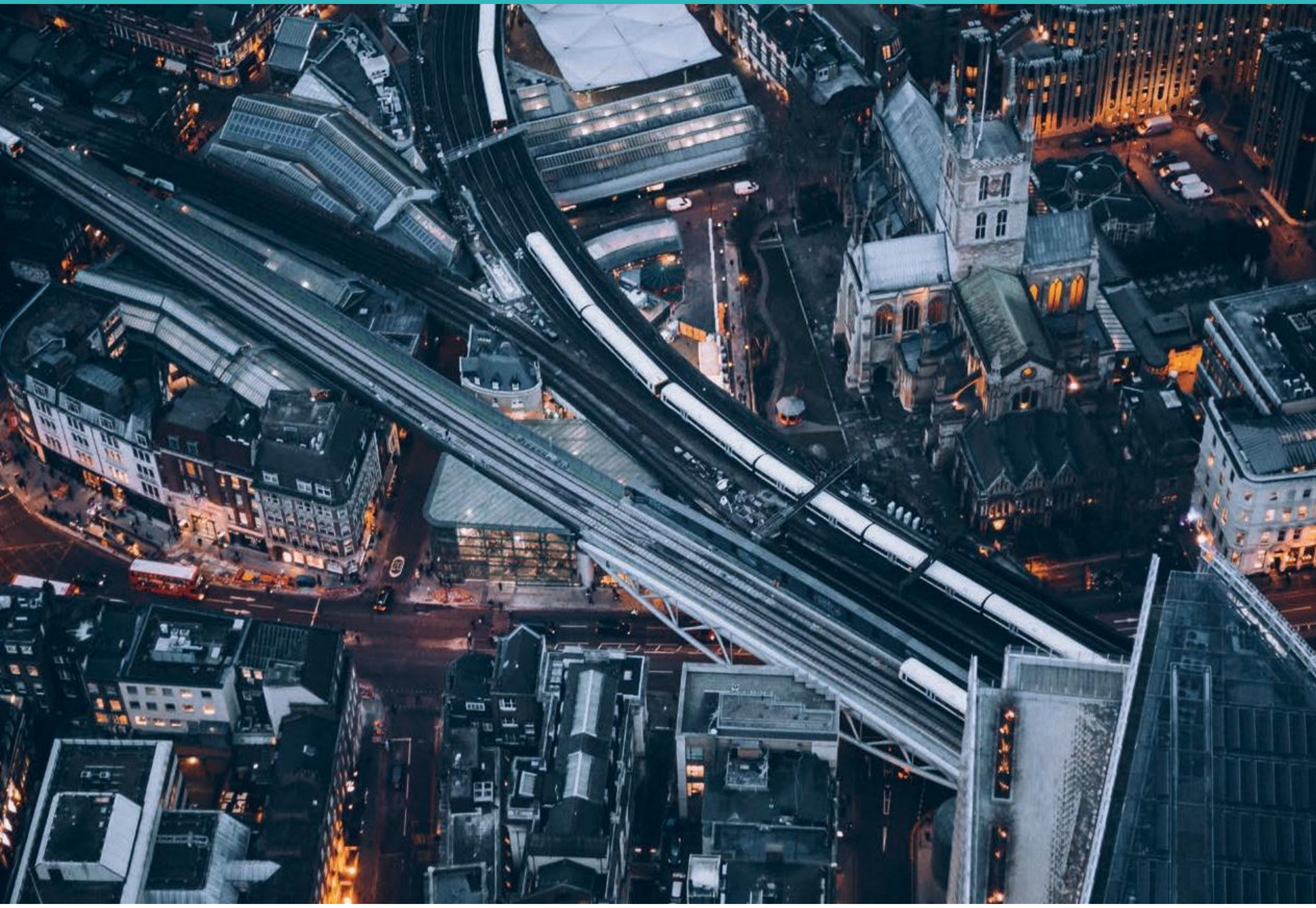

REPORT

SILVERSMITH - Load flow analysis of novel solutions

Prepared for: National Grid Electricity Distribution

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06/03/2023	1.1	Andrew Bower Thomas Stone	Revision addressing client comments
27/03/2023	1.2	Andrew Bower Thomas Stone	Revision addressing client comments
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Business	17/02/2023	1.0	David Mills (Head of Net Zero Transition)
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Executive Summary

Background to the Project

The SILVERSMITH (Solving Intelligent LV – Evaluating Responsive Smart Management to Increase Total Headroom) project has examined the effects of increasing penetration of Low Carbon Technologies (LCTs) into the Low Voltage Distribution Network. This has been done in two distinct ways, first using the Transform Model® to explore the overall expectations on a licence area wide assessment and secondly in a more detailed assessment of the effects on specific LV networks.

The second approach illustrated the effects of the increasing penetration of LCTs into sample networks which represent an example of Dense Urban, Urban, and Rural circuits. For consistency between approaches, the networks selected have been assessed as corresponding with LV2, LV6, and LV10 in the Transform Model®.

A literature search and discussions with manufacturers identified a number of potential novel solutions to be applied to the network which have the potential to alleviate some of the issues caused by the increased penetration of LCTs

This report describes the modelling carried out in PowerFactory to assess the effect of the novel solutions compared to Business-as-Usual solutions on load flow, hosting capacity, power quality and fault levels.

Scope and Objectives

The scope of this report is to examine the effects and benefits of the novel solutions identified during the literature review element of the wider SILVERSMITH project when applied to the example networks studied in report EA16141-TR3 [1]. These studies only examine the effects of power system equipment rather than monitoring equipment which may inform the need for particular interventions and also provide useful measured inputs to improve the operation and effectiveness of the power system interventions.

The objective is to establish the benefit offered by each solution .

Conclusions

The main conclusions of this report are

C1. Since the voltage problem to be solved presents at the customer supply terminals during periods of export from DER all of the voltage control solutions are inherently limited if the voltage used to reflect the setpoint is that seen on the LV busbar .

C2. Controlling the voltage by importing reactive power does not maximise the capacity for DER export since the available thermal capacity of upstream conductors and equipment is degraded.

C3. Network monitoring is essential to provide the necessary insights into network conditions to aid in setting up the selected interventions to provide the optimum solution.

C4. The smart transformer solution offers the finest degree of control of the busbar voltage avoiding the potential problem highlighted with the on-load tap changer and the increased losses and reduction in available transformer capacity associated with absorbing reactive power with a Statcom..

Recommendations

The main recommendations following this report are:

R1. Enhanced Monitoring of the LV network should be considered as an important enabler for other targeted interventions.

R2. Further studies should be considered to explore the effects of voltage drop in the HV network which has been excluded from these studies.

R3. Further studies should be undertaken to consider the most appropriate nominal ratio and tap ranges and step sizes for future distribution transformers

R4. Further studies should be considered to understand the potential Power Quality effects of large scale LCT take up.

Contents

Figures

1. Background and Introduction

The SILVERSMITH (Solving Intelligent LV – Evaluating Responsive Smart Management to Increase Total Headroom) project has examined the effects of increasing penetration of Low Carbon Technologies (LCTs) into the Low Voltage Distribution Network. This has been done in two distinct ways, first using the Transform model to explore the overall expectations on a licence area wide assessment and secondly in a more detailed assessment of the effects on specific LV networks.

The second approach illustrated the effects of the increasing penetration of LCTs into sample networks which represent an example of Dense Urban, Urban, and Rural circuits. The networks selected have been assessed as corresponding with LV2, LV6, and LV10.

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The PowerFactory analysis does not make any attempt at determining the cost-effectiveness of particular solutions, but rather focuses on the technical effects of solutions on the network. A complimentary Transform model study has been conducted as a Cost Benefit Analysis to determine the most cost-effective solutions to the network constraints encountered. The results of this study are presented in report EA16141-TR4 [2].

Solutions Modelled

For the purposes of modelling the effect of the novel solutions, the devices were added to the Urban and Rural models. The results seen in the Urban model would be equally applicable to their effectiveness in a Dense Urban scenario.

Full details regarding the market engagement and literature review process to identify the novel solutions was reported in the SILVERSMITH literature review, EA16141-TR2 [3].

'Smart' Transformer

There were two 'smart' transformer type solutions presented, one a retrofit add-on to an existing distribution transformer and the other a complete replacement unit. In terms of the potential benefits offered the devices were similar in the features offered, stepless variation of the output voltage, phase balancing and active filtering of lower order harmonics.

In terms of their effect on the network and the way in which the power electronics employed control the low voltage network busbar voltage, the phase balancing and the harmonic filtering both of these devices appear to use very similar if not the same principles of operation albeit implemented in a different manner. The operation of the power electronics applies a voltage to the control coil to increase or decrease the voltage applied to the low voltage busbar.

The smart transformer solution has been modelled consistent with a discrete retrofit solution using a booster transformer with a voltage source driving the control winding to control the voltage at the substation busbar as shown in Figure 1 below.

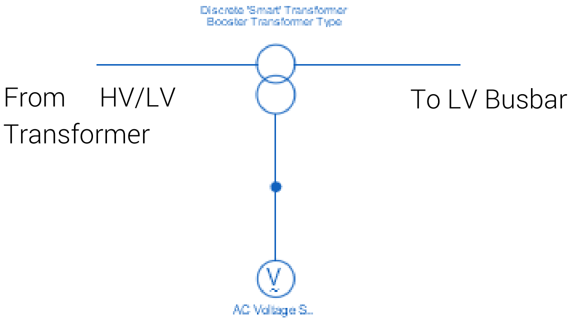

Figure 1 'Smart' transformer model

Statcom

The Statcom offers voltage control by varying the generation or absorption of reactive power. Absorbing reactive power acts to lower the downstream voltage due to increased voltage drop through the upstream network components. Supplying reactive power from the Statcom acts to raise the downstream voltage by reducing the voltage drop through the upstream components due to them no longer supplying both the real and reactive components of the load. Where the Statcom acts to supply only the reactive power of the load the capacity of the transformer to supply Watts to the LV network would be increased. The Statcom is modelled in PowerFactory as a 'Static Generator' with a voltage-q droop characteristic and a target setpoint voltage for the connection, the reactive power flow into or out of the static generator is varied to lower or raise the voltage to the target setpoint .

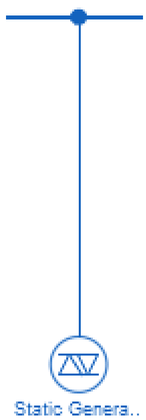

Figure 2 PowerFactory Static Generator

On-load Tap Changer

The on-load tap-changer replaces the traditional off-circuit tap-changer employed at secondary distribution transformers with an on-load tap-changer to manage the voltage on the LV system. The step change voltage for frequent events is limited to 3%. The step-change resulting from a tap-change step on a typical HV/LV distribution transformer is 2.5%.

The modelling of this solution is enabled through the automatic tap changer element in PowerFactory and selecting the target voltage. A target voltage of 1.03 p.u. (0.412kV) was used for this analysis along with ensuring a discrete tap setting to highlight the effect of a tap position change.

Remote Switching / Meshing

With the models reviewed in the first stage of this project there are limited opportunities to study the effect of meshing. Meshing between different substation networks cannot be examined since the scope of the network modelling only involved a single substation LV network.

It is however possible to model the effect of closing an open point between two feeders within the Urban model. One of the feeders in this case is the highest loaded of the four feeders in the Urban model.

Urban

'Smart' Transformer

Summer – Peak PV Export

The smart transformer can control the voltage on the transformer in a stepless continuous range within the capacity of the trimming transformer. For these studies the transformer was set on tap position 4 that is -2.5% below nominal ratio which equates to a no-load busbar voltage of 243.75V or approximately 1.06pu against 230V nominal voltage. Setting the voltage source controller of the trimming transformer to control the voltage applied to the substation busbar at 1.04pu yields the changes shown between Figure 3 and Figure 4 below. This brings the voltage rise due to PV export at the remote end of the feeder down to a value within the statutory limits whilst the highest peak load seen in the evening remains well within the statutory lower limit. The peak voltage seen in Figure 3 is 1.116pu whereas with the smart transformer controlling the voltage at the busbar to 1.04pu the peak voltage seen at the remote customer is 1.095pu.

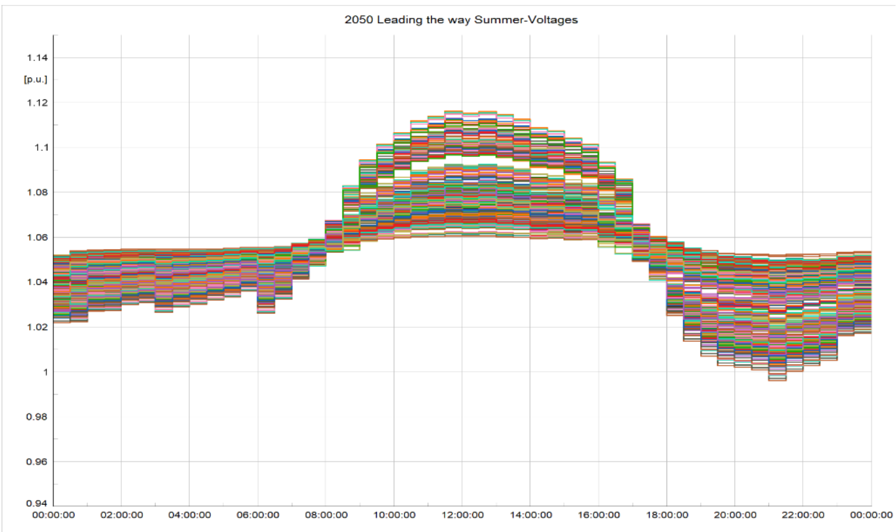

Figure 3 2050 Leading the Way summer voltages – without 'Smart' Transformer

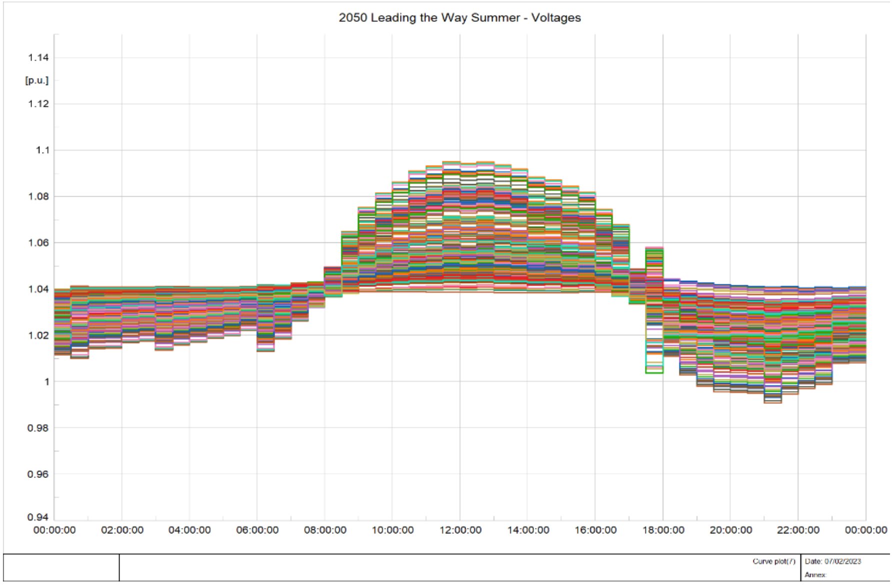

Figure 4 2050 Leading the Way summer voltages – with 'Smart' Transformer

The controlling node for this study was set as the substation LV busbar and it is clearly a simple matter in the model to adjust the setpoint on the LV busbar until the results are satisfactory. However, in the real-world determination of the required setpoint at the LV busbar will require knowledge of the extent of the voltage rise (and drop) along the network under maximum export and import conditions. This requires measurements to be made at the ends of the network to determine the maximum voltage rise seen. Smart meters could be one potential source of such measurement data, whether that is provided as an historical record or in real time. Real time measurement offers the opportunity to adjust the busbar voltage setpoint to ensure that the remote points remain within the statutory voltage envelope. Historical after the fact measurements at the remote ends of the network combined with the measurement data of feeder current magnitudes from network monitoring could be utilised to determine the potential voltage rise/drop conditions at the remote end of the network. Allowing some additional margin between the highest and lowest measured voltage rise and drop conditions, compared to the busbar voltage, and the maximum and minimum statutory voltages could allow the setpoint to be determined based on historic after the fact data. This may not make full use of the available voltage envelope and may require more changes to the busbar setpoint voltage than might otherwise be the case with real-time measurement of remote customer voltages.

The setpoint applied at the busbar in the model is at the level necessary to bring the remote customer voltages within statutory limits at the time of peak PV export into the network. The setpoint is not required at this level to maintain voltages within statutory limits at other times during the day.

Winter – Peak Demand

Taking the 2050 Winter peak demand voltage profile and applying the same setpoint adjustment (1.04 p.u.) required to bring the summer voltage rise within the statutory limits the difference between pre- and post-smart transformer results are shown in Figure 5 and Figure 6 below. The breach of the lower statutory voltage that is shown under this scenario is clearly going to be exacerbated by the lowering of the LV busbar voltage. However, as can be seen in Figure 7, the loading applied to Feeder 3 is significantly in excess of the thermal capacity of the circuit. Breaking out the voltage profiles into individual Feeders as shown in Figure 8 it can be seen that the only Feeder where voltage issues are present is Feeder 3 where the thermal capacity of the feeder is significantly exceeded. The exceedance of the Feeder 3 cable capacity also drives the breach of the transformer thermal capacity.

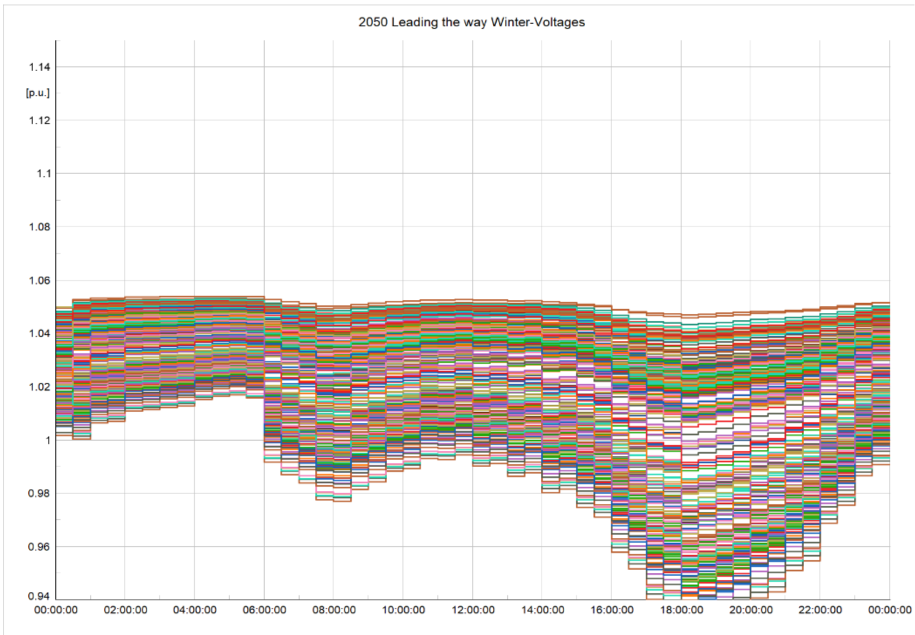

Figure 5 2050 Leading the Way winter voltages – without 'Smart' Transformer

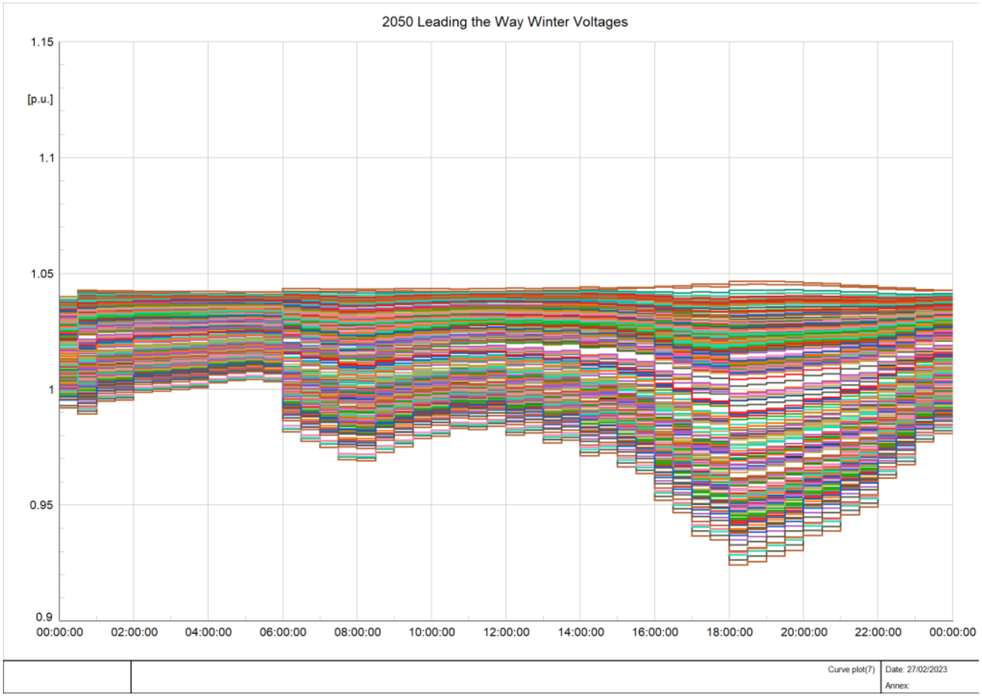

Figure 6 2050 Leading the Way winter voltages – with 'Smart' Transformer

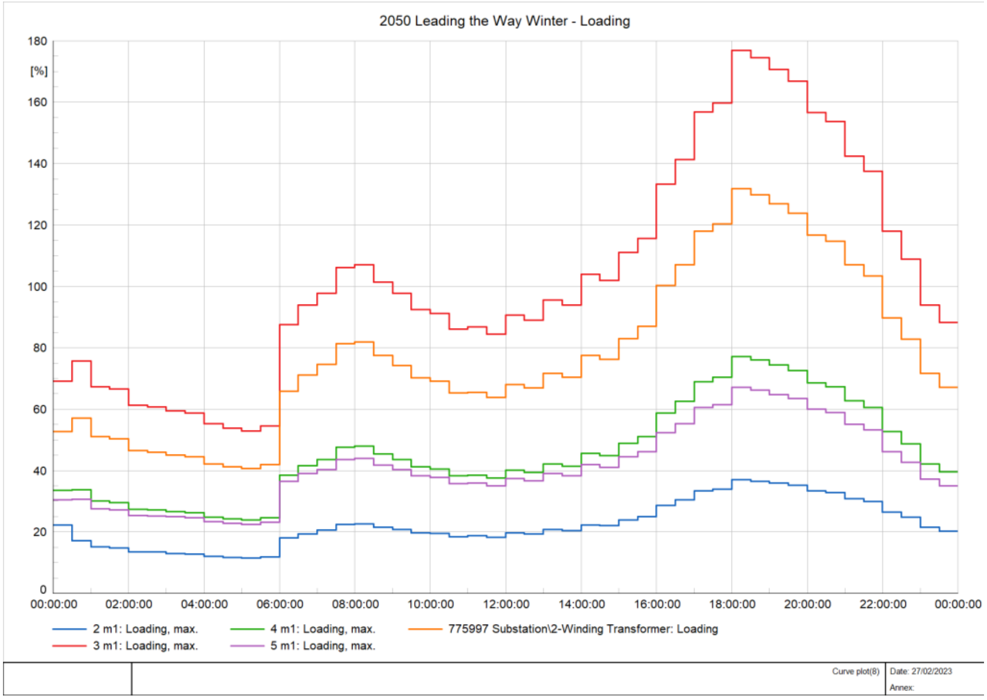

Figure 7 2050 Leading the Way winter loading – with 'Smart' Transformer

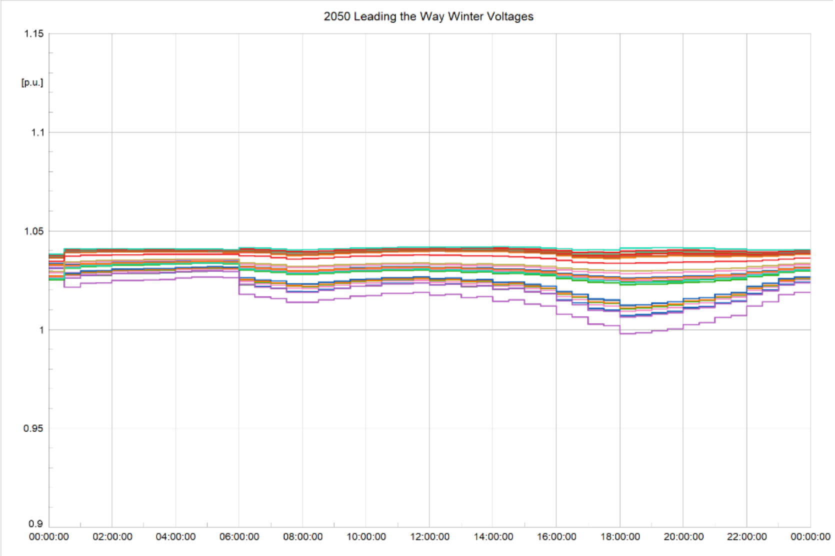

Figure 7a feeder 2 voltage profiles

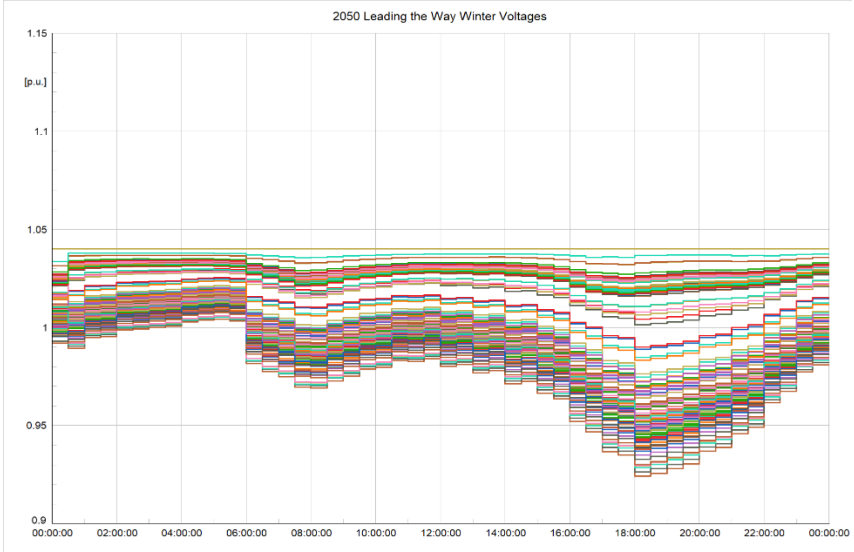

Figure 7b feeder 3 voltage profiles

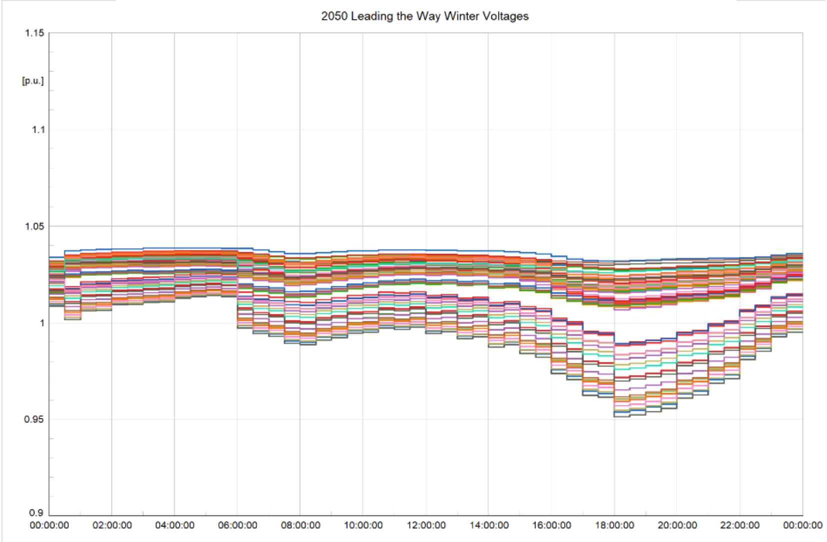

Figure 7c feeder 4 voltage profiles

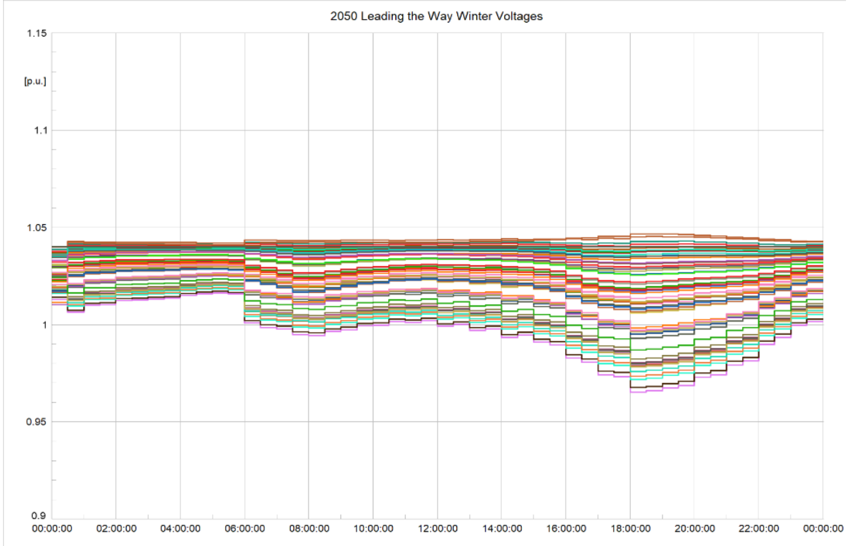

Figure 7d feeder 5 voltage profiles

Figure 8 2050 Leading the Way winter voltages – individual feeders

Statcom

An alternative method to control the LV busbar voltage is to connect a Statcom to the LV busbar and use reactive power flows to control the voltage, absorbing vars to lower the voltage and injecting vars into the network should it be necessary to raise the busbar voltage. Figure 9 below shows the effect of applying the Statcom at the substation busbar to control the busbar voltage in this case absorbing vars to lower the voltage. Figure 3 above shows the voltage profile without the Statcom. For urban deployment of a Statcom it was considered more likely that it would be installed within the source substation rather than requiring the acquisition of an additional parcel of land to install and connect the Statcom at the end of the feeder so only that scenario has been modelled. In a rural environment the Statcom could likely be more easily installed at the last pole with a simple variation to the wayleave granting permission for the pole and so both scenarios are considered.

Figure 10 below shows the Feeder and transformer loading without the Statcom lowering the voltage to accommodate the peak PV export during the daytime. The target setpoint necessary to bring the remote network voltages within the statutory voltage limits results in the Statcom absorbing vars throughout the day. The flow of the reactive current through the transformer does lower the voltage but as shown in Figure 11 it also significantly increases the loading of the transformer (orange curve) to a point where the peak exceedance is not offset in anyway by a significant reduction in demand at other times of the day as would be required to permit a high cyclic overload. Coupled with the fact that this scenario is for the peak summer PV output when the ambient temperature would be expected to be elevated increases the chance of thermal damage to the transformer and a consequent shortening of life. Comparing the traces seen in Figure 10 and Figure 11 it can be seen that the lowering the voltage does slightly increase the loading seen on the feeders in the middle of the day. This is because the PV output is determined by the energy form the sun on the panels and so long as the inverters have the capacity the output current will increase at lower voltage levels to produce the same power output. The PV systems have been modelled with a profile that does not reach the full peak output, so this capacity does exist within the model.

The continuous flow of reactive current in the transformer to pull the busbar voltage down increases the losses in the transformer and the high voltage network.

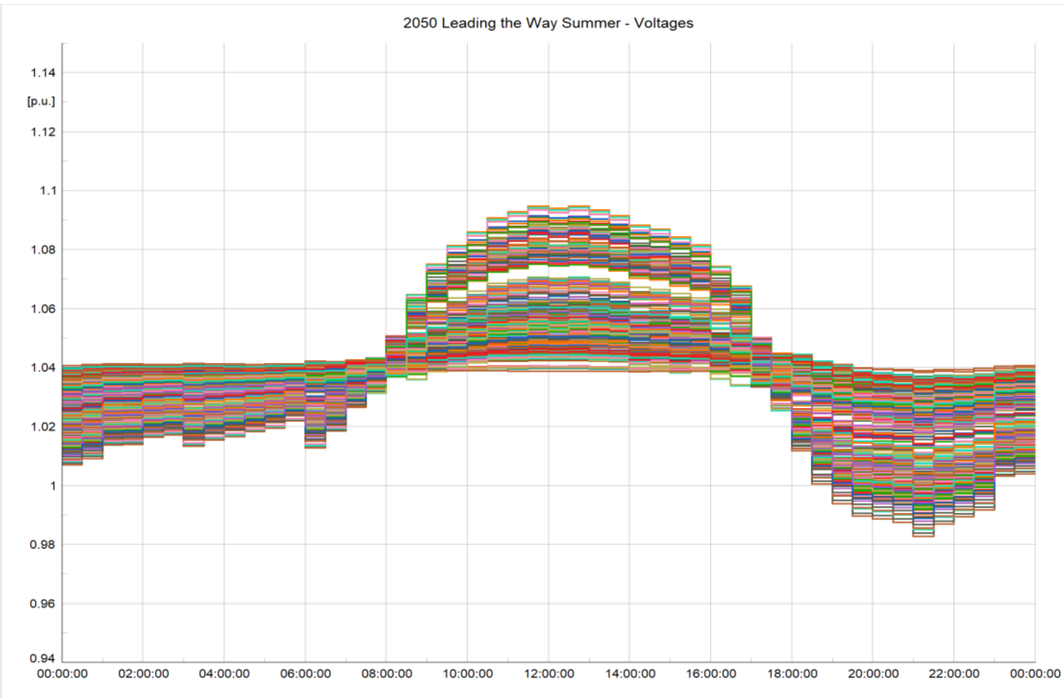

Figure 9 2050 Leading the Way summer voltages – with LV busbar Statcom

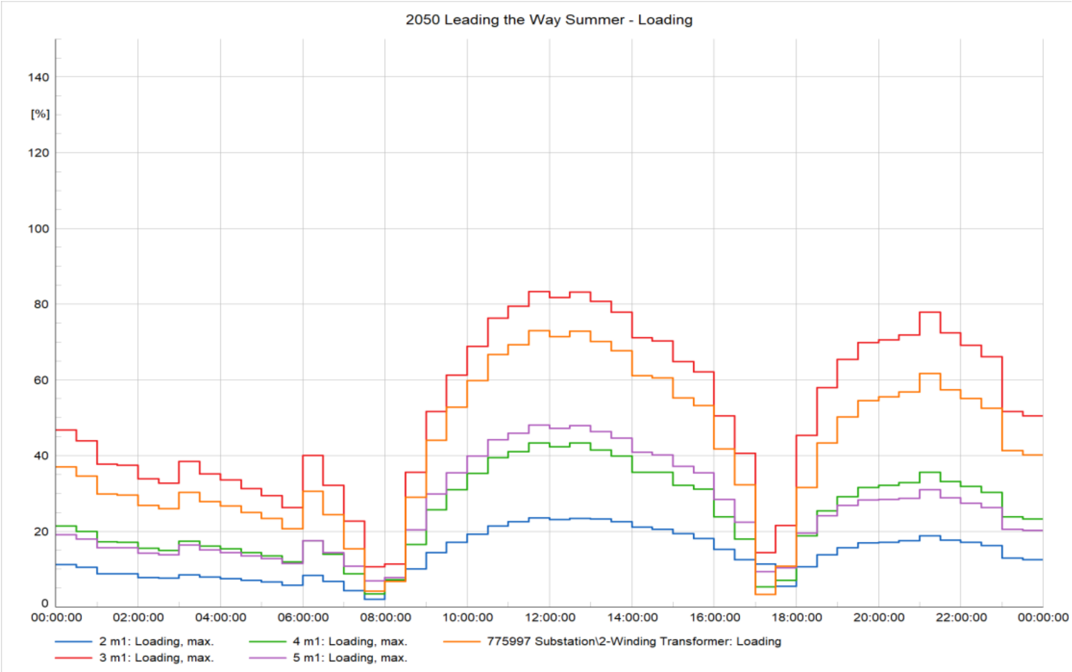

Figure 10 2050 Leading the Way summer loading–- without LV busbar Statcom

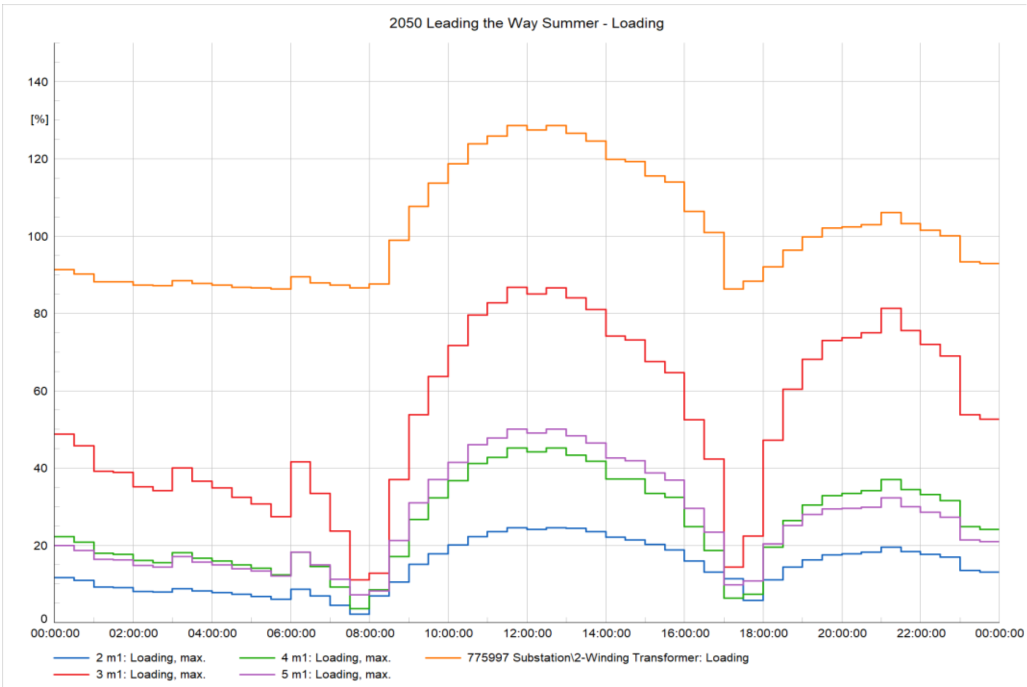

Figure 11 2050 Leading the Way summer loading–- with LV busbar Statcom

On-load Tap-Changer

Using a transformer equipped with an on-load tap changer rather than the off-circuit tap changer typically employed on HV/LV distribution transformers clearly offers the opportunity to alter the transformer ratio to control the LV busbar voltage. As with the "smart" transformer solution it is necessary to know the extent to which the network voltage remote from the substation rises above the no-load conditions to determine the required setpoint. Figure 12 shows the network voltage profiles when the setpoint voltage has been adequately set (1.03 p.u.) to fully manage the voltage rise within the network feeders. This requires knowledge of the extent of voltage rise at remote customer connections as well as variation of the voltage at the LV busbar under given tap positions. This allows the setpoint to be determined while ensuring the voltage at remote customers remain within statutory limits throughout the variation in the output of PV systems. In this case study the PV export is at such a level that it is necessary to operate the transformer at tap 5 to lower the voltage sufficiently to bring the remote customer voltages in line with statutory limits.

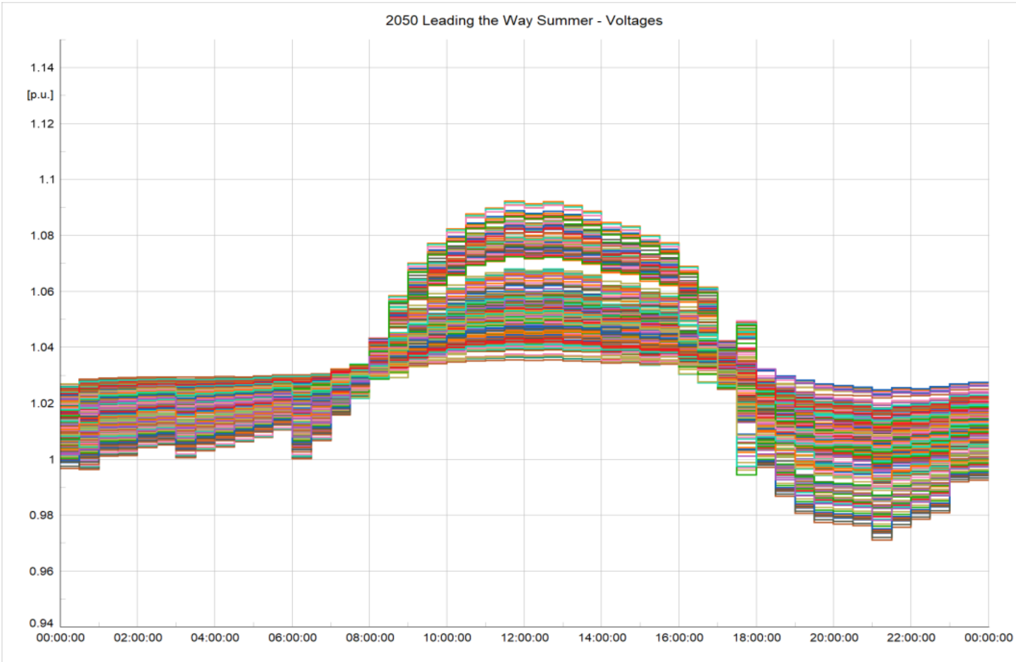

Figure 12 2050 Leading the Way summer voltages - tap changer ideal setting

Figure 13 shows the busbar voltage from within the traces shown in Figure 12, this trace shows that within this model where the 11kV voltage remains at a steady 1.0pu the variation of the busbar voltage would likely not be sufficient to require a variation of the tap position given a setpoint low enough to accommodate the generation. The tap step size of 2.5% would require a dead-band around the setpoint that is larger than the variation seen in this trace. This suggests that once the voltage has been adjusted to a setpoint where the highest voltage rise seen on a customer service is accommodated, that the tap changer would not need to tap again to adjust the voltage from that setpoint. However, the model used for this study is set up only to look at the LV network, the HV infeed to the substation is held at a constant 1.0pu voltage.

Further work to examine the effects of multiple substations with similar levels of LCT deployment would allow the effect to be considered on the immediate upstream HV network and would be expected to show a greater level of variation in the HV voltage. This may lead to conditions where the tap position needs to be varied from the setpoint achieved in this example study. The present specification of distribution transformers requires a nominal ratio of 11000/433V with a typical tap variation of ±5% in 2.5% steps. To accommodate the maximum PV export conditions the transformer tap was set to 1.03pu which would require -5% tap position meaning that if the voltage rose on the 11kV network due to export from multiple such substations then under normal conditions there may be insufficient tap positions available to lower the voltage further to achieve the target.

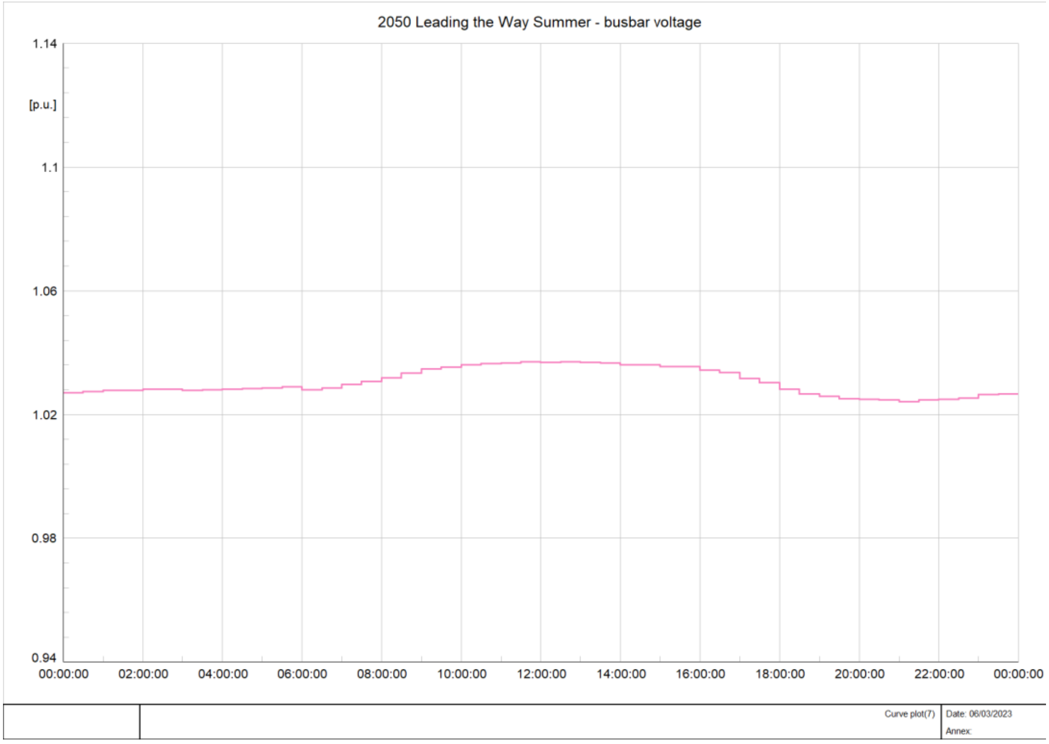

Figure 13 2050 Leading the Way summer voltages – busbar voltage

Remote Switching / Meshing

Closing up open points within the network has the potential to alleviate situations where voltage problems maybe beginning to manifest themselves and to reduce the loading on more heavily loaded circuits by sharing the load on parallel paths. Figure 14, and Figure 15 illustrate how the voltage profile can be slightly improved if the circuit open-point is closed, similar improvements are also possible by moving the open-point to the null point on the feeder. The null-point is not a fixed location as loading changes and there are limited locations where it is possible to physically open the circuit.

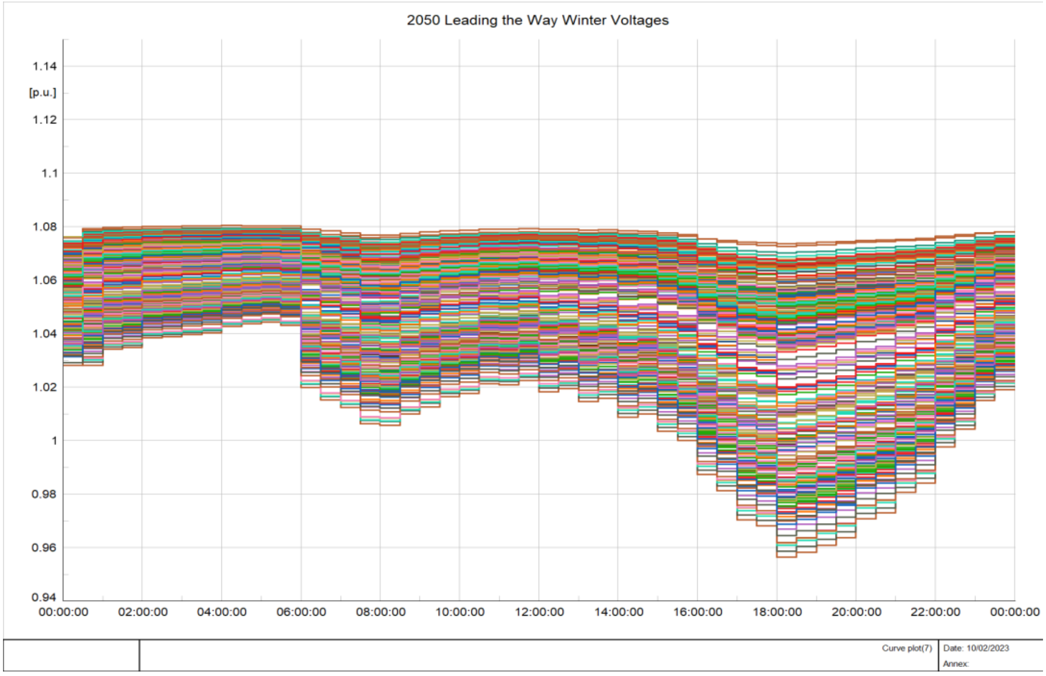

Figure 14 2050 Leading the Way winter voltages – without feeder meshing

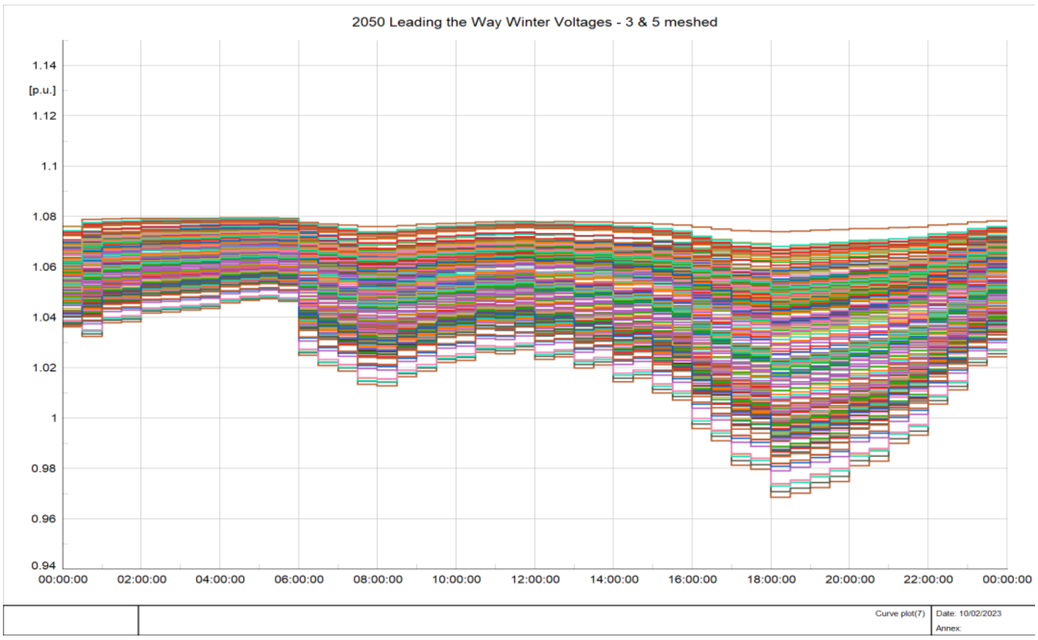

Figure 15 2050 Leading the Way winter voltages – with feeders 3 & 5 meshed

Figure 16 and Figure 17 below illustrate the kind of improvement in feeder loading which can be achieved by the meshing of feeders. Prior to meshing, the peak load on Feeder 3 is over 180% of feeder rating. Whereas, when meshed with Feeder 5 the loading on Feeder 3 decreases to just under 130%. Clearly this results in an increase in the loading applied to Feeder 5 and does not sufficiently reduce the Feeder 3 loading to within thermal limits, but it is illustrative of the benefits in reducing feeder loading

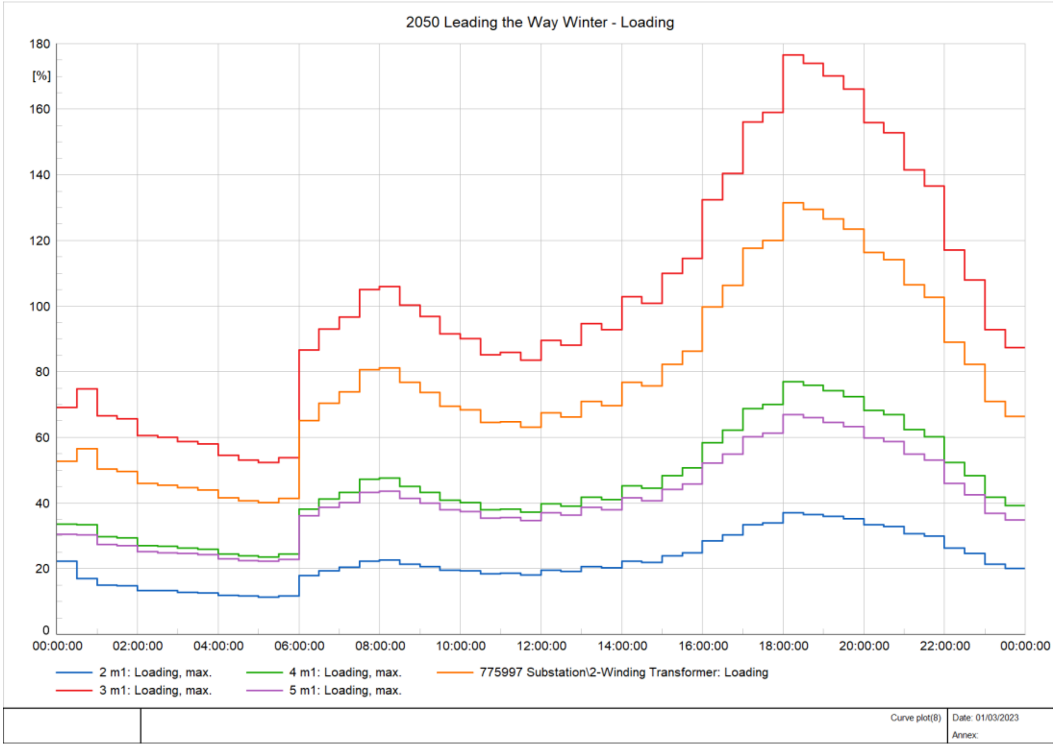

Figure 16 2050 Leading the Way winter loading - without meshing

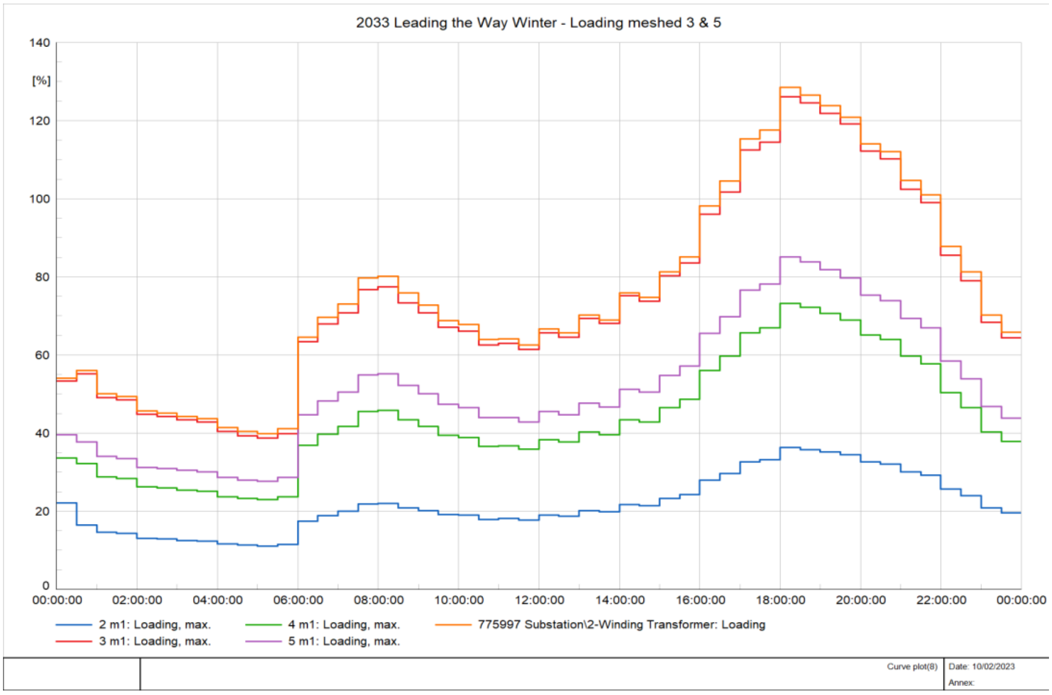

Figure 17 2050 Leading the Way winter loading - with feeders 3 & 5 meshed

Rural

The assessments of smart transformer and on-load tap changers carried out for the urban archetype are equally valid for the rural archetype, so they have not been repeated separately again for the rural studies. The Statcom has been separately assessed for the rural archetype to compare the two possible connection arrangements that might be applicable to a rural circuit, at the source transformer or at the remote end of a LV feeder from the source substation.

Statcom

LV Busbar

Figure 18 shows the voltage profiles with the busbar Statcom. Figure 19, Figure 20, and Figure 21 show the effects of the Statcom when operating at different setpoint voltages , 1.07pu, 1.06pu and 1.05 pu respectively. In all of these cases the Statcom successfully reduces the busbar voltage lowering the network voltage profiles by the same amount. The lower setpoint voltages released more headroom for PV generation in terms of the voltage profile of the feeders. This reduction in busbar voltage is achieved through the absorption of reactive power by the Statcom. The absorption of reactive power will increase the thermal loading of the transformer and add to the losses in the transformer and the HV network.

Conventionally the voltage setpoint for any voltage control arrangement would be measured on the busbar where the voltage needs to be controlled. However, the elevated voltages which must be controlled in this scenario are remote from the busbar and unless these are used to inform the operation of the Statcom, rather than a setpoint on the LV busbar, then the Statcom will be required to absorb reactive power at times of the day when the remote voltages are not going to breach the statutory limits.

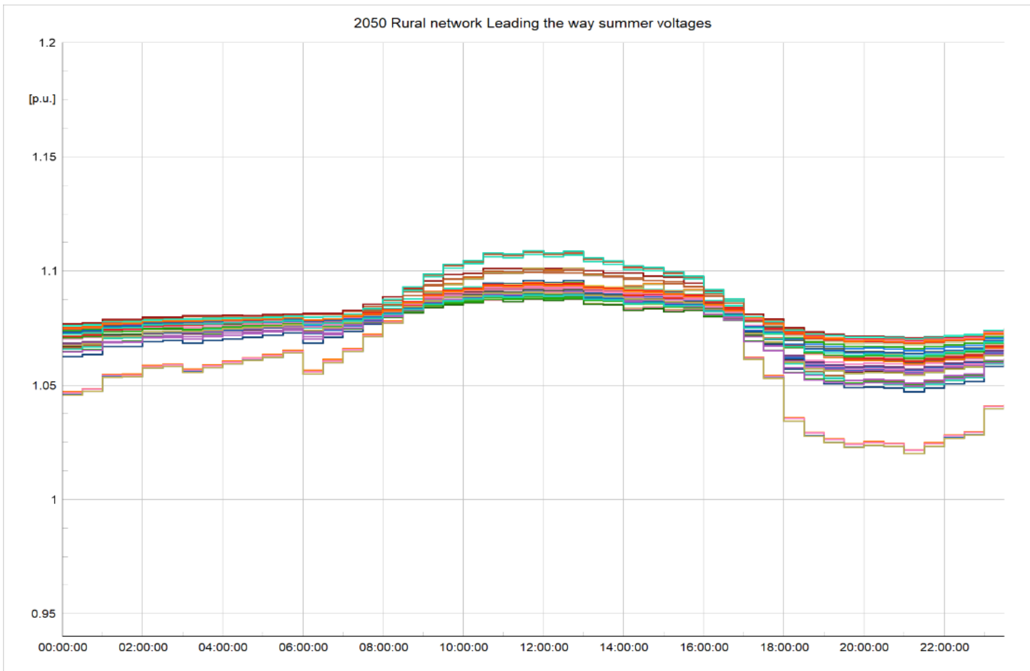

Figure 18 2050 Leading the Way summer voltages – without LV busbar Statcom

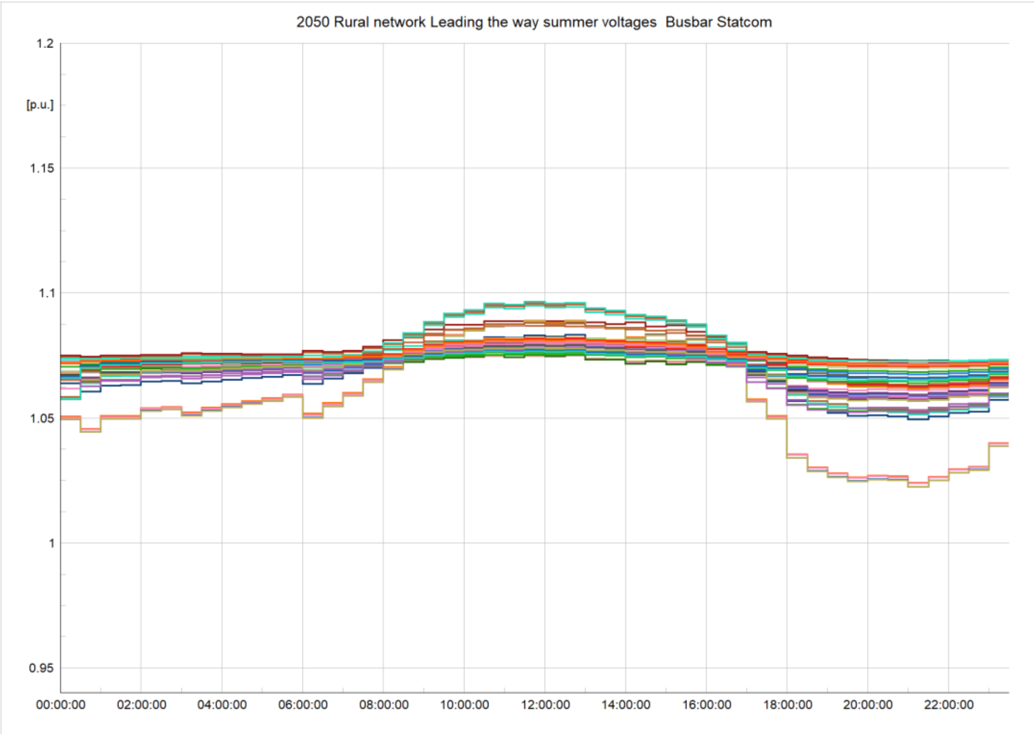

Figure 19 2050 Leading the Way summer voltages - With LV busbar Statcom setpoint 1.07pu

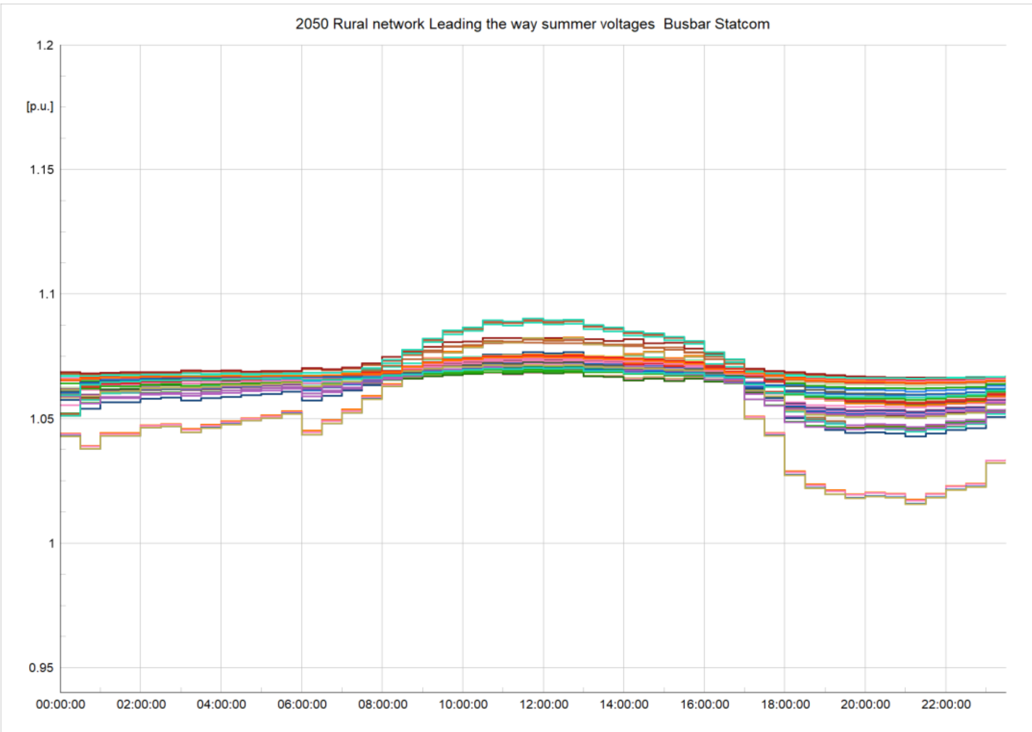

Figure 20 2050 Leading the Way summer voltage - With LV busbar Statcom setpoint 1.06pu

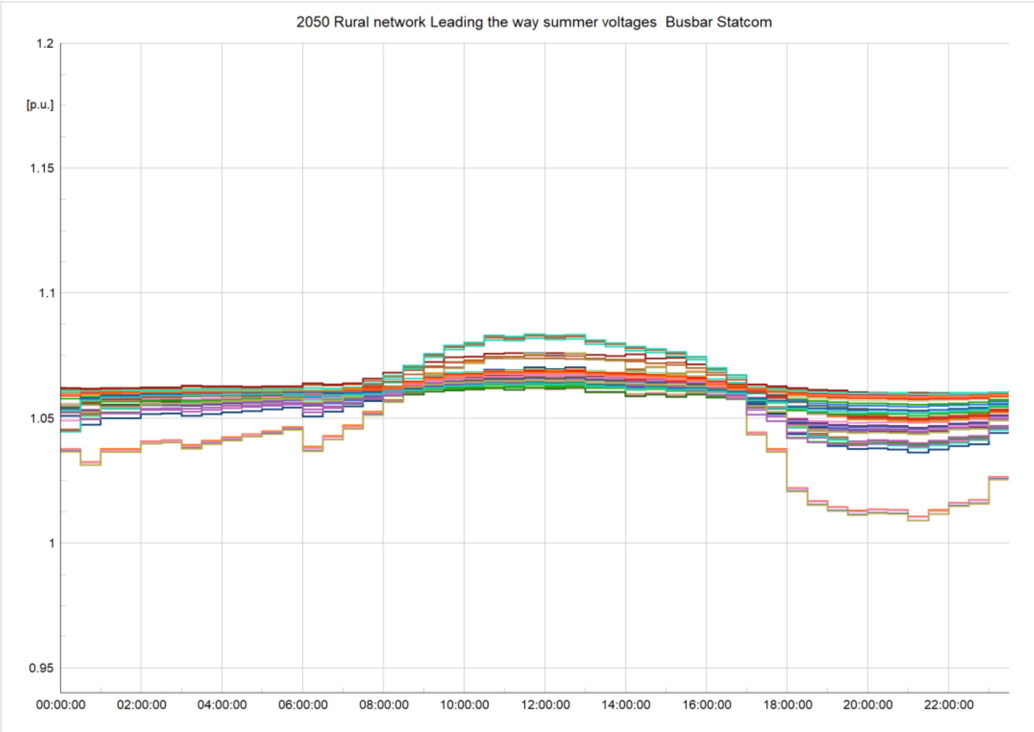

Figure 21 2050 Leading the Way summer voltages - with LV busbar Statcom setpoint 1.05pu

Figure 22 shows the load profiles without the Statcom in service. Figure 23, Figure 24, and Figure 25 show the effect on the load profile of the Statcom operating with a voltage setpoint of 1.07pu, 1.06pu and 1.05pu respectively. With the busbar Statcom in service and acting to lower the voltage, the transformer loading is significantly increased and although the headroom for PV generation is increased the actual thermal capacity for it to export is reduced.

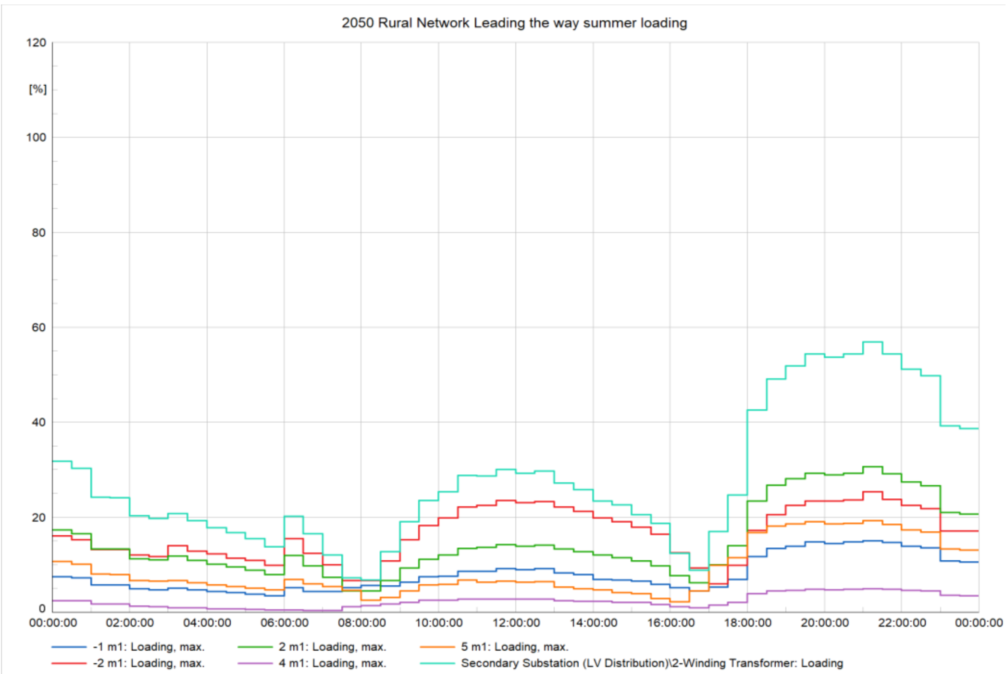

Figure 22 2050 Leading the Way summer loading – without LV busbar Statcom

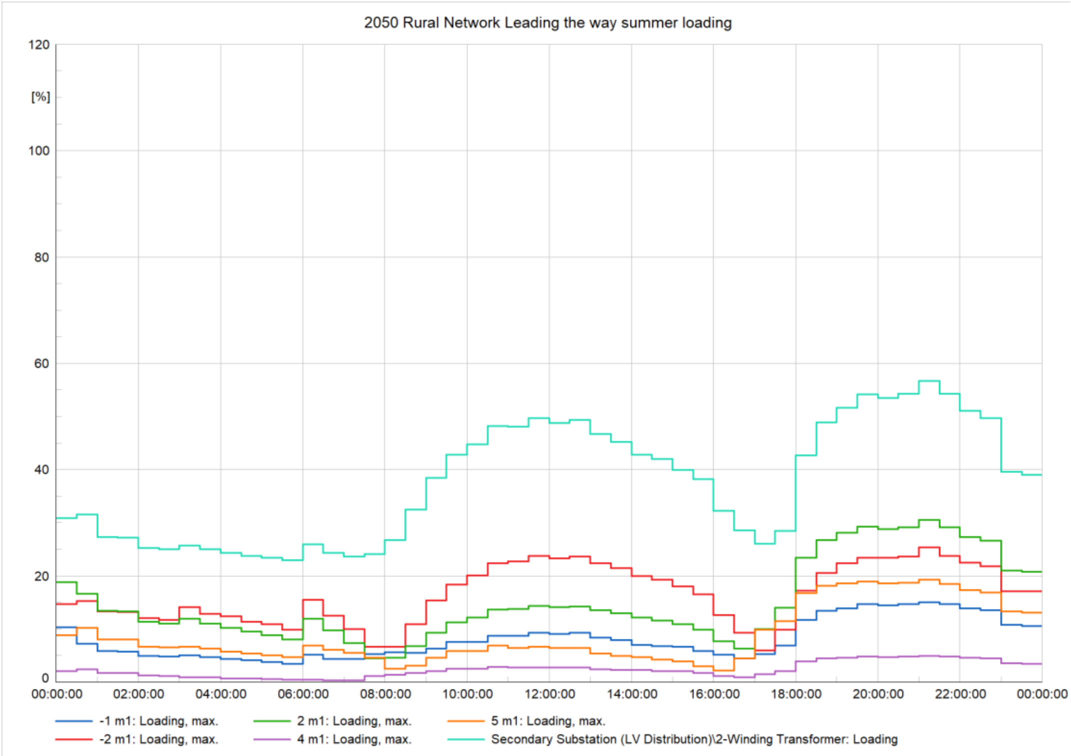

Figure 23 2050 Leading the Way summer loading - with LV Busbar Statcom setpoint 1.07pu

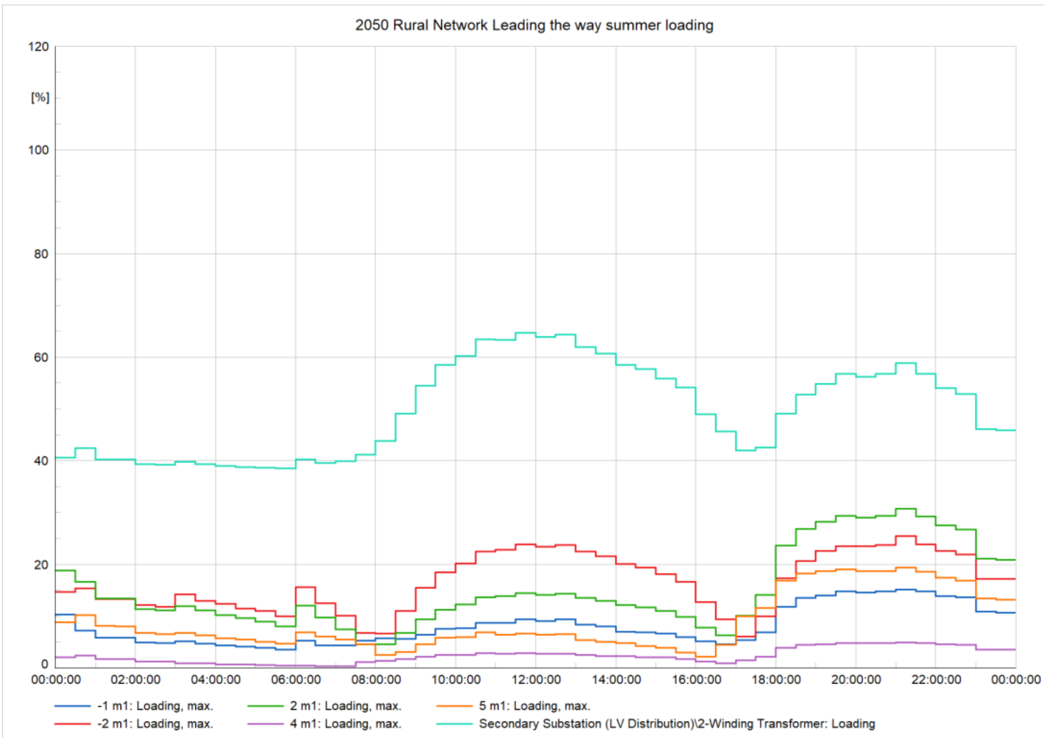

Figure 24 2050 Leading the Way summer loading - with LV busbar Statcom setpoint 1.06pu

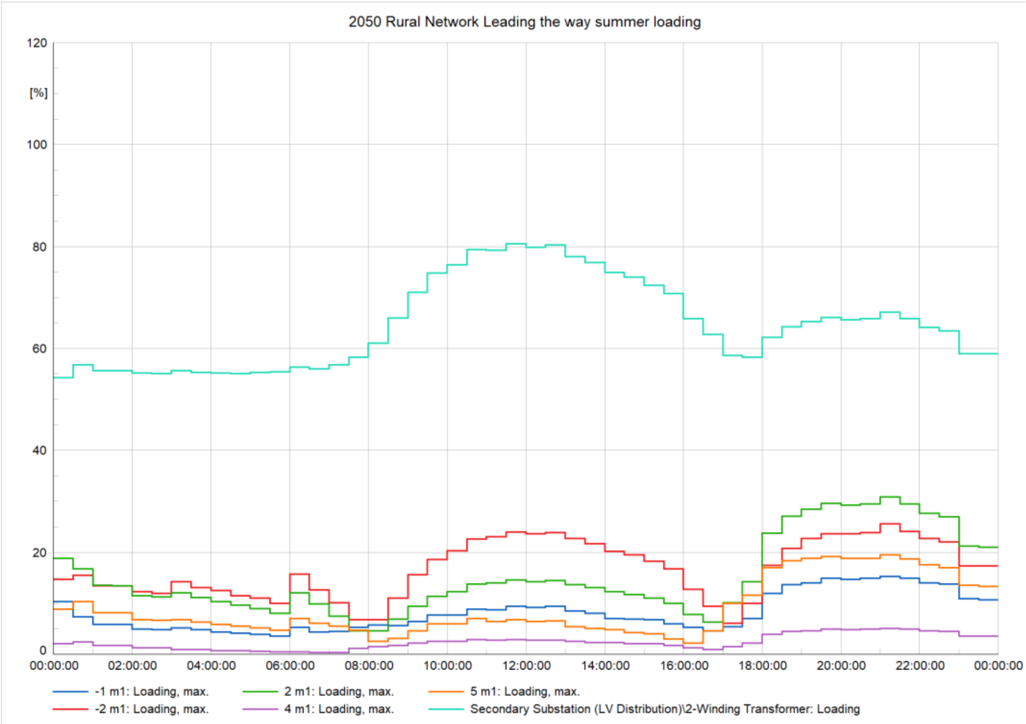

Figure 25 2050 Leading the Way summer loading – with LV busbar Statcom setpoint 1.05pu

As with the Urban calculations previously, the load curve does not exhibit the typical distribution cyclic curve. Although in this case the transformer rating is not exceeded, the losses in the transformer and HV network will be increased due to the reactive power flow. Additionally, the change in profile associated with the transformer loading may impact the basis from which its rating has been determined and risks accelerated thermal ageing, particularly during the warmer summer months.

Other technologies could offer similar benefits in terms of reducing the LV busbar voltage to a level where the remote voltages will not breach statutory voltages. Simply setting the tap position to maintain the busbar voltage at this lower level would deliver the same benefits without the increase in losses. Some care would be necessary to ensure that the variation of the voltage along the HV network did not result in problems but the assessment of voltage effects at HV is outside the scope of these studies.

LV Feeder

This section focusses on the -1 feeder which has been equipped with a Statcom at the end of the feeder to examine the effects of locating the Statcom remote from the substation. Figure 26 shows the range of voltages at customers along feeder -1 without the Statcom connected. Figure 27 shows the effect of the Statcom on the voltage profile of feeder -1

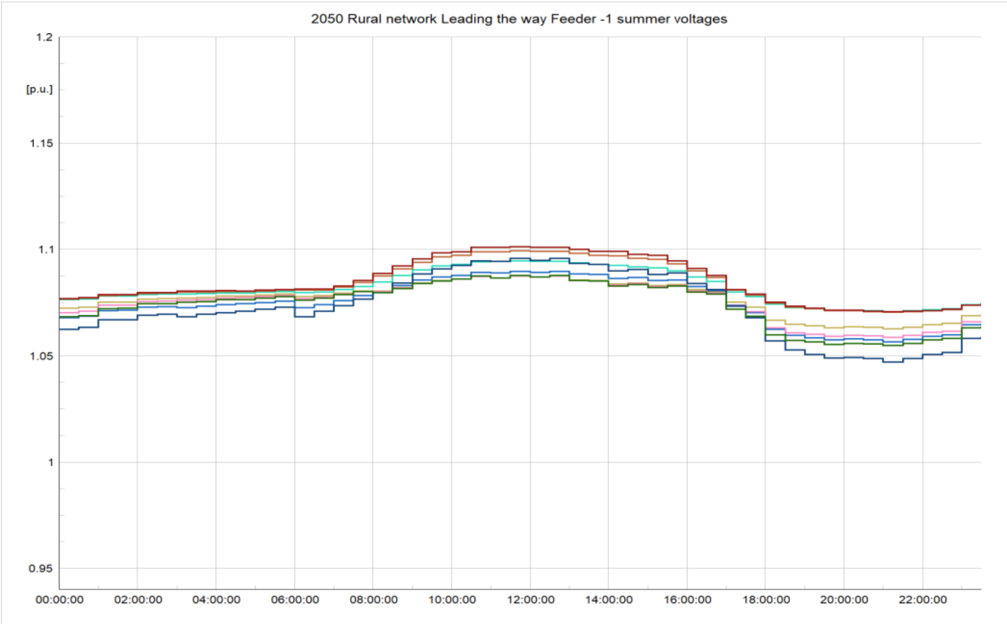

Figure 26 2050 Leading the Way Feeder -1 summer voltages – without LV feeder end Statcom

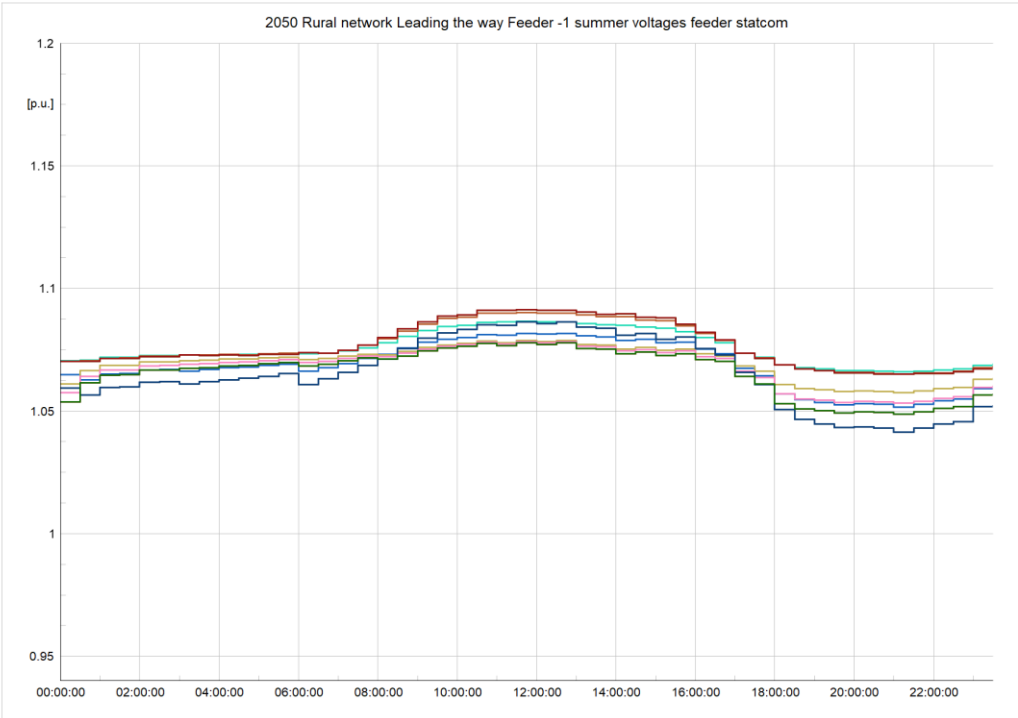

Figure 27 2050 Leading the Way summer feeder -1 voltages – with LV feeder end Statcom setpoint 1.04pu

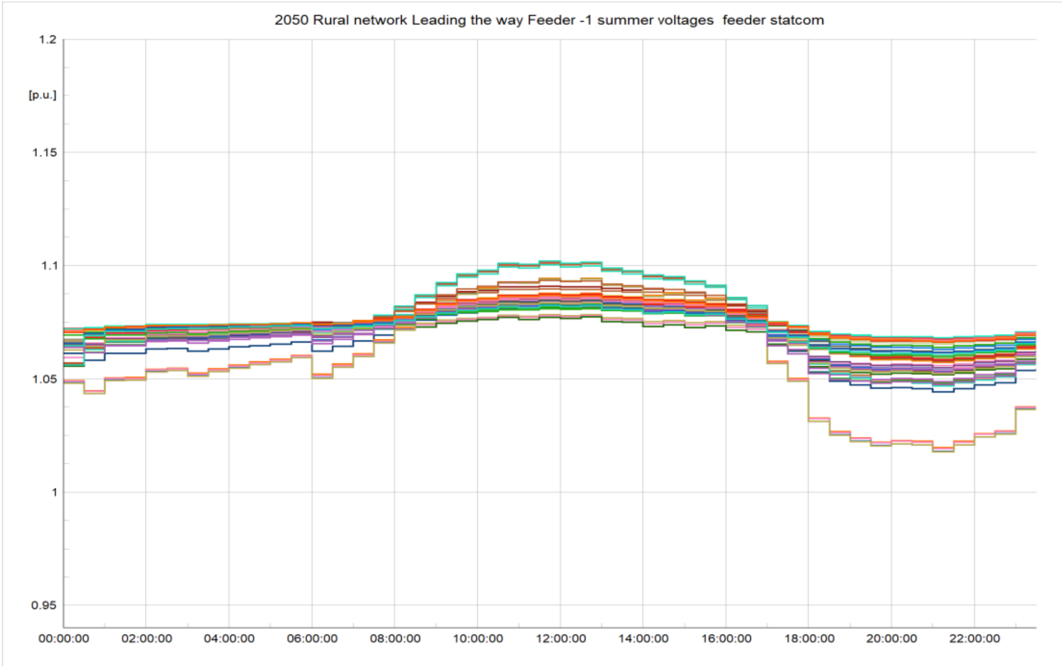

Figure 28 2050 Leading the Way summer voltages all feeders LV feeder -1 Statcom setpoint 1.04pu

Figure 28 shows that although the voltages on the feeder with the Statcom are reduced within statutory limits not all of the voltages are brought within limits. A feeder connected Statcom has the potential to provide a more targeted voltage reduction primarily affecting the feeder it is connected to with a reduced increase in the transformer loading compared to a busbar connected Statcom. A feeder connected Statcom has the disadvantage that it requires a location at or near the end of the feeder to accommodate the Statcom, this may be more readily achieved in a rural environment with LV overhead feeders than on an underground feeder.

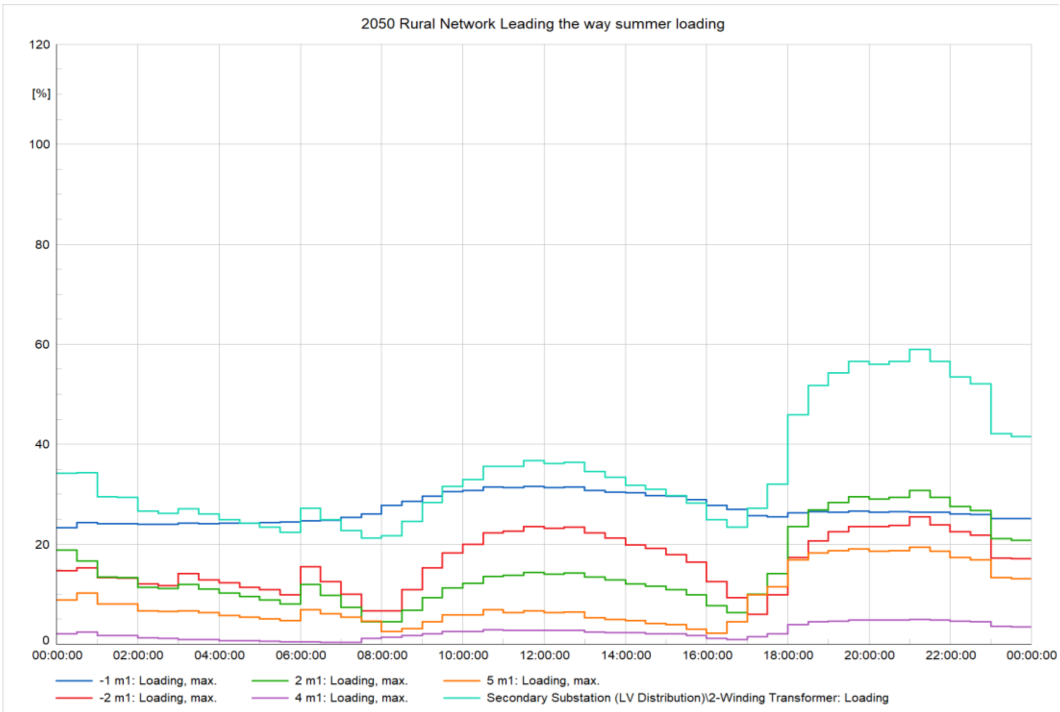

Figure 29 2050 Leading the Way summer loading – with LV feeder end Statcom setpoint 1.04pu

Figure 29 shows the loading of the feeders and transformer with the Statcom located at the end of one of the feeders. The dark blue line represents the feeder -1 which has seen a significant increase in loading despite which it remains well within the circuit capacity. The transformer has also seen an increase in loading although nowhere near as large as for the busbar connected Statcom (Figure 25).

Discussion

Network Monitoring

To achieve the aim of reducing the voltage at the LV busbar to facilitate the connection of more Distributed Generation and Low Carbon Technologies such as EVs and HPs it is essential that the scale of the issue is understood, that is the voltage magnitude at the remote ends of the network should be known so that appropriate setpoints can be determined. Network monitoring at the substation has a key part to play in showing how trends in the network loading are changing. Combining this with smart metering can also provide important insights regarding the voltage magnitude at the service locations and overall network impact of interventions.

‘Smart’ Transformer

This device offers fine control of the busbar voltage around whatever tap position is adopted for the neutral position. This avoids the larger step changes which may be seen with devices such as the on-load tap changer.

The same device can offer a level of phase balancing and active harmonic filtering for a range of lower order harmonics. The amount of phase balancing, voltage control and harmonic filtering that can be achieved is dependent upon the relative levels of each required with the limiting factor being the rating of the control winding. The power electronics controlling the smart transformer and the energy input to the control winding increases the loading applied to the network over and above that of the LCTs being examined. The effect of the LCTs on levels of harmonic distortion varies depending on the specific LCT being considered. PV inverters typically produce effects seen as higher order harmonics due to their switching frequency and these would be outside the filtering range of the smart transformers. HPs employing variable speed drives may produce additional harmonics within the range that a smart transformer mitigates and EVs thus far appear to have been designed to maintain their emissions within the limits which will allow their unconditional connection within the terms of international standards IEC 61000-3-2 and IEC 61000-3-12. That is not to say that under higher uptake scenarios the summation of all of these emissions won’t be a source of concern, with measurement and monitoring of the network conditions being required to inform the need for mitigating measures.

Harmonic filtering and phase balancing offer benefits which primarily apply to the transformer and the HV network upstream of the connection point, the harmonic currents flowing in the LV network will still flow in that part of the network the active injection to cancel the harmonics will only be seen upstream of the filter as a cleaner waveform. There will be a level of reduction in the harmonic distortion within the LV network as a result of the reduction in voltage distortion at the LV busbar which will occur due to the cancellation of the harmonic currents from the LV network that would be flowing in the transformer and HV network.

Statcom

The Statcom solutions do lower the network voltage which has the potential to increase the network headroom for voltage rise due to generation export. However, since this voltage reduction is achieved by absorption of reactive power in the Statcom this does erode some of the thermal capacity of the network. The Statcom is not required all of the time since the worst voltage conditions apply at the peak generation export around the middle of the day. With a time-based controller rather than one only considering busbar voltage it would be possible to avoid the unnecessary additional losses when the Statcom is not required but it would still have the limitation that this solution does not maximise the thermal capacity for DER export.

On-load Tap Changer

The on-load tap changer offers relatively simple voltage control and providing that the most appropriate setpoint is determined using monitoring data it should be possible to avoid the step change which pushed customers out of limits in one of the study runs. Traditional network design was based on a setpoint voltage and an assessment of the voltage drop expected under After Diversity Maximum Demand (ADMD) conditions. The increasing uptake of embedded generation technologies such as PV panels coupled with additional demands from other LCTs dramatically affects the status quo within the distribution networks. As we have seen in the studies, the customers which experience the greatest voltage rise under peak PV output and the greatest voltage depression under peak demand are all towards the remote end of the LV feeders. As the uptake of the LCTs examined in these studies increases it will become increasingly important that the remote customer voltages are used to inform the operation of tap changing systems. Voltage control may need to move away from a tiered time delay based system to a more interactive and holistic system where the effects at LV may inform and even amend the target settings at HV.

Network meshing

This has the potential to share capacity more equally between feeders freeing up some thermal capacity. However, there are different effects on the fault level within the network depending upon whether the meshing is carried out between circuit from the same LV board as reviewed in this study, from different substations on the same HV feeder or between substations fed from different HV feeders and even between substations supplied by different Primary substations.

The first of these will increase the fault level along the LV feeders slightly and will lead to longer clearance times as fuses operate.

The other scenarios described will likely have similar clearance times but higher fault levels and also present the possibility of back energising a faulty HV feeder depending upon where HV protection has operated.

Fault Level Effects

Photovoltaic generation

PV inverters as a rule produce a maximum output of 1.1 times their rated output under fault conditions. Assuming a limit of 3.6kVA at 230V we assume a fault contribution of around 4kVA per single phase unit. At an individual transformer level that does not appear to be any more onerous than some of the estimates of fault level contribution from induction motors in ENA Engineering Recommendation P25. The combined effect at HV of the contribution from several substations cannot be assessed with the models developed for this project.

Smart Transformer

Accounting only for the effect of the discrete trimming transformer the LV fault level contribution from the system is reduced in the urban example by around 3% compared to conditions without the smart transformer. This level of reduction is unlikely to be large enough to have any serious effects on the network, any effect on the level of harmonic distortion will likely be offset by the filtering capabilities offered by the ‘smart transformer’. The difference in the fault level which results from using the smart transformer is not sufficient that it would be the most cost-effective method of delivering a reduction in source fault contribution.

Meshing

Between circuits on the same substation

Where circuits are meshed between the same source LV fuse board there will be an increase in the fault level along the meshed feeders, However, nothing will exceed the fault level at the source substation. The fault current will be shared along these two circuits according to the relative position between the two sources and the impedances of the cables in those two routes. Examining the range of results along the length of feeders 3 and 5 yields the results given in Table 1 below. Figure 30 shows the location of the points on the meshed circuits reported in Table 1.

Very close in to the substation (Feeder 5 first joint) the fault current is essentially the same as the busbar fault current in an unmeshed condition, however when the fuse blows clearing the fault from one end the fault current infeed from the other side of the meshed feeder then increases to a point where fuse operation will occur although the duration will be extended.

Further along the feeders (Feeder 3 first joint) the total fault current reduces but the share of the fault current also shifts. Again, one side will clear rapidly yielding an increased fault current in the other side of the mesh which will mean the overall energy released into the fault is increased.

At the meshing point on the network we can see that the fault current would normally be that seen after the initial clearance (3.276kA) but in this case the overall fault current increases to 6.972kA, clearly this increases the energy released into the fault.

Table 1 Meshed circuit fault currents

Location	3 phase fault current (kA)	Feeder3 fault current (kA)	Feeder 5 fault current (kA)	Fault current after initial clearance (kA)
Feeder 3 first joint	14.930	14.22	0.796	2.177
Feeder 5 first joint	19.823	0.055	19.878	2.086
Mesh point	6.972	2.745	4.266	3.276

Between circuits on adjacent substations

This scenario cannot be modelled in the models that have been developed for this project. Experience of a similar assessment in an industrial setting shows that where there are two separate transformer infeeds the fault current is increased at the busbar and the clearance by the remote end is likely to take longer than the close in end. Along the feeder the fault infeeds swap over, reducing as the fault location moves away from one infeed and increasing as it moves towards the other infeed. At the midpoint of the two feeders the fault current is lower than at the busbars but still increased compared to what it would have been from a single infeed.

One key difference between meshing between circuits on the same substation and meshing between circuits fed from different substations is the question of how to manage the correct protection of the networks. Where the feeding substations are on separate HV feeders there is scope following a HV fault for one substation to back-energise the other and hence the faulty HV feeder. Whilst this would not occur if the two substations were on the same feeder it cannot be guaranteed that they will always remain on the same feeder either due to routine switching or automatic fault sectionalising on networks with secondary automatic points in the HV network.

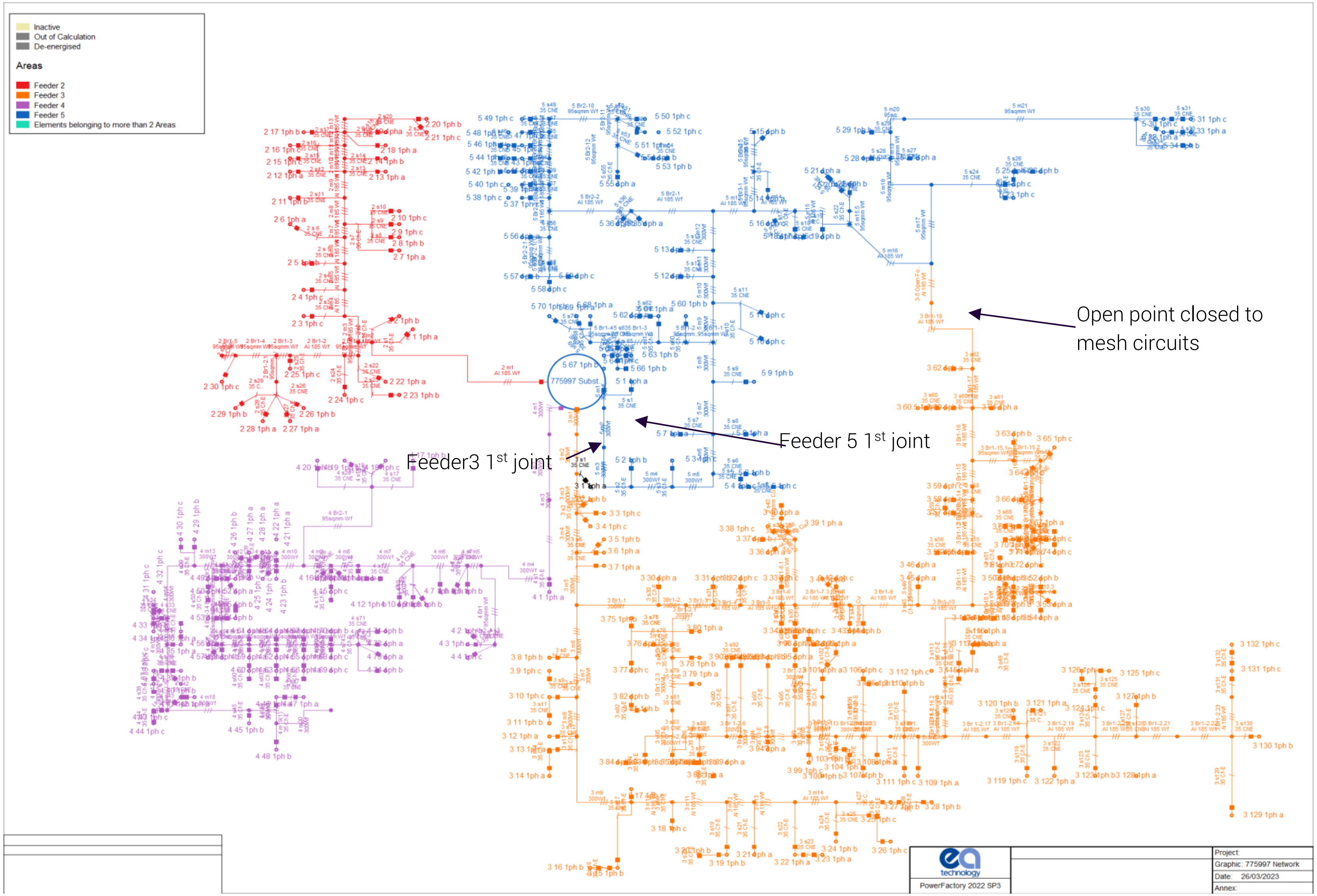

Figure 30 Meshed circuit locations

Summary

Table 2 below shows a summary of the innovative technologies, the benefits claimed, the successes and issues identified.

Table 2 Summary of Technologies examined

Innovative Technology	Claimed benefit	Benefit achieved	Potential Issues
Smart Transformer	Fine voltage control	Yes	Must increase overall loading applied to the source transformer for all of the benefits offered.
	Phase balancing	Not modelled	Benefits will only be realised upstream of the transformer
	Harmonic Filtering	Not modelled	Benefits primarily expected to be realised upstream of the transformer with some improvement expected at LV switchboard
Statcom	Voltage control	Yes	Under PV export absorbs reactive power which reduces available thermal capacity of upstream cables and transformers.
On-load tap-changer	Voltage control	Yes	May be limited capacity to reduce voltage under conditions when HV voltage rises on feeder due to PV export and limited tap ranges of existing transformers
Meshing	Shared loading	Yes	Offers limited benefits to defer reinforcement for a period, does affect the fault level on the network.

Conclusions

The main conclusions of this report are:

Since the voltage problem to be solved presents at the customer supply terminals during periods of export from DER all of the voltage control solutions are inherently limited if the voltage used to reflect the setpoint is that seen on the LV busbar .

Controlling the voltage by importing reactive power does not maximise the capacity for DER export since the available thermal capacity of upstream conductors and equipment is degraded.

Network monitoring is essential to provide the necessary insights into network conditions to aid in setting up the selected interventions to provide the optimum solution.

The smart transformer solution offers the finest degree of control of the busbar voltage avoiding the potential problem highlighted with the on-load tap changer and the increased losses and reduction in available transformer capacity associated with absorbing reactive power with a Statcom.

Recommendations

The main recommendations of this report are:

Enhanced Monitoring of the LV network should be considered as an important enabler for other targeted interventions.

Further studies should be considered to explore the effects of voltage drop in the HV network which has been excluded from these studies.

Further studies should be undertaken to consider the most appropriate nominal ratio and tap ranges and step sizes for future distribution transformers

Further studies should be considered to understand the potential Power Quality effects of large scale LCT take up.

References

[1] A. Bower and T. Stone, "EA16141-TR3: SILVERSMITH - PowerFactory Network Study Results," EA Technology Ltd., Chester, UK, 2023.

[2] T. Stone and K. Gebremichael, "EA16141-TR4 SILVERSMITH Functional Requirements Report," 2022.

[3] S. Lindmark and T. Stone, "EA16141-TR2 SILVERSMITH Literature Review," 2022.

[4] T. Stone and D. Mills, "EA16141-TR1 - SILVERSMITH Network Study Results," EA Technology, Chester, UK, 2022.

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