

Title: **Report for Deliverable 1.1 "Creation of initial models and AVC control logic"**

Synopsis: This document presents initial LV network, load and low-carbon technology models for the substations *Landgate* and *Leicester Avenue*. The initial voltage control logic for the corresponding on-load tap changers is also presented. These models provide a solid foundation for the LV network simulations to be carried out and the further development of control logic within the LoVIA project.

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Executive Summary

This report corresponds to Deliverable 1.1 "Creation of initial models and AVC control logic" 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 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.

This document presents initial LV network, load and low-carbon technology models for the substations *Landgate* and *Leicester Avenue*. The initial voltage control logic for the corresponding on-load tap changers is also presented. These models provide a solid foundation for the LV network simulations to be carried out and the further development of control logic within the LoVIA project.

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

- **LV Network Modelling.** The two trial LV networks, *Landgate* and *Leicester Avenue*, have been adequately modelled considering their three-phase nature and single-phase connections. The distribution system analysis software OpenDSS has been used for this purpose.
- **Load Modelling.** The CREST tool, developed by Loughborough University, is used for modelling the domestic load profiles given its high granularity (one minute). The load of each individual household is modelled realistically considering type of day, seasonality, occupancy and the associated use of electrical appliances.
- **PV Modelling.** Monitored sun irradiance from 10 substations (part of the LV Network Solutions project) and the CREST tool are used for modelling the PV generation. The latter takes into account the correlation between the domestic lighting demand and PV generation. These models are then allocated to specific locations and sizes of PV installations.
- **Transformer and On-Load Tap Changer (OLTC) Modelling.** Transformers consider the real transformation ratio (11kV/433V). OpenDSS provides the internal control response of the OLTC considering the manufacturer characteristics (+/-8%, 2% per tap). The main input for the OLTC is the voltage target at the busbar or any remote node.
- **Initial Voltage Control Algorithm.** This initial control logic for regulating voltages at the remote ends of LV feeders categorises monitored voltages in three voltage zones (red, orange and green). Within a control cycle, the monitored voltages are compared to the voltage zones. This comparison is used to calculate a compensating voltage. The voltage target, which is a key input for the OLTC, is determined by the monitored busbar voltage (as a reference) and the calculated compensating voltage. The proposed voltage control logic was tested in *Landgate* and *Leicester Avenue* considering twice the current PV penetration levels (in those feeders already with PV installations). The results show the proposed logic works and keeps the voltages within the statutory limits.

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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 Background

In conventional electrical distribution systems the power flows in one direction, from the network supply point to the consumer. Conventional passive distribution networks are expected to be transformed into active networks, i.e., distribution networks that generate and consume power, due to increasing penetration of distributed generation (DG). In particular, residential-scale PV systems are expected to reach higher penetration levels over the next decades but are already leading to technical challenges in areas where cluster exists.

In an LV network, when the electrical power generated by PV systems exceeds local demand, power flows from the load side upstream to the grid supply point. The voltage at the remote end of the LV feeders can be higher than the busbar of the distribution transformer. According to the standard BS EN 50160, all 10-minute average voltages in LV networks must be within +10% / -15% of nominal, and 95% of the time during a week voltages must be within +10% / -6% [1].

Distribution transformers are typically equipped with off-load tap changers which are set to meet the requirements of the corresponding network. The tap ratio is determined based on current (and future) loading level of the network and estimates of the voltage drop at the end of the feeders. The drawback, however, is that tap positions can only be changed when off-load. Indeed, with the adoption of low carbon technologies such as PV systems or electric vehicles (EVs) a more active management of voltages is required.

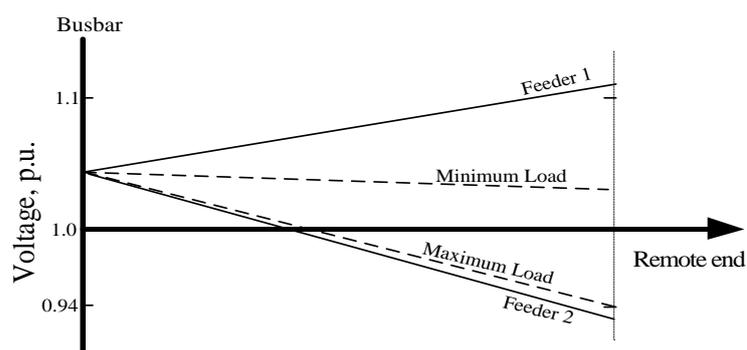


Figure 1 Node voltage at the LV network lines/cables

Figure 1 shows the voltage drop/rise along two LV feeders from the busbar to the remote ends. Dashed lines are for the typical load-led voltages at the maximum and minimum load conditions. With PV systems, voltages could exceed the upper voltage limit (e.g., feeder 1). With new loads, on the other hand, voltage could be lower than lower limit (e.g., feeder 2). The simultaneous presence of these two types of feeders (or similar in behaviour) creates a significant technical challenge in terms of voltage management.

1.2 Deliverable 1.1

The LoVIA project will integrate existing and new LV network equipment such as OLTC transformers, monitoring (including mid and end points of feeders), and capacitor banks to provide coordinated voltage management of LV networks. The suitable voltage control approaches will be developed and implemented through remote terminal units (RTUs) acting as centralised control devices.

In this Deliverable 1.1, first the models and recommendations to date achieved/produced by the Tier 1 projects "LV Network Solutions" and "Voltage Management at LV Busbars" are used to produce models of each of the different voltage regulation devices to be trialled in this project, i.e., LV OLTC transformers and bank of capacitors. The performance of these models will be tested/benchmarked using the LV networks *Landgate* and *Leicester Avenue*. These basic models will first cater for local and independent (i.e., stand-alone) control of the corresponding devices. Of particular interest will be the coordinated control of these devices associated with LV OLTC transformer.

Once the independent models have been produced, the first milestone is to investigate the best strategy for control of the LV OLTC. A brief initial coordinated automatic voltage control (AVC) methodology is also presented here. Figure 2 presents a simple flow diagram representing the process by which the most suitable control approach will be chosen.

This report is structured as follows. First, the two trial networks, i.e., *Landgate* and *Leicester Avenue* are introduced, summarising their main characteristics. Then the application of the Loughborough University CREST tool [2] to produce time-series one-minute resolution domestic load and PV profiles is presented. Finally, a brief initial coordinated AVC methodology is proposed.

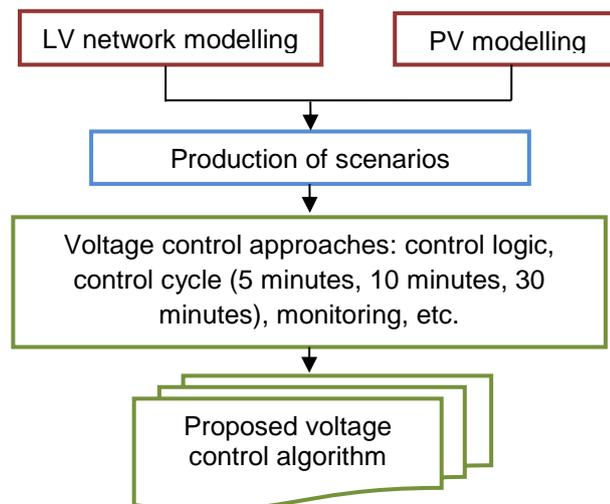


Figure 2 Process to find the most suitable control approach

2 Modelling

2.1 Landgate and Leicester Avenue

Two trial LV networks, *Landgate* and *Leicester Avenue* located in North West of England and operated by ENWL, are analysed in this project as these two networks have already had installed OLTC transformers, monitoring devices and other voltage control equipment. The topology of the two LV networks is shown in Figure 3. Each of the two networks has 6 feeders. The triangles in Figure 3 represent distribution transformers. Different feeders in each LV network are shown in different colours. The general characteristics of the two LV networks are presented in Table 1.

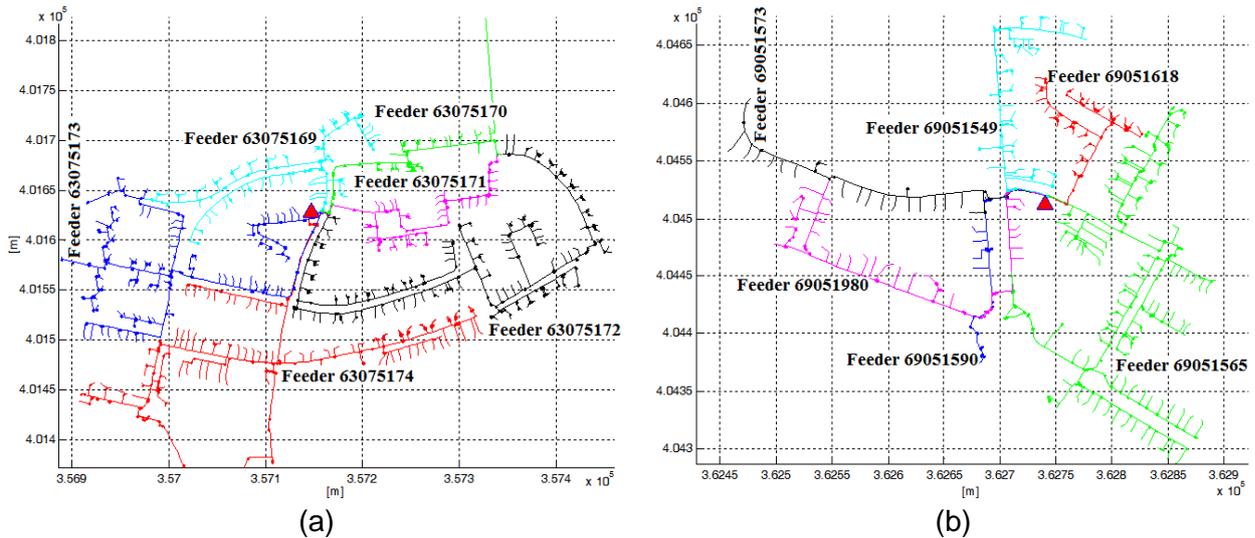


Figure 3 Topology of the two LV networks: (a) *Landgate* (b) *Leicester Avenue*

Table 1 General Characteristics of the two LV networks

LV network	Transformer capacity (kVA)	Number of feeder	Number of customers	Total length of feeders (km)
Landgate	500	6	351	9.3
Leicester Ave.	500	6	175	5.7

In terms of PV panels, there are currently 103 and 39 PV panels installed in *Landgate* and *Leicester Avenue*, respectively. The summary of PV capacity in the two networks is shown in Table 2. The sites where PV panels are located can be seen from Figure 4. Each *orange* dot represents a customer having PV panels installed. The penetration level of PV panels at each feeder is presented in Table 3.

In this report, the PV penetration level is calculated as the number of customers having PV panels installed (disregarding the nominal capacity) in relation to the total number of houses in the corresponding network or feeder.

Table 2 Summary of PV capacity in LV networks *Landgate* and *Leicester Avenue*

Networks	Distribution transformer rating (kVA)	Total number of PV	PV penetration level (%)	Min PV capacity (kW)	Max PV capacity (kW)	Total PV capacity (kW)
Landgate	500	103	29.3	2.0	3.2	269.3
Leicester Ave.	500	39	22.3	1.9	3.84	112.0

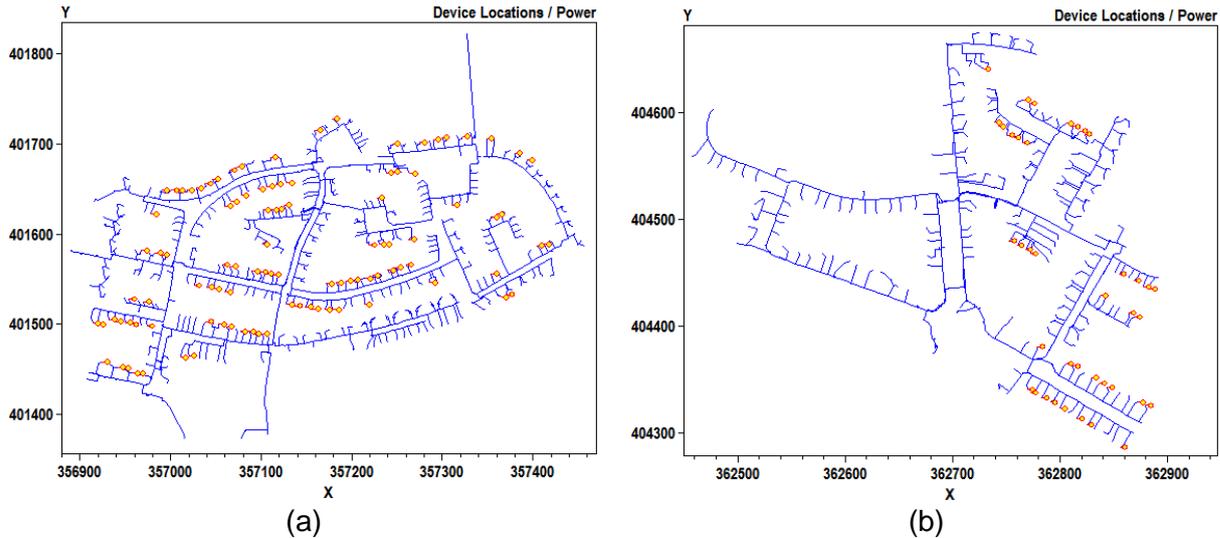


Figure 4 PV geographical distribution of the two LV networks: (a) *Landgate* (b) *Leicester Ave.*

Table 3 Penetration levels of PV panels in LV networks *Landgate* and *Leicester Avenue*

Landgate	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
	Total PV capacity (kW)	48.06	19.86	14.78	66.4	71.54	48.7
	Penetration (%)	38.8	38.1	20	28	35.3	21.7
Leicester Avenue	Feeder ID	69051549	69051565	69051573	69051590	69051618	69051980
	Total Feeder Length (km)	0.77	2.51	0.63	0.32	0.54	0.89
	Customers	20	82	17	4	27	25
	Total PV capacity (kW)	3.36	77.38	0	0	31.3	0
	Penetration (%)	5	32.9	0	0	40.7	0

The *Landgate* and *Leicester Avenue* network models have been retrieved from the "LV Network Solutions" project. They have been modelled using the state-of-the-art, open source distribution system analysis software OpenDSS developed by the Electric Power Research Institute (EPRI, USA). The modelled networks consider the three-phase four-wire nature of the circuits and the single-phase connections of the customers. These detailed modelling allows catering for the actual effects of voltage unbalance (and other phenomenon) found in low voltage networks.

More details of the methodology adopted for the network models can be found in the report "Deliverables 1.3 and 1.4: Creation of non-validated computer-based models of monitored and generic LV networks ready to be used for planning studies" part of the ENWL "LV Network Solutions" project.

2.2 Domestic Load Profiles

An available tool developed by the Centre for Renewable Energy Systems Technology (CREST) at Loughborough University [2] is used for modelling domestic loads given its high time-granularity (one

minute). The load of each individual household is modelled realistically considering type of day, seasonality, occupancy and the associated use of electrical appliances [3]. Figure 5(a) shows a daily (weekday, July) load profile of a household with one occupant and Figure 5(b) shows a daily load profile with two occupants.

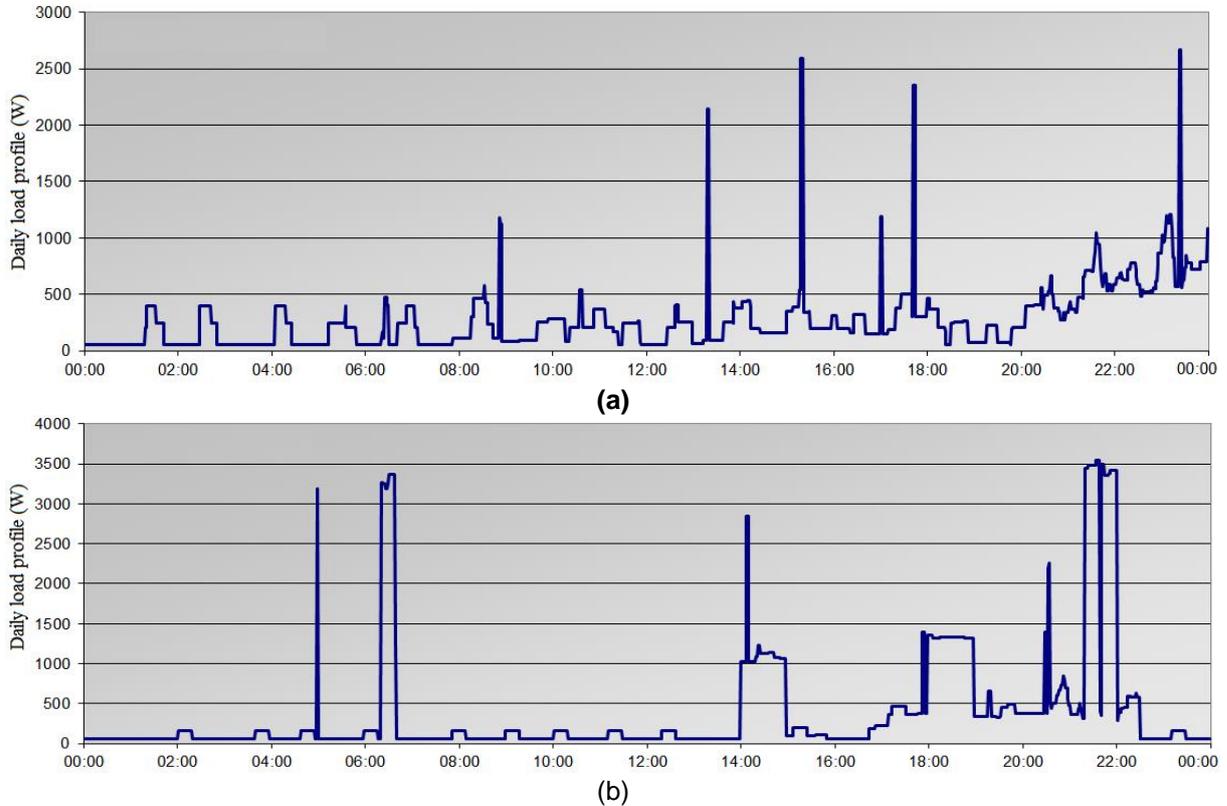


Figure 5 Daily load profile of a household in July: (a) 1 occupant (b) 2 occupants

According to the census conducted by UK Office for National Statistics, the percentage of households in the UK by household size in 2013 is illustrated in Figure 6[4]. In this project, when modelling domestic loads for each feeder of the two trial networks, the percentage of households with different numbers of occupants will be proportional to the percentage shown in Figure 6.

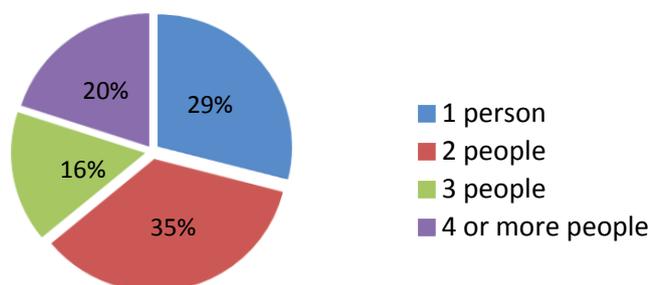


Figure 6 Percentage of households in the UK by household size in 2013 [4]

The geographical distribution of the load in *Landgate* and *Leicester Avenue* is shown in Figure 7. Each orange dot represents a customer (351 customers in *Landgate* and 175 in *Leicester Avenue*). Using the CREST tool, the aggregated load profile (weekday, July) of feeder 63057169 and 63057172, for instance, are illustrated in Figure 8.

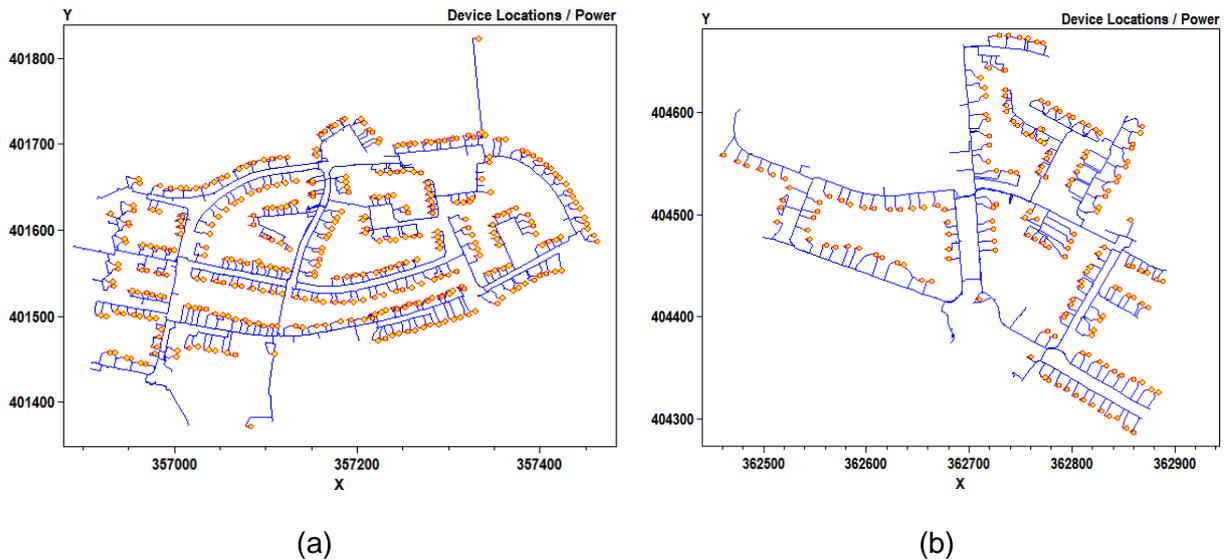


Figure 7 Load geographical distribution the two LV networks: (a) Landgate (b) Leicester Ave.

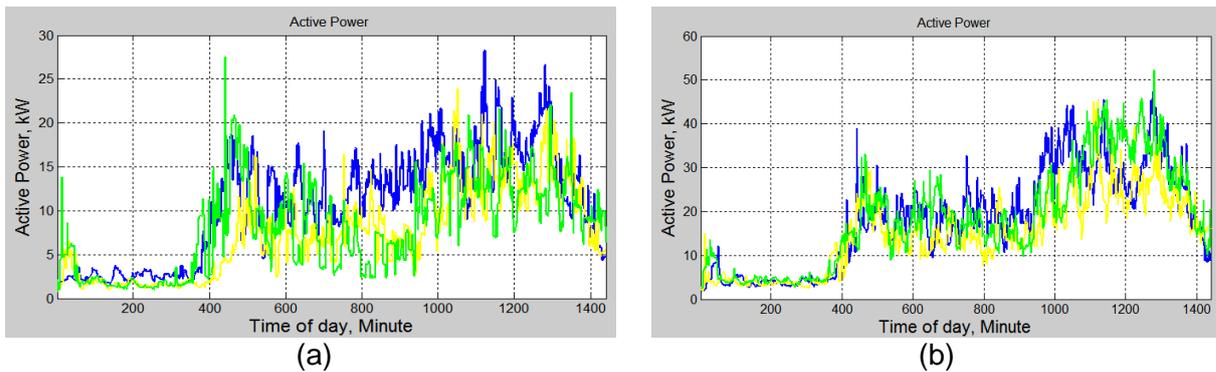


Figure 8 Aggregated daily load profiles per phase of feeders (a) 63057169 (b) 63057172

2.3 Photovoltaic Profiles

The CREST tool [5] is also used for modelling photovoltaic (PV) generation profiles. The domestic PV generation can partially offset the electricity demand within an individual dwelling. PV generation is closely related to the outdoor irradiance, while the domestic electricity demand depends on the use of different appliances including electric lighting, which is also influenced by the level of outdoor irradiance. When modelling the domestic load and the PV generation, the CREST tool considers the outdoor irradiance as a common representation. Therefore, the correlation between the domestic lighting demand and PV generation has been taken into account [6].

In the CREST tool, once the day, number of occupants of a house and the configuration information of the installed PV panel (e.g., location, efficiency, area, etc.) are determined, one-minute resolution load and net radiation profiles can be produced. Both of the profiles correspond to the outdoor irradiance on that day of the year.

As stipulated in Engineering Recommendation G83/1, distributed generation units rated up to 16A per phase can be connected to LV networks [7]. To create a more challenging scenario to the voltage control approaches to be assessed, the rating of all PV panels has been taken as 3.5 kWp. Figure 9 shows a daily (weekday, July) profile of net electricity demand for a house with 2 occupants. The electricity consumption and PV generation at that house are also shown in the figure.

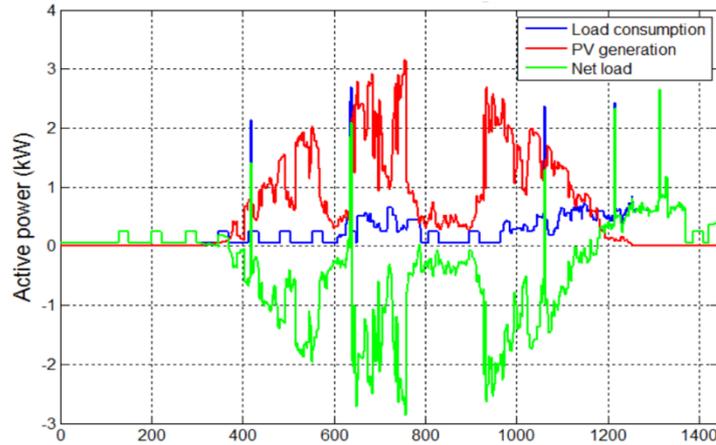


Figure 9 Daily (weekday, July) profile of net electricity demand for a house with 2 occupants

Monitored sun irradiance from 10 substations (part of the "LV Network Solutions" project) will also be used to model PV generation. These particular data will be more realistic (in intensity and cloud transients) as it will be located at or close to the substations of *Landgate* and *Leicester Avenue*.

2.4 Transformer and On-Load Tap Changer Modelling

Transformers for both *Landgate* and *Leicester Avenue* are modelled considering their real transformation ratio of 11kV to 433V. The corresponding on-load tap changers (OLTCs), already installed, have a range of +/- 8% with 2% per tap, i.e., 9 tap positions in total, according to the manufacturer's specifications [8]. Assuming that the voltage at the primary of the HV/LV transformer is the nominal line-to-line voltage (i.e., 11,000V), the voltages at the busbar corresponding to different tap positions are shown in Table 4.

Table 4 Voltage Regulation of MR LV OLTC-fitted transformer

Transformer Tap position	HV	LV	
	L-L (V)	L-L (V)	L-N (V)
9 (+8%)	11000	400.9	231
8 (+6%)	11000	408.5	236
7 (+4%)	11000	416.3	240
6 (+2%)	11000	424.5	245
5 (0%)	11000	433.0	250
4 (-2%)	11000	441.8	255
3 (-4%)	11000	451.0	260
2 (-6%)	11000	460.6	265
1 (-8%)	11000	470.7	271

The embedded OLTC model found in OpenDSS allows the control of the device by providing a new voltage target at every control cycle. This voltage target, either for the busbar or a remote node, is then automatically translated into an internal tap control command to achieve the desired value.

The set of rules or intelligence needed to calculate the most adequate voltage target for different load/generation scenarios in *Landgate* and *Leicester Avenue* networks will be discussed in the following section.

2.5 Summary

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

- **LV Network Modelling.** The two trial LV networks, *Landgate* and *Leicester Avenue*, have been adequately modelled considering their three-phase nature and single-phase connections. The distribution system analysis software OpenDSS has been used for this purpose.
- **Load Modelling.** The CREST tool, developed by Loughborough University, is used for modelling the domestic load profiles given its high granularity (one minute). The load of each individual household is modelled realistically considering type of day, seasonality, occupancy and the associated use of electrical appliances.
- **PV Modelling.** Monitored sun irradiance from 10 substations (part of the LV Network Solutions project) and the CREST tool are used for modelling the PV generation. The latter takes into account the correlation between the domestic lighting demand and PV generation. These models are then allocated to specific locations and sizes of PV installations.
- **Transformer and On-Load Tap Changer (OLTC) Modelling.** Transformers consider the real transformation ratio (11kV/433V). OpenDSS provides the internal control response of the OLTC considering the manufacturer characteristics (+/-8%, 2% per tap). The main input for the OLTC is the voltage target at the busbar or any remote node.

3 OLTC-Based Voltage Regulation

3.1 LoVIA Architecture

A schematic of the project's communication, monitoring and control architecture is shown in Figure 10. The metrology and communications units (MCUs) are installed at the mid and end points of LV feeders. The MCU is connected to the nearby sensors that are monitoring voltage and current. The MCU sends monitoring data to remote terminal unit (RTU) located at the LV distribution substation. Thereafter, the RTU is able to obtain all the voltage and current data of the LV feeders. With the voltage control logic programmed in the RTU, RTU will send the target busbar voltage command to the OLTC tap controller—TAPCON230. All the corresponding data, including tap changing information, can be accessed by the human machine interface (HMI) or the remote web access.

In addition, capacitor banks are to be installed on the feeders with larger loads or no PV installations. The control of these capacitors banks will ultimately be coordinated with the OLTC in a centralised fashion by the RTU.

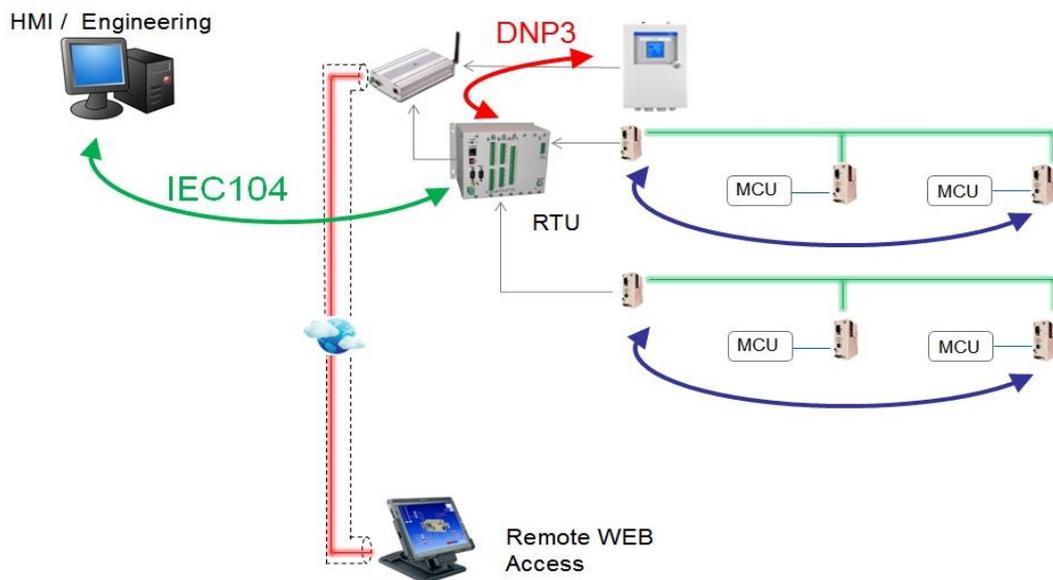


Figure 10 LoVIA Project Architecture (reproduced from [9])

3.2 Automatic Voltage Control Logic

The automatic voltage control logic is to change the busbar voltage target at different times of the day, considering voltages at the busbar as well as mid and end points.

The voltage target, as a key input for the OLTC, will be determined for every control cycle. Considering the busbar line-to-neutral (L-N) voltage as a reference, a compensating voltage, V_{comp} , is calculated by a voltage control logic that takes into account the monitoring voltages. The new voltage target ($V_{new\ target}$) is then obtained by comparison with the monitored L-N busbar voltage (V_{busbar}) and the compensating voltage (V_{comp}). This process takes place every control cycle (e.g., every 5 minutes, every 10 minutes, etc.).

$$V_{new\ target} = V_{busbar} - V_{comp} \quad (1)$$

The monitoring data from mid and end point voltages come from MCUs. However, for the busbar voltages it is proposed the use of the monitoring data directly used by the TAPCON230. This is mainly for consistency given that the TAPCON230 will ultimately control voltages based on its busbar

measurements. Beyond the LoVIA project, in a business as usual implementation context, the RTU and the TAPCON230 are likely to be truly integrated, i.e., only one measurement device (TAPCON230 or MCU) for the busbar voltages should exist and be used.

Note that the ratio between the set point received by the TAPCON230 and the desired busbar line-to-line (L-L) voltage is 1:4 (e.g., 104V should be sent to the device when the desired busbar L-L voltage is 416V).

$$V_{setpoint} = \frac{\sqrt{3} * V_{new\ target}}{4} \tag{2}$$

The L-N voltage limits at the connection point of the customers are 253 and 216V, i.e., 1.10 and 0.94 p.u. With the OLTC, the lowest phase voltage at busbar would be 231V (tap position 9). This means that, assuming a voltage drop of no more than 6%, customers at the far end of the feeders would still see adequate voltages. However, this might not be the case for some feeders, hence the need of further flexibility (to be provided in this project by capacitor banks). On the other hand, the highest phase voltage at the busbar will be ultimately limited by the (unavoidable) presence of customers close to the substation, i.e., the busbar cannot exceed 253V (tap position 4).

The automatic voltage control logic has also considered scenarios when mid and end point voltages are close to the boundary: 2% near the boundary (i.e., from 248 to 253V and from 216 to 221V) are considered as orange zones.

Based on the above, three voltage zones (red, orange and green) can be defined as shown in Figure 11. This provides a graphical idea of the extent to which the voltage control logic will be able to use the available voltage range provided by the OLTC.

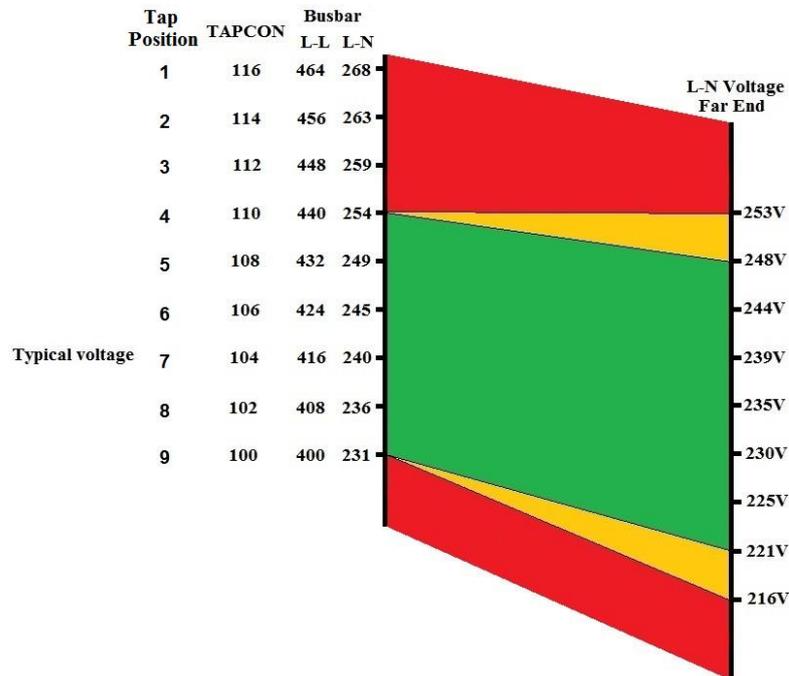


Figure 11 Voltage zones (integer values)

At every control cycle (e.g., every 5 minutes), the average busbar L-N voltage (average of the three phases) and the minimum and maximum L-N voltages of all the mid and end points of the LV feeders are monitored. Within the control cycle, the monitored voltages are then compared to the voltage zones (Figure 11), i.e., green, orange and red. In the red zone, if voltages breach the upper limit, a lower voltage target will be set. If voltages breach lower limit, a higher target value is adopted. For the orange zone, a similar approach is taken. For the green zone, however, a subzone is adopted so at

the time when there is no impact from the low-carbon technology (e.g., no PV generation), the OLTC can bring the busbar voltage back to the typical voltage (416V L-L, tap position 7).

A detailed flow chart containing the actual values adopted in this initially proposed voltage control logic is presented in the Appendix. In this flowchart, *Max* and *Min* represent the maximum and minimum of the monitored L-N voltage of the mid and end points of all feeders. For each control cycle, the compensating voltage, V_{comp} , can be determined based on the voltage zone of the *Max* and *Min* values. The parameter V_{unit} considers the 'gap' of busbar L-N voltages for different tap positions (which is approximately 4.6V). Knowing the monitored average busbar L-N voltage (V_{busbar}) during the previous control cycle and the compensating voltage (V_{comp}), a new voltage target ($V_{new\ target}$) for the current control cycle can be calculated using equation (1). Then, the TAPCON230 receiving voltage can be calculated by equation (2).

For this automatic voltage control logic, in the cases when *Max* is larger than 253V (red) and *Min* is lower than 216V (red) or when *Max* is between 248 and 253V (orange) and *Min* is between 216 and 221V (orange), the compensating voltage (V_{comp}) is zero. In this case, the busbar voltage target remains the same as the previous control cycle. Further flexibility resources will be necessarily to provide a solution. For instance, lower busbar voltage targets could be used to decrease the voltage rise in some feeders whilst simultaneously capacitor banks can be used to raise the voltages for those feeders experiencing significant drops.

3.3 Performance of the Proposed Control

According to the available data from the "LV Network Solutions" project, during winter time (January 2013), the maximum and minimum busbar phase voltages in *Landgate* are 247.6 and 230.1V. For *Leicester Avenue* they are 248.5 and 231.9V. During summer time (July 2013), the maximum and minimum busbar phase voltages in *Landgate* are 255.7 and 237.1V. For *Leicester Avenue* they are 258.2 and 241.3V. The variation in busbar voltages is caused by changes on LV network (load, PV generation) but also on the HV network side (load, generation, primary substation OLTC). However, to investigate the performance of the proposed voltage control algorithm, initially the voltage at the primary of the HV/LV transformer is assumed to be constant. According to the above mentioned real data, the daily average busbar voltages for *Langate* during winter and summer are 239.6 and 247.1V, respectively. For *Leicester Avenue*, they are 239.7 and 250.4V. Given that these initial studies focus on the summer time, 11.22kV have been taken as the corresponding voltage at the primary side of the transformer.

First, power flow simulations of *Landgate* and *Leicester Avenue* with current PV locations (i.e., 29.3 and 22.3%, respectively, Figure 4) have been carried out in OpenDSS. For simplicity, all PV panels installed in the networks are assumed to be 3.5kWp (a slightly higher overall installed capacity than what is actually in place). Figure 12 and Figure 13 show daily (weekday, July) voltage profiles at the far ends of the feeders in each of the two networks. Voltage rise can be clearly seen following sun irradiance particularly in the four feeders with higher number of PV installations. However, according to these simulations, none of these feeders have problems in terms of voltage violations (assuming the voltage at the primary of the transformer is 11.22kV, 1.02 p.u.).

To implement the proposed voltage control in the two trial networks, a worst-case scenario twice the current PV penetration in each feeder (already with PV) have been considered (i.e., 58.6% in *Landgate* and 44.6% in *Leicester Avenue*). For comparison, Figure 14 and Figure 16 show the daily (weekday, July) voltage profiles for both networks under this scenario without voltage control, i.e., using taps fixed in position 7. Figure 15 and Figure 17 illustrate the performance of the proposed voltage control on the networks. Figure 15(a) and Figure 17(a) show in particular the tap changing profile, the voltage target and the achieved voltage at the busbar as well as the active power flow per phase. Negative values of active power correspond to reverse power flows. Figure 15(b) and Figure 17(b) show the daily voltage profiles at the far ends of the feeders.

In these simulations, the monitoring devices are assumed to be equipped at the far ends of all the six feeders. According to the voltage zones of the maximum and minimum phase-voltage of these six far ends, the compensating voltage (V_{comp}) is calculated following the proposed voltage control logic. Then, the voltage target is determined by equation (1) – presented previously.

It can be seen from Figure 15, in terms of voltage violations, the problematic feeders in *Landgate* are feeders 63057172, 63057173 and 63057174. From minutes 500 to 1080 the voltage target at the busbar constantly changed to reduce the voltage of these feeders and keep the remainder feeders within voltage limits. As for *Leicester Avenue*, the problematic feeder in is 69051565 (Figure 17). In the same way, from minutes 550 to 1100, the busbar voltage targets are reduced to improve the voltage profile.

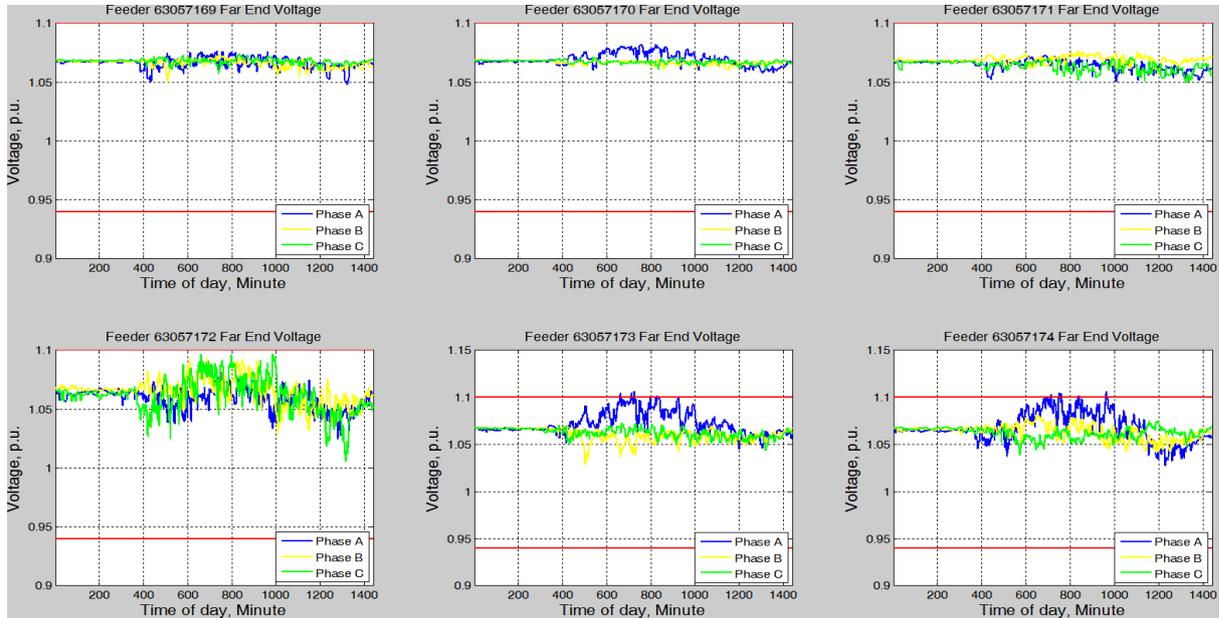


Figure 12 Daily (weekday, July) voltage profiles at the far ends of the 6 feeders in *Landgate* considering 29.3% of PV penetration

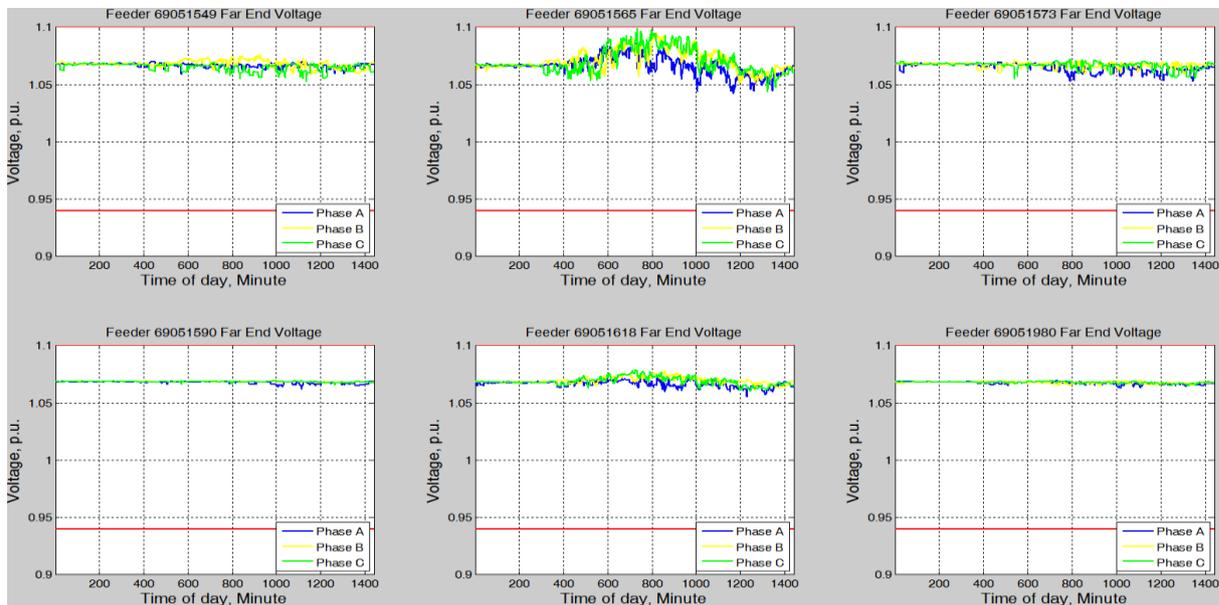


Figure 13 Daily (weekday, July) voltage profiles at the far ends of the 6 feeders in *Leicester Avenue* considering 22.3% of PV penetration

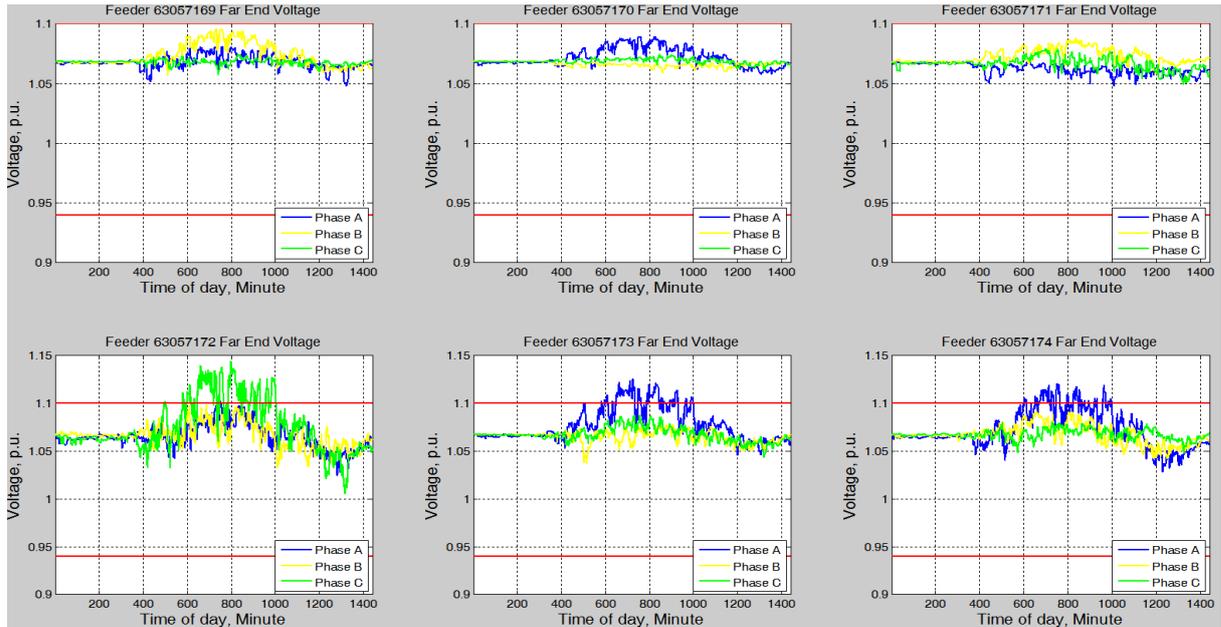
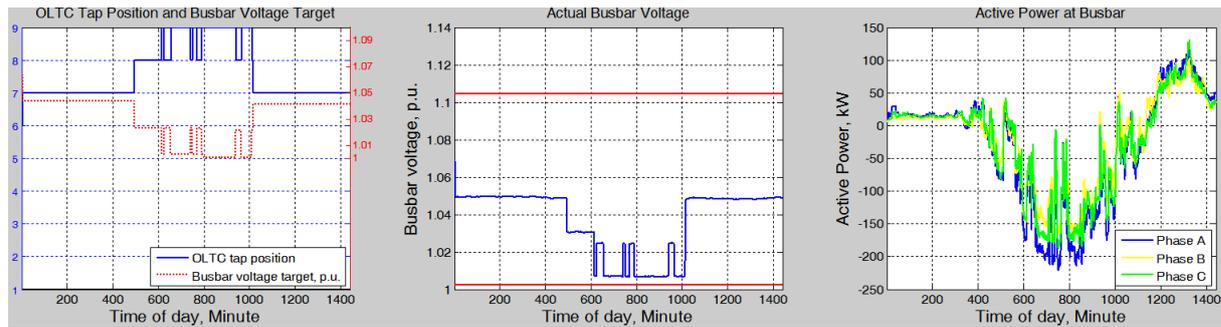
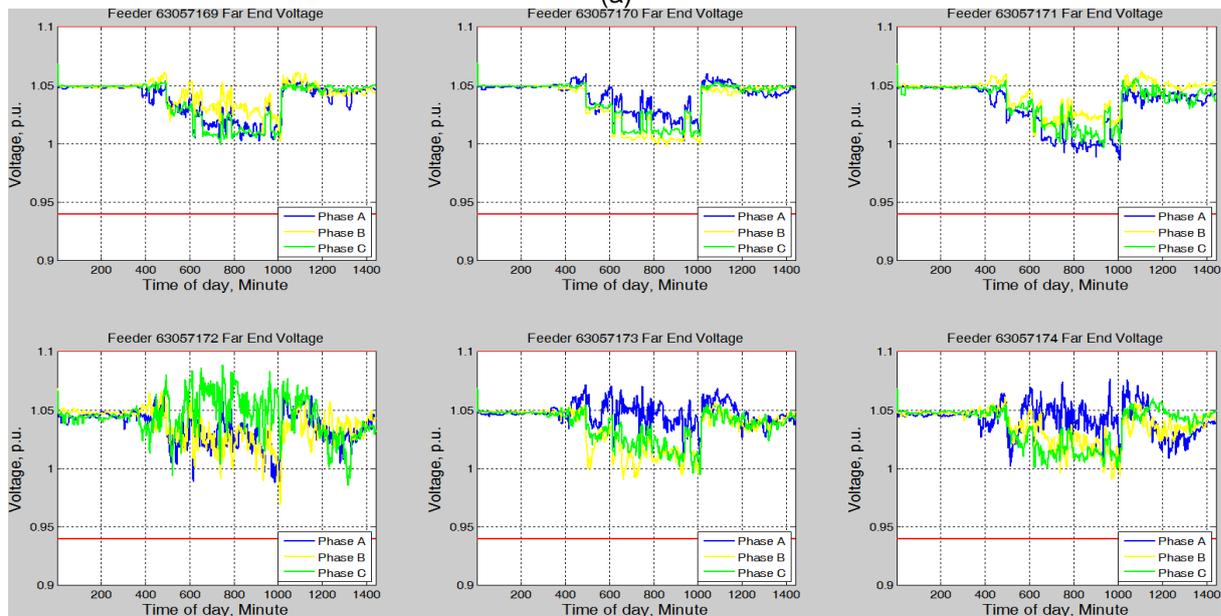


Figure 14 Daily (weekday, July) voltage profiles at the far ends of the 6 feeders in *Landgate* considering 58.6% of PV penetration and no voltage control



(a)



(b)

Figure 15 Performance of the proposed voltage control in *Landgate* considering 58.6% of PV penetration: (a) Tap position, busbar voltage and the active power flow per phase at busbar; (b) Daily (weekday, July) voltage profiles at the far ends of the 6 feeders

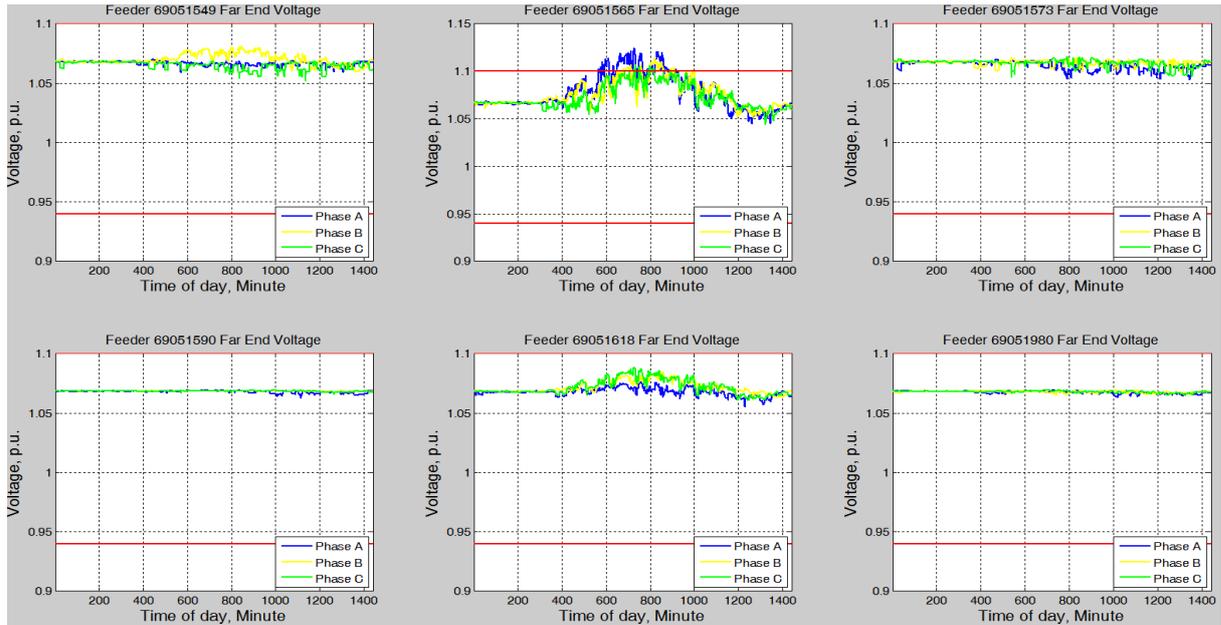
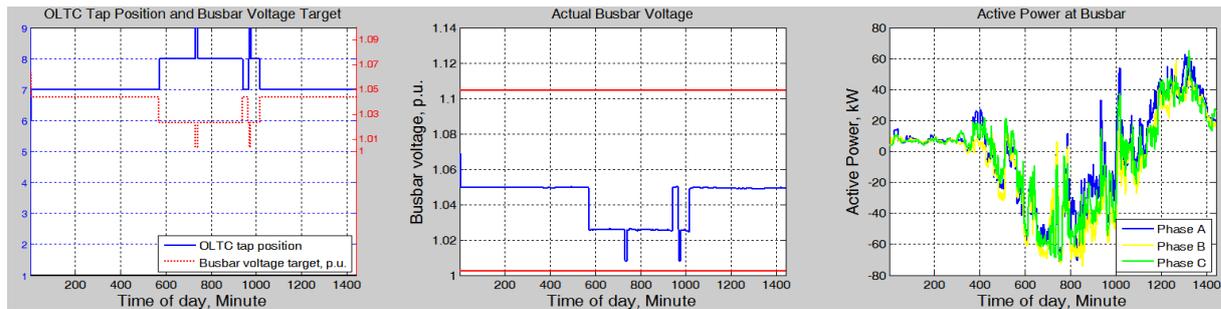
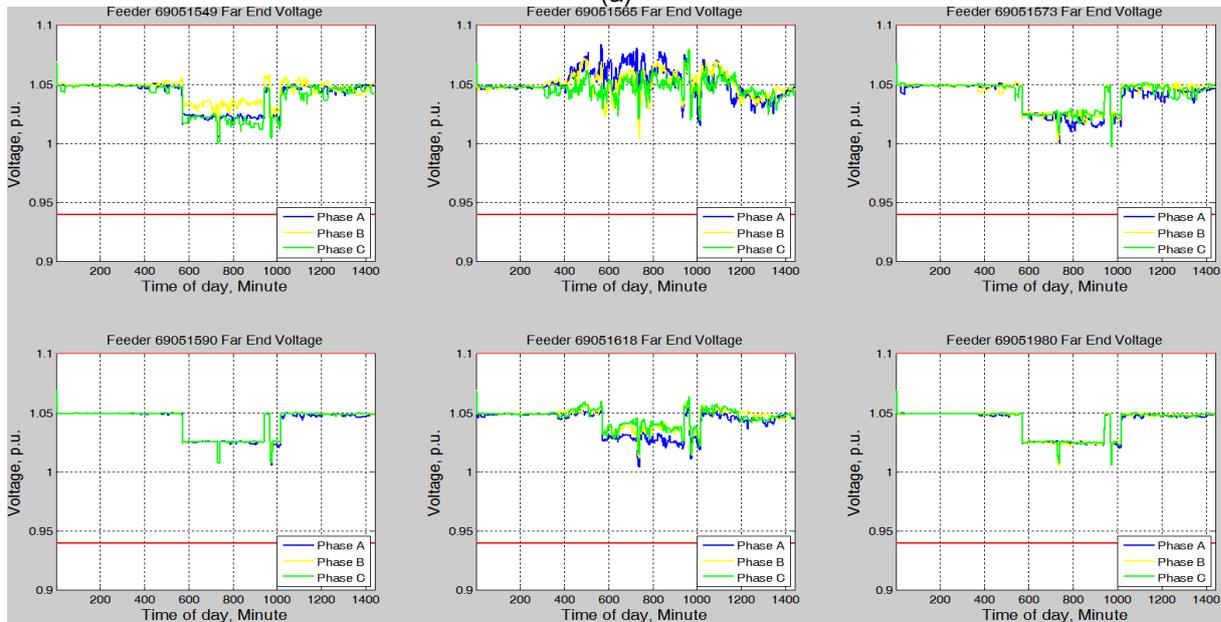


Figure 16 Daily (weekday, July) voltage profiles at the far ends of the 6 feeders in Leicester Avenue considering 44.6% of PV penetration and no voltage control



(a)



(b)

Figure 17 Performance of the proposed voltage control in Leicester Avenue considering 44.6% of PV penetration: (a) Tap position, busbar voltage and the active power flow per phase at busbar; (b) daily (weekday, July) voltage profiles at the far ends of the 6 feeders

Voltages at all customers in the feeders are used to calculate the corresponding 10-minute average voltages following the standard BS EN 50160 [1]. As shown in Table 5, considering the worst-case scenario, voltages at the far ends of feeders 63057172, 63057173, 63057174 and 69051565 are 80.6, 86.1, 88.2 and 84.0% of the studied day within the statutory limit (+10%/-6% of nominal). The corresponding percentage of customers having voltage violation problems as per BS EN 50160 (i.e., voltages within limits less than 95% of the time) are shown in Table 6.

Without voltage control there are 27.6, 15.7, 5.0 and 24.3% customers having the voltage violation problems in feeders 63057172, 63057173, 63057174 and 69051565, respectively. However, by using the proposed voltage control, voltages at all loads are kept within the statutory limits. Indeed, no customers in the two trial networks are affected by voltage violations.

Table 5 Percentage (%) of 10-min average voltages at the far ends within statutory limits

Landgate	Feeder ID	63057169	63057170	63057171	63057172	63057173	63057174
	Without voltage control	100	100	100	80.6	86.1	88.2
	With voltage control	100	100	100	100	100	100
Leicester Avenue	Feeder ID	69051549	69051565	69051573	69051590	69051618	69051980
	Without voltage control	100	84.0	100	100	100	100
	With voltage control	100	100	100	100	100	100

Table 6 Percentage (%) of customers having voltage violation problems

Landgate	Feeder ID	63057169	63057170	63057171	63057172	63057173	63057174
	Without voltage control	0	0	0	27.6	15.7	5.0
	With voltage control	0	0	0	0	0	0
Leicester Avenue	Feeder ID	69051549	69051565	69051573	69051590	69051618	69051980
	Without voltage control	0	24.3	0	0	0	0
	With voltage control	0	0	0	0	0	0

3.4 Discussion

The simulations presented in this report did not consider the daily voltage variations on the primary side of the HV/LV transformer. In addition, due to lighter domestic loading and higher PV generation during summer, the voltage at the primary of the transformer is likely to increase. To cater for the latter, it was assumed a flat but higher voltage of 11.22kV (1.02 p.u.). In practice, these daily and seasonal voltage variations can have significant effects on the far end voltages of *Landgate* and *Leicester Avenue* feeders, even with current PV penetrations.

Only one PV generation profile was adopted in the studies. Consequently, the results, particularly in terms of the behaviour of generation (i.e., cloud transients, etc.), are limited to this specific PV profile. In terms of the load profiles, as realistic they might be, limitations exist.

In the proposed voltage control algorithm, the maximum and minimum phase voltages of all feeders are taken into account. The voltage control will attempt to take tap changing actions to achieve the target voltage at the busbar based on the needs of all feeders. Consequently, the voltage control action resulting from voltage breaches in a given feeder will influence all the other feeders. This will become more challenging when heavily loaded feeders without PV installations and those with PV installation are present in the same networks.

3.5 Summary

An initial control logic for regulating voltages at the remote ends of LV feeders has been presented. It categorises monitored voltages in three voltage zones (red, orange and green). These zones are defined considering the voltage limits at the connection point of the customers and the specifications of the voltage output of the OLTC transformer. Within a control cycle, the monitored voltages, such as the busbar and the minimum and maximum single-phase voltages of all the mid and end points of the LV feeders, are compared to the voltage zones. This comparison is used to calculate a compensating voltage. The voltage target, which is a key input for the OLTC, is determined by the monitored busbar voltage (as a reference) and the calculated compensating voltage.

The proposed voltage control logic was tested in *Landgate* and *Leicester Avenue* considering twice the current PV penetration levels (in those feeders already with PV installations). The results show the proposed logic works and keeps the voltages within the statutory limits.

4 Next Steps

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

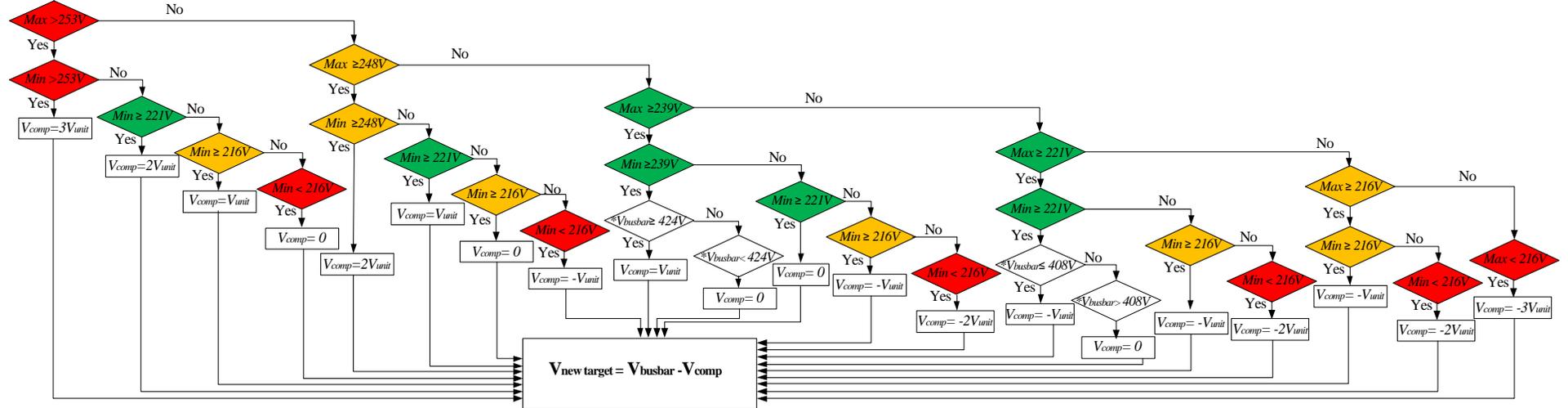
- **RTU Implementation.** The proposed control logic and corresponding improvements will be coded in the RTU language for the corresponding testing and deployment.
- **Further Analysis.** More scenarios will be studied in order to cater for potential cases where PV generation disparity can lead to voltage regulation challenges, e.g., networks with both heavily loaded feeders without PV installations and lightly-loaded feeders with PV installations. The advantages of different lengths of control cycles (e.g., one minute, five minutes, etc.) will also be quantified. Different daily PV generation profiles and bandwidths for the target voltage will also be considered. The voltage variations in the primary of MV/LV transformers will be considered.
- **Coordinated Voltage Control.** Capacitor banks and their corresponding control modes will be modelled in OpenDSS. The improved voltage control logic will be adapted to cater for these devices in a coordinated fashion.

5 References

- [1] British Standard on Voltage Characteristics of Electricity Supplied by Public Distribution Networks, BS-EN-50160, 2007.
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- [3] I. Richardson *et al.*, "Domestic electricity use: A high-resolution energy demand model," *Energy and Buildings*, 2010, 42 (10):1878–1887.
- [4] Office for National Statistics, "Statistical Bulletin: Families and Households, 2013", Available: http://www.ons.gov.uk/ons/dcp171778_332633.pdf (accessed 22/11/2013).
- [5] I. Richardson and M. Thomson, "CREST_Integrated_PV_electricity_demand_model_1.0A.xlsm", Available: <https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/7773> (accessed 21/11/2013).
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- [7] *Recommendations for the Connection of Small-scale Embedded Generators (up to 16 A per phase) in Parallel with Public Low-voltage Distribution Networks*, Engineering Recommendation G83/1, Sep. 2003.
- [8] MR, "GridCon, Transformer-The voltage regulated distribution transformer," http://www.reinhausen.com/desktopdefault.aspx/tabid-1516/1835_read-4652/ (accessed 6/12/2013).
- [9] CG Automation, presentation report, "ENW_Kickoff_Draft Slides_v200", 26th, Jun. 2013.

6 Appendix

The Max and Min voltage of mid and end point of all feeders



* denotes the voltage is line-to-line voltage
 $V_{unit} = 4.6V$