analysis vs Deterministic Analysis

For the deterministic analysis, the results are limited to the specific week analysed and therefore cannot be generalised. For example, both the CSC and TC control strategies resulted in zero non-compliant customers during winter (Table 3). However, due to the uncertainties of PV generation and demand, results could be different in another simulated week. These uncertainties, however, are catered for when adopting the Monte Carlo analysis. Due to the multiple simulations (fifty) carried out, the average and standard deviations are obtained as a way to generalise the results. This can show not only the number of non-compliant customers and the tap changes for the corresponding control strategies, but also the likelihood of these values. Therefore, by using the Monte Carlo analysis it is possible to show a much more general picture of the results of interest.

3.5 Discussion

The same PV penetration is considered among all of the 6 feeders in all simulations. However, in practice, different feeders may have different PV penetrations. Dissimilar penetrations per feeders should be considered as it is crucial to understand the extent to which the use of OLTC-fitted transformers provides voltage management flexibility.

The LoVIA is the best 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.

3.6 Summary

The control strategies CSC, TS, and LoVIA have been applied to the trial network *Landgate* to assess the corresponding performances. Power flow simulations are carried out on a weekly basis using the deterministic and Monte Carlo-based analysis methods and also considering three seasonal categories, i.e., summer, spring/autumn and winter.

The season-weighted average (i.e., annual average) shows that with the off-load tap changer customers present voltage issues from 30% of PV penetration. With a 70% penetration (the maximum possible for *Landgate* due to congestion issues), one in four customers in the network would be 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. The Monte Carlo analysis showed that considering the voltages as well as the use of the OLTC, the LoVIA strategy outperformed the CSC and TC. Although the TC has a good performance in terms of voltages, this is mostly done at the expense of more tap operations. Indeed, for PV penetrations above 50%, the TC strategy leads to a mitigation of voltage issues comparable to that of the LoVIA but it requires five times the number of tap operations.

4 Performance of the Deployed LoVIA Logic in *Landgate* and *Leicester Ave*

The LoVIA strategy was commissioned in the real OLTC-fitted transformers in *Landgate* and *Leicester Ave* on 13th and 14th May 2014, respectively. The bandwidth set to both of the OLTCs is +/- 2.2%, the tap operation delay is 120 seconds and the control cycle is 30 minutes.

The data of the tap position and the monitoring voltages at the busbar as well as the mid and end points of the LV feeders are recorded and can be extracted from the corresponding human machine interface (HMI). The data made available for this analysis starts on 27th June 2014.

The behaviour of the real OLTC-fitted transformers in *Landgate* and *Leicester Ave* are shown in Figure 19 and Figure 21. The blue line represents the measured busbar line-to-line voltage divided by 4, which is obtained from the measurement of the TAPCON 230. 104 is equal to 1.04 p.u. (240.2V line-to-neutral). As shown in Figure 19 and Figure 21, when using the LoVIA logic, the set-point follows the trend of the busbar voltage and estimates the needed compensation. For a given set-point, the actual tap change occurs if the bandwidth has been exceeded for longer than a pre-defined delay.

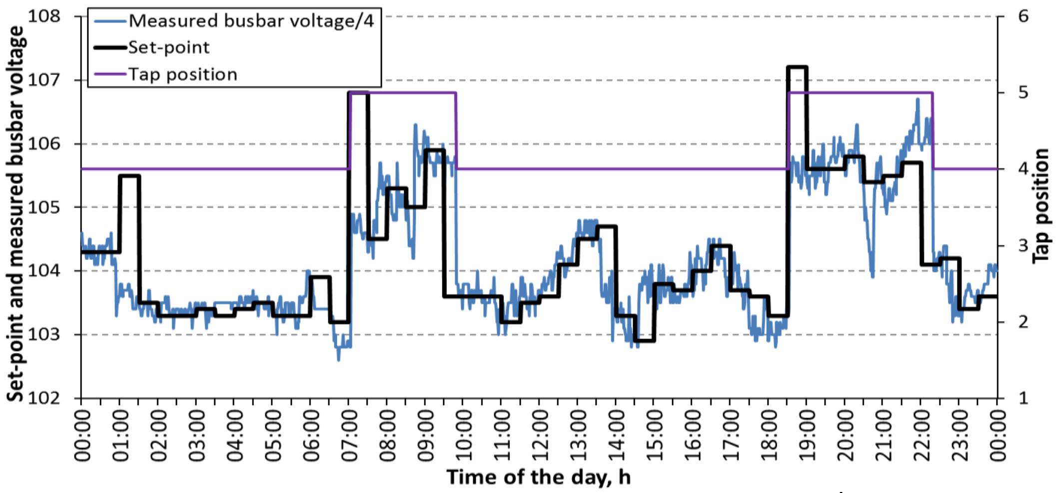

Figure 19 Actual tap operation of the OLTC in Landgate on 22nd August 2014

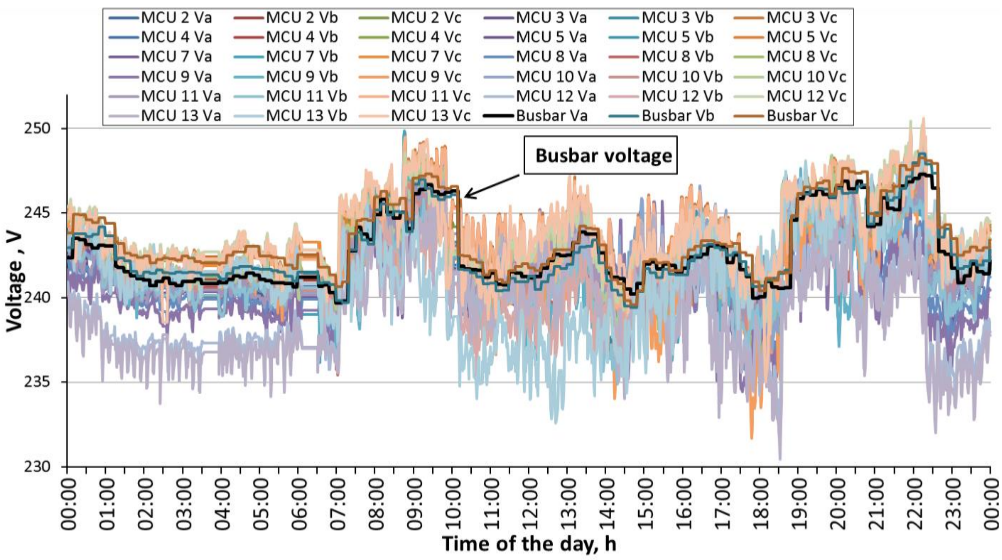

Figure 20 Monitoring voltages in *Landgate* on 22nd August 2014

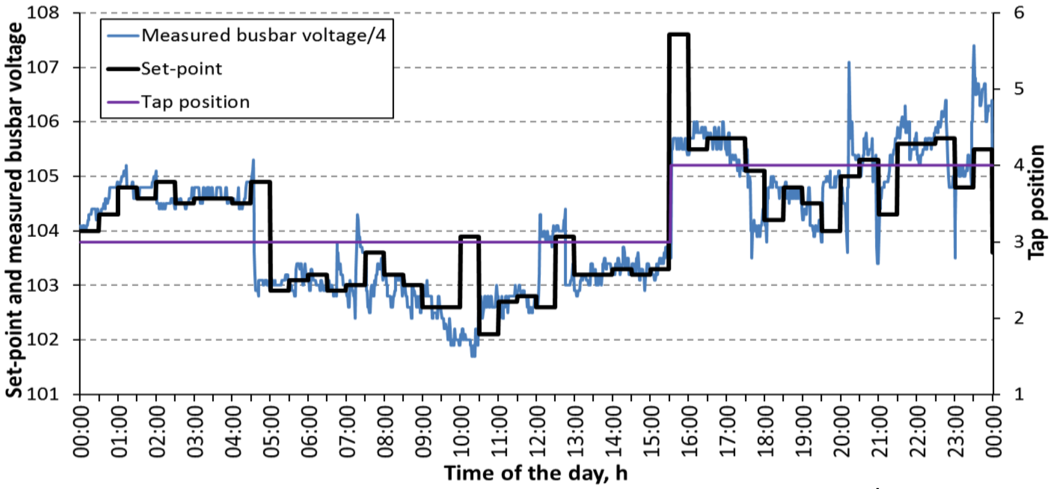

Figure 21 Actual tap operation of the OLTC in *Leicester Ave* on 19th July 2014

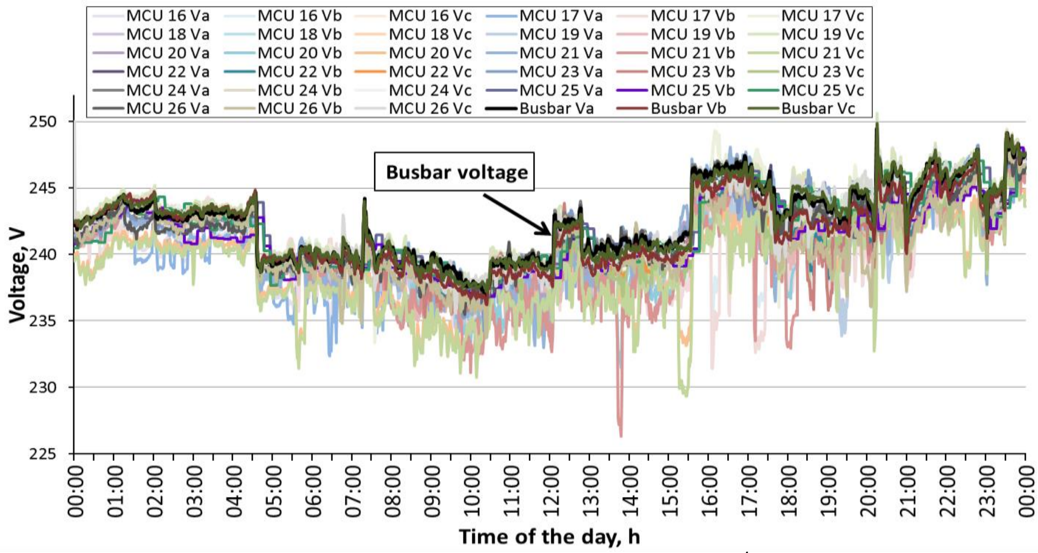

Figure 22 Monitoring voltages in *Leicester Ave* on 1st September 2014

Figure 20 presents the monitoring voltages at the busbar as well as the mid and end points for *Landgate* on 22nd August. The MCUs 2 to 13 correspond to the monitoring at the mid and end points of the 6 LV feeders (data for MCU 6 was not available). Similarly, Figure 22 presents the monitoring voltages for *Leicester Ave*. The MCUs 16 to 27 correspond to the monitoring at the mid and end points of the 6 LV feeders (data for MCU 27 was not available).

From Figure 20 it can be seen that when the household demand in *Landgate* started to increase at 07:00, the deployed LoVIA logic led to a significant increase for the set-point. As a result, as shown in Figure 19, the OLTC had one tap operation (from position 4 to 5) to increase voltages of the LV feeders. When the net demand decreased (due to PV generation and/or lower demand), a lower set-point was given, moving the tap back to position 4 at 9:30. A similar process happened in the evening (18:30 to 22:00) when demand increased.

For *Leicester Ave* (Figure 21), tap operations only happened once (from position 3 to 4) at 15:30 – when the household demand increased. The tap was kept in the position for the rest of the day. Based on Figure 19 and Figure 21 it can be said that, for the two networks with current PV penetration of approximately 30%, the tap operation mainly occurs in response to the variation in household demands (tap positions go up) rather than the stochastic variation in PV generation.

At the time of writing of this report, monitoring data from 27th June to 18th October were made available for both networks. However, some data was missing during several days or hours, e.g., no data exist from 10th to 15th July and 8th to 15th August. In addition, the tap was in a fixed position from 23rd June to 6th August 2014 in *Landgate* and 2nd September to 2nd October 2014 in both networks and hence the performance of the LoVIA logic could not be assessed during these periods of time. Consequently, the analysis of data was limited to 5 weeks and 2 days for *Landgate* and 10 weeks and 3 days for *Leicester Ave*.

According to the analysed data, monitoring voltages at all mid and end points of the LV feeders were within statutory limits. In addition, there were 50 tap operations (1.4 per day on average) in *Landgate* and 136 in *Leicester Ave* (1.9 per day on average).

It is important to highlight that the bandwidth of the deployed LoVIA logic is twice larger than that of the simulations. Although this setting makes the deployed control less sensitive, the overall performance was aligned with those find through simulations (see Figure 17 and Figure 18 for 30% of PV penetration). Therefore, it can be concluded that the LoVIA control strategy has performed as expected in the two networks.

5 Conclusions

According to the power flow analyses carried out in this report and the performance of the control strategy in the real networks, the following conclusions have been drawn:

- **Performance of the OLTC control strategies.** The Monte Carlo season-weighted average shows that 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 Time-Based Control (TC) strategy results in a better mitigation of voltage issues than Constant Set-Point Control (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.

- **Deployed LoVIA Control in *Landgate* and *Leicester Ave* Networks**. These two networks have an approximate PV penetration of 30%. According to the monitoring data during the summer and autumn of 2014 (5 weeks and 2 days for *Landgate* and 10 weeks and 3 days for *Leicester Ave*), voltages at all mid and end points of the LV feeders were within the statutory limits. There were 50 tap operations (1.4 per day on average) in *Landgate* and 136 in *Leicester Ave* (1.9 per day on average). These values are aligned with those find through simulations. Therefore, it can be concluded that the LoVIA control strategy has performed as expected in the two networks.

6 References

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