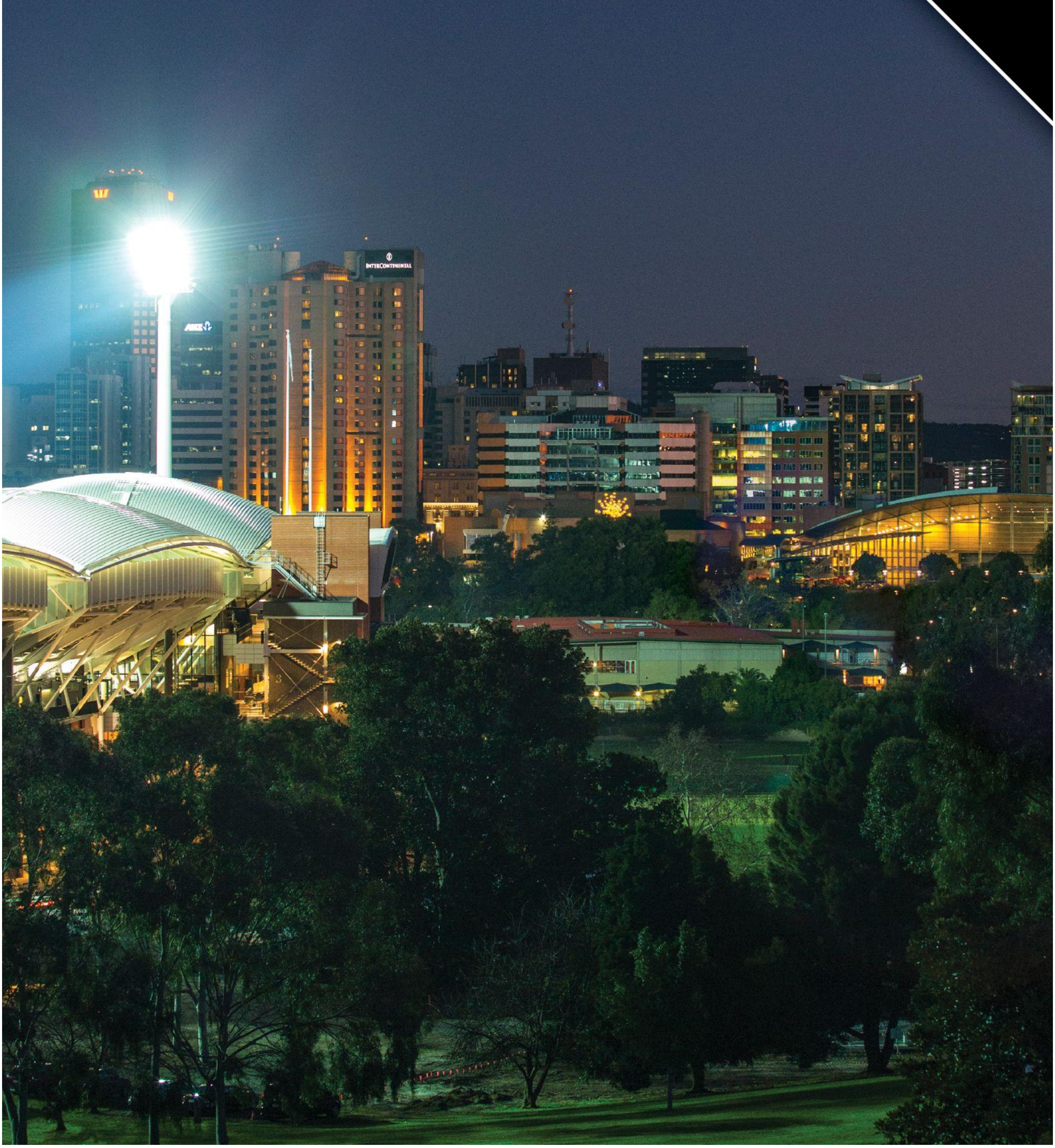
Attachment 13.2

Power Systems Consulting (PSC): Impact of distributed energy resources on quality of supply

May 2014



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SA POWER NETWORKS

CONSULTANCY SERVICES FOR

IMPACT OF DISTRIBUTED ENERGY RESOURCES ON QUALITY OF SUPPLY

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Executive Summary

SA Power Networks is required, by the South Australian Electricity Distribution Code and the National Electricity Rules, to meet specific criteria relating to quality of supply. With recent and forecast increases in penetration of distributed energy resources (DER) in the low voltage (LV) and SWER (HV) systems, SA Power Networks engaged PSC to assess the impact of DER penetration on quality of supply. Quality of supply parameters examined in this report are steady state voltage regulation, voltage fluctuations and voltage unbalance. Harmonics, a further quality of supply parameter regulated by the Electricity Distribution Code, have been excluded from the scope of the study.

The increase in photovoltaic solar is of particular interest in the South Australian context. The study scope has also included electric vehicles, energy storage and controllable load.

The investigation has been carried out by creating models of fifteen representative feeders, spanning several categories of supply area, including underground, overhead and single-wire earth return (SWER). Typical per-customer energy ratings for the various DER types have been included for varying penetration levels. Simulations have been run on the models to assess the quality of supply parameters under study.

Key findings of the investigation are:

1. On some old LV feeders in both overhead and underground networks, voltage regulation requirements limit acceptable photovoltaic solar (PV) penetration to around 25% of customers.
2. For SWER feeders, voltage regulation limits are stressed under peak demand prior to the introduction of DER. Addition of photovoltaic penetration to 100% of customers introduces no new voltage regulation violation under minimum demand.
3. Voltage fluctuations are, with one exception, within the acceptable range suggested by AS/NZS 61000-3-7 across the scenarios studied.
4. Voltage unbalance, which simulations show to be in excess of the present 2% limit for one feeder, is exacerbated by the addition of credible penetration levels of DER, including DER other than solar.

Analysis of mitigation measures on a subset of representative LV feeders suggests that:

1. HV substation voltage regulation can be used, in most instances, to overcome voltage regulation issues provided that the voltage regulation range of the LV network is known.
2. Changes to transformer tap settings (where available) or reconductoring feeder backbones may be sufficient to enable substantial increases in acceptable DER penetration levels.
3. Feeder load balancing and controllable load are also effective, provided that the HV voltage can be kept in the lower half of its usual range – that is, (i) the full LV network operates at a lower voltage, and (ii) the

HV voltage is managed to avoid introducing voltage regulation violations under peak demand.

4. Forecast levels of energy storage do not offer substantial increases in the acceptable photovoltaic solar penetration level.
5. Dynamic VAr support is also broadly effective as a mitigation measure, while offering the disadvantage of requiring additional capital investment.

For the SWER feeders, analysis of mitigation measures suggests that:

1. Changes to HV voltage regulation, such as replacement or optimal placement, and / or the addition of LV voltage regulation for specific customers may be sufficient to allow addition of DER load during feeder peak demand periods.
2. Changing the taps of the SWER transformer to control voltage regulation issues arising during peak demand introduces new voltage regulation issues under minimum demand.
3. Discharging of storage load is not an effective mitigation measure.
4. Dynamic VAr support is also broadly effective as a mitigation measure, while offering the disadvantage of requiring additional capital investment.

1. Introduction

1.1 Objective

This project assessed the likely impact of photovoltaic solar (PV), plug-in electrical vehicle (EV) and other distributed energy resources (DER) on the Quality of Supply (QoS) for typical LV and SWER network areas. For example, increasing penetration of distributed PV within the network can lead to challenges in complying with upper bounds on voltage requirements; increasing penetration of distributed EV load within the network can lead to challenges complying with lower bounds.

The results of the investigation and details of proposed remediation are intended to be used by SA Power Networks to underpin the future approach to Quality of Supply issues, as well as to provide support to current and future reset submissions.

1.2 Scope of work

The scope of this project was to develop a power systems model predicting the impacts on Quality of Supply of increasing distributed energy resource penetration for typical LV network areas within the SA Power Networks service area. Whilst the primary concern was steady state voltage regulation, for the purposes of this investigation QoS was taken to encompass broader issues of power quality, in line with the principles of Section 1.1.5 of the South Australian Electricity Distribution Code EDC10:

- Steady-state voltage at the customer's supply address, per AS 60038.
- Voltage fluctuations at the customer's supply address, per AS/NZS 61000.3.7 which is called up by Schedule 5.1a.5 of the National Electricity Rules.
- Voltage unbalance factor in three-phase supplies, per SA Power Networks specification via Power Quality Manual clause 3.9.2.

Four DER categories have been considered in this analysis:

1. [PV] photovoltaic solar;
2. [EV] plug-in electrical vehicles;
3. [CL] controllable load, considered to be hot water systems; and
4. [ST] battery storage.

The scope of work has been executed via a collaborative approach between SA Power Networks and PSC.

2. Approach to the study

2.1 Overview of methodology

At a high level, the work carried out for this investigation has been:

a) the selection of a representative sample of the SA Power Networks network in the form of 15 representative feeders, three each representing the area types of old and newer underground, old and new overhead and SWER (single-wire earth return) networks;

b) obtaining feeder topology and load profile data in preparation for modelling analysis;

c) DER scenario configuration including PV, EV, CL and ST implemented in each of the LV models; and

d) an assessment of the quality of supply parameters and limits which include voltage regulation, voltage fluctuation and voltage unbalance conducted.

This section outlines the methodology used in the study.

2.2 DER scenario configuration

Figure 2-1 outlines the PV, EV, CL and ST categories to be constructed and assessed for both a peak (D1) and minimum (D2) demand level for each of the test cases.

Demand levels were obtained from feeder load profile data and correspond to time periods when feeder demand is generally at a peak or at a minimum. The 12-2PM time slot was used to construct D2 since this corresponds to maximum PV output and minimum demand; the 5-7 PM time slot was used to construct D1 since this corresponds to maximum residential customer load and minimum PV output.

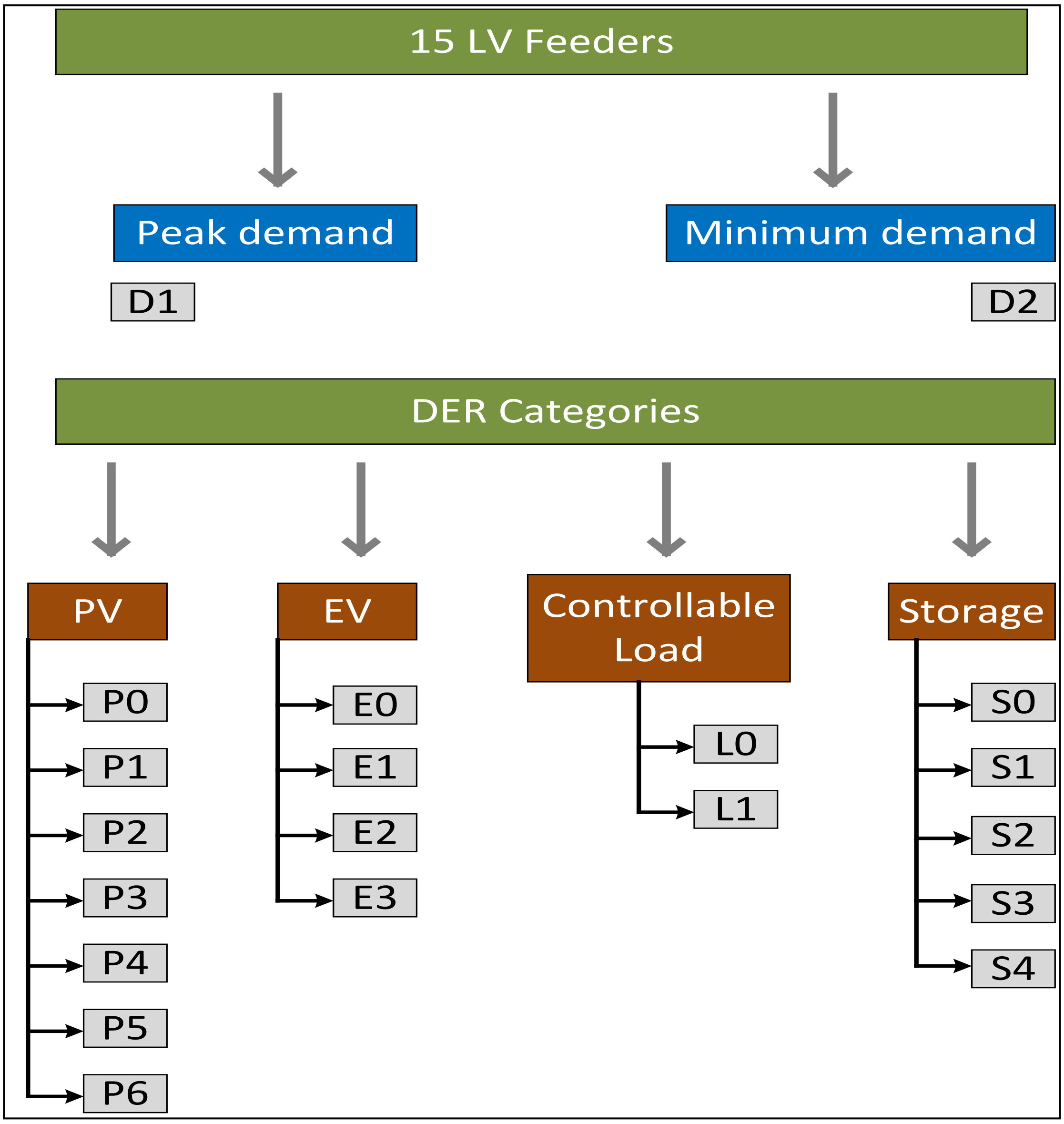


Figure 2-1: Construction of DER scenarios to be assessed for the 15 test cases

Table 2-1 provides a description of each of the DER categories shown in Figure 2-1.

Table 2-1: DER penetration levels to be employed in scenario construction

DER Category	ID	DER Penetration Level
PV Generation	P0	No PV installed
	P1	Present level of PV installed on LV feeder
	P2	25% of customers on LV feeder; each inverter @ 2.5 kW
	P3	50% of customers on LV feeder; each inverter @ 2.5 kW
	P4	75% of customers on LV feeder; each inverter @ 2.5 kW
	P5	100% of customers on LV feeder; each inverter @ 2.5 kW
	P6	50% of customers on LV feeder; each inverter @ 5 kW
Electric Vehicle Load	E0	No EV
	E1	5% of customers on LV feeder, each EV @ 0.8 kW
	E2	10% of customers on LV feeder, each EV @ 0.8 kW
	E3	15% of customers on LV feeder, each EV @ 0.8 kW
Other Controllable Load	L0	No Other Controllable Load is available for control
	L1	Existing Controllable Hot Water Load on LV feeder , each hot water system @ 2.5 kW
Storage	S0	No storage
	S1	5% of customers on LV feeder; each storage system @ 2.5 kW – charging (load)
	S2	10% of customers on LV feeder; each storage system @ 2.5 kW – charging (load)
	S3	5% of customers on LV feeder; each storage system @ 2.5 kW – discharging (generation)
	S4	10% of customers on LV feeder; each storage system @ 2.5 kW - discharging (generation)

The DER categories were based on the following assumptions as provided by SA Power Networks:

- PV inverter size of 2.5 kW for P1 to P5.
- PV inverter size of 5 kW for P6 (enabling assessment of the impact of a larger PV inverter size).
- Typical EV load to be 0.8 kW.
- Typical size of hot water system to be 2.5 kW.
- Typical size of battery storage to be 2.5 kW, capable of storing the power provided by the PV output, at any time and capable of charging at minimum load and discharging under peak load scenarios.

Solar profile data provided by SA Power Networks (sourced from Energeia) was analysed to determine likely PV utilisation factors1 to be assumed under each of the peak and minimum load cases. This data was used to construct load duration curves to determine PV utilisation versus percentage of time under each of the peak and minimum load periods. In order to represent a worst case scenario for PV utilisation, a PV utilisation factor at 20% of the time was derived from each of these load duration curves. Based on this assumption, a PV utilisation factor of 80% was assumed for minimum load

[1] PV utilisation factor describes the solar PV performance in relation to the installed capacity. At a PV utilisation factor of 80%, a 2.5 kW inverter would be generating 2 kW

case (12-2PM) as shown in Figure 2-2. A PV utilisation factor of 20% was assumed for the peak load case (5-7PM) as shown in Figure 2-3. [2]

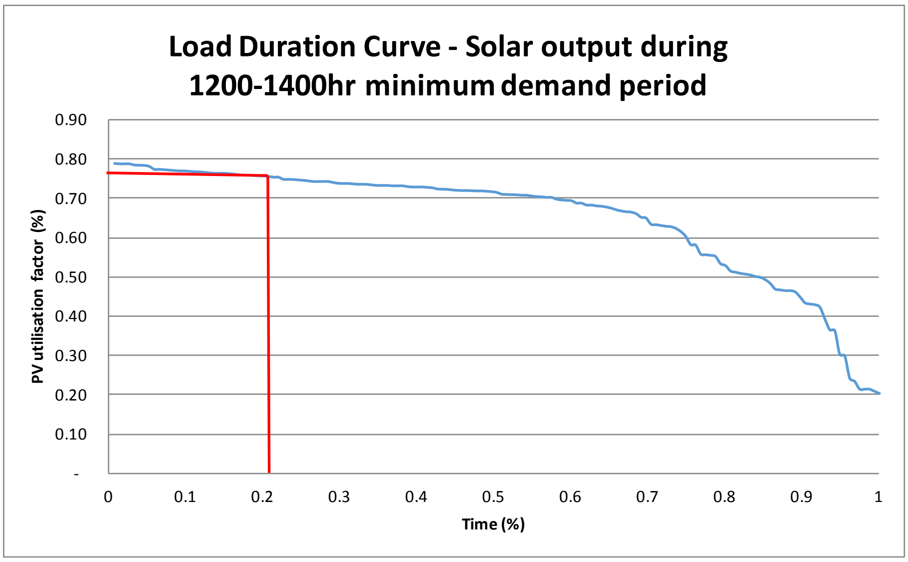


Figure 2-2: Load duration curve – PV output during 12-2PM load period

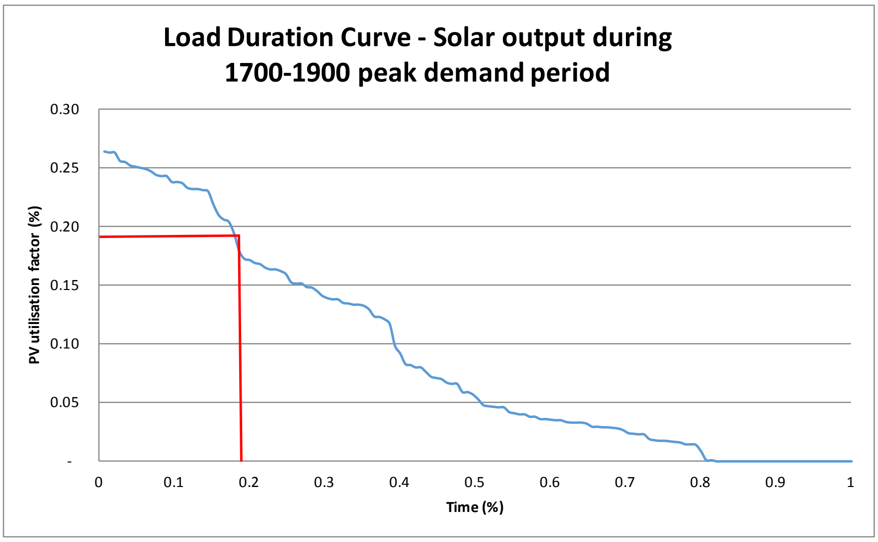


Figure 2-3: Load duration curve – PV output during 5-7PM load period

[2] A sensitivity analysis was also conducted on one LV feeder under the assumption of average solar output, i.e. 50% of the time, which corresponds to 70% PV during 12-2PM and 5% PV during 5-7PM demand periods. The sensitivity analysis showed only slightly lower voltages under each of these assumptions but no difference in the amount of PV able to be connected to the feeder. The assumption of a maximum 80% PV utilisation therefore represents a worst case scenario for minimum demand conditions. For the 5-7PM peak demand period, a sensitivity analysis was conducted on one SWER feeder. Since the P0 scenario assumes no PV on the feeder, where P0 shows no undervoltage issues, the rest of the penetration scenarios will only result in voltage increases if the PV utilisation factor is reduced from 20% to 5%.

2.3 Representative test cases

Three feeders from each of the area type categories (old and newer underground, old and new overhead, and SWER) were selected for study. The representative sample of feeders was based on:

- area type;
- a combination of 11 kV and 7.6 kV HV feeder voltages;
- various levels of existing PV penetration;
- availability of feeder monitoring; and
- SWER feeders with known quality of supply issues.

Table 2-2 shows the list of LV and SWER feeders selected for the analysis, which represent typical feeders in their respective area types.

Table 2-2: Selection of representative feeders for study

Area Type	LV Feeder / Transformer	Voltage (V)	Substation	HV Feeder
Old Overhead	HH341A - 81	11000/433	Norwood	Kensington 11 kV
	AP351B - 2034	7600/433	Woodville	Cheltenham 7.6 kV
	AP344D - 15	7600/445	Port Adelaide	Alberton 7.6 kV
New Overhead	SM126A - 159	11000/433	Blackwood	Glenalta 11 kV
	EL13 – 57	11000/433	Elizabeth Downs	Anderson Walk 11 kV
	HH177F - 253	11000/433	Ingle Farm	Montague Farm 11 kV
Old Underground	EL14 – TC54743	11000/433	Elizabeth Downs	JK Cable Elizabeth Downs 11 kV
	AP125B - 15350	7600/433	Blackpool	Pelican Point 7.6 kV
	AP529E - 30156	7600/433	Largs North	Military Road 7.6 kV
Newer Underground	HH496C - 26079	11000/433	Golden Grove	Wynn Vale South 11 kV
	HH121B – TC46352	11000/433	Campbelltown	Felixstow 11 kV
	HH409F - 29068	11000/433	Woodforde	Morialta 11 kV
SWER	GU - 37	11 / 19 kV		Cookes Hill 19 kV SWER
	MTB – 82	11 / 19 kV		Bremer 19 kV SWER
	M - 23	11 / 19 kV		Rockleigh 19 kV SWER

2.4 Feeder data

2.4.1 Feeder topology

Transformer ratings, cable / conductor types and lengths, customer numbers and locations for each of the representative feeders were extracted from FieldView[3]. For the overhead networks the conductor types were not available in FieldView and were provided following a visual inspection of these feeders by SA Power Networks. For some old overhead LV feeders (AP344D-15 and AP351B-2034), typical conductor types were modelled instead of actual, in order to provide a more accurate representation of a typical old overhead area.

[3] The geographical information system used by SA Power Networks.

2.4.2 Load profile data

Load profile data (September to December 2013) was extracted from OpenGrid[4] for each of the metering points of most of the test cases. For the test cases with no meters in OpenGrid, the load profile data was provided by the QoS Planning team.

Figure 2-4 provides a graphical overview of each feeder showing the peak and minimum load in relation to the transformer rating as well as the existing PV penetration on each of the feeders.

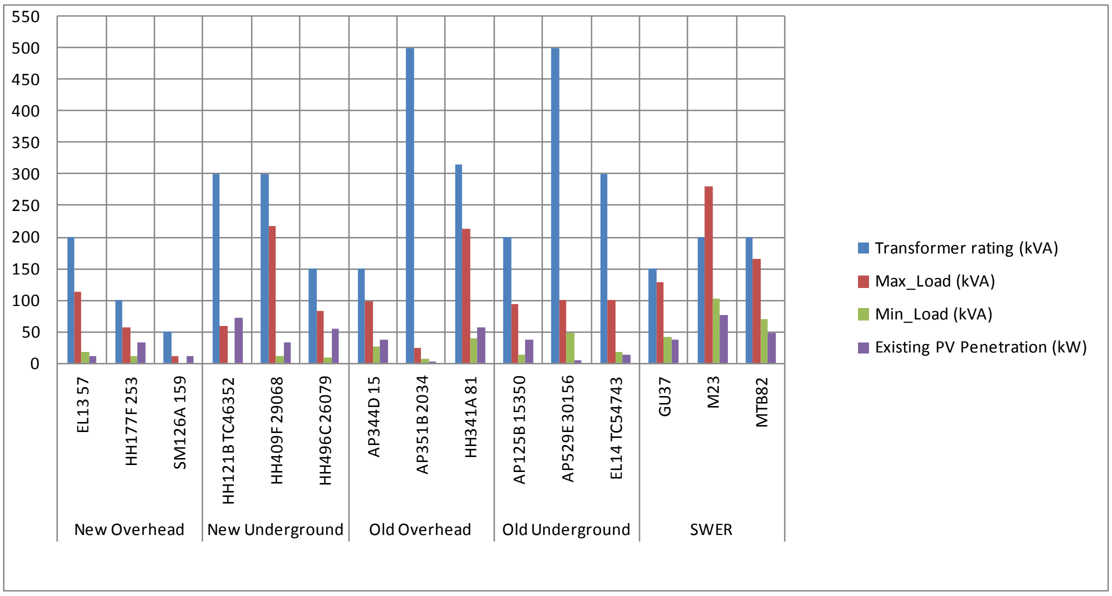


Figure 2-4 : Feeder overview of 15 test cases

2.5 Quality of supply parameters

The limits against which the QoS parameters are assessed are shown in Table 2-3. AS 61000.3.100 only provides the nominal steady state voltage limits for 230/400 V low voltage systems but since the LV networks in the study are predominantly 433/248 V, these limits have been adjusted based on the nominal values used in the standard, as shown in Table 2-3[5].

Table 2-3: Quality of supply limits

QoS Parameter	**Nominal steady state voltage limit (phase to neutral)[6]**		**HV steady state voltage limit (phase – phase)[7]**
Voltage Regulation	**400/230V LV systems**	**433/248V LV systems**	**19.1 kV SWER**

[4] A data management tool used to collect and store data from LV transformer monitoring trial.
[5] One LV feeder, AP344D-15, is a 445/256V system and thus has a overvoltage limit of 0.98 pu and an undervoltage limit of 0.83 pu
[6] AS 61000.3.100-2011 – Table 2
[7] AS 61000.3.100-2011 – Table 4

Overvoltage limit	1.1 pu	1.02 pu	1.06 pu
Undervoltage limit	0.94 pu	0.87 pu	0.90 pu
QoS Parameter	**Voltage fluctuation[8]**		
Voltage Fluctuation limit	Within 3-5 %		
QoS Parameter	**Voltage unbalance factor[9]**		
Voltage Unbalance limit	2% continuous		

Voltage fluctuations can be identified by determining voltage changes attributable to changing cloud cover. For each representative feeder, the voltage change occurring between PV at full output and PV off was calculated and tested against the 3-5% criterion in AS/NZS 61000.3.7.

For voltage unbalance, the results are taken directly from the PowerFactory results and have been calculated as:

$$\text{Voltage unbalance} = V_{negative} / V_{positive} * 100\%$$

Voltage unbalance is tested against the voltage unbalance limit of 2% as specified in the SA Power Networks Power Quality Manual clause 3.9.2.

[8] AS/NZS 61000.3.7
[9] SA Power Networks Power Quality Manual clause 3.9.2

3. Power system modelling and analysis

This section outlines the methodology behind the development of three-phase unbalanced PowerFactory models for the representative feeders. Each of the 15 representative feeders include both a peak demand and a minimum demand case.

3.1 Data requirements

3.1.1 Cable / conductor parameters

Table 3-1 outlines the conductor types used for each of the area types as well as the electrical parameters used in the models. Full details of the data employed in the models are given in Appendix A.

Table 3-1: Cable / conductor types and parameters

Area type	Cable / conductor types	Cable / conductor electrical parameters					
		Rpos (Ω/km)	Xpos (Ω/km)	Rzero (Ω/km)	Xzero (Ω/km)	B (μS/km)	Rating (A)
Underground	XLPE AL 150 mm^2	0.265	0.088	0.825	0.088	-	235
	XLPE AL 35 mm^2	1.11	0.095	3.47	0.095	-	100
	PVC Cu 0.06 sq in	0.627	0.083	1.95	0.083	-	110
	PVC Cu 0.0225 sq in	1.5	0.086	4.67	0.086	-	66
Overhead	0.06 Cu	0.252	0.378	0.428	1.361	-	252
	0.1 Cu	0.272	0.361	0.463	1.30	-	349
	0.2 Cu	0.139	0.336	0.236	1.211	-	528
	7/14 Cu	0.787	0.395	1.339	1.421	-	183
	7/16 Cu	1.231	0.409	2.093	1.471	-	140
	4x95 ABC	0.385	0.119	0.654	0.429	-	225
	7/2.75 AAC	0.689	0.376	1.171	1.352	-	208
	7/3.75 AAC	0.37	0.356	0.629	1.282	-	304
	7/4.75 AAC	0.232	0.341	0.394	1.229	-	404
SWER	3/12 SCGZ	10.352	0.634	-	-	2.029	47
	SC/AC-MET 3/2.75	4.8	0.390	-	-	2.086	73
	SC/AC-IMP 3/.1019 3/10	5.416	0.417	-	-	2.029	68

3.1.2 Load profile data preparation

For each case the load profile data was sorted according to demand level. From each of these data sets, a maximum load kVA value was extracted from the 5-7 pm (peak demand) data set and a minimum load kW value was extracted from the 12-2 pm (minimum demand) data set[10].

To obtain the load balance between the phases, the percentage load balance for each of the three phases was calculated at the time the maximum load occurred. The percentage load balance is the phase loading divided by the total load across the three phases. This was then used to determine the loading per phase and thereafter the number of customers on each of the

[10] Since the 12-2 pm time slot is when maximum PV penetration occurs, it was necessary to use the kW (real power) values in order to see the effect of PV on the feeder, which was represented as a negative value on the kW profile.

phases. The peak demand data was used to determine the load balance across the phases since very little PV is expected during this time; the peak therefore most closely represents the actual customer connection configuration.

To determine the minimum demand value to be used to scale the feeder load in each of the test cases, since this data includes the PV penetration, some manipulation of the minimum load data was required. To determine the actual minimum load value, the actual number of PV customers on a particular feeder was related to a kW value (assuming each PV inverter at 2.5 kW and 80% utilisation), which was then added to the minimum kW from the load data to obtain the actual minimum load value on the feeder.

3.2 Model construction

3.2.1 PowerFactory model

Each of the test cases has been modelled from the actual feeder data extracted from FieldView and the HV/LV transformer data provided. Distribution legs have been numbered sequentially, originating from the low voltage busbar. Connection points along the feeder backbone have been numbered in order to derive voltage profile plots according to distance from the LV busbar. Figure 3-1depicts the PowerFactory model of one of the representative feeders (AP125B-15350).

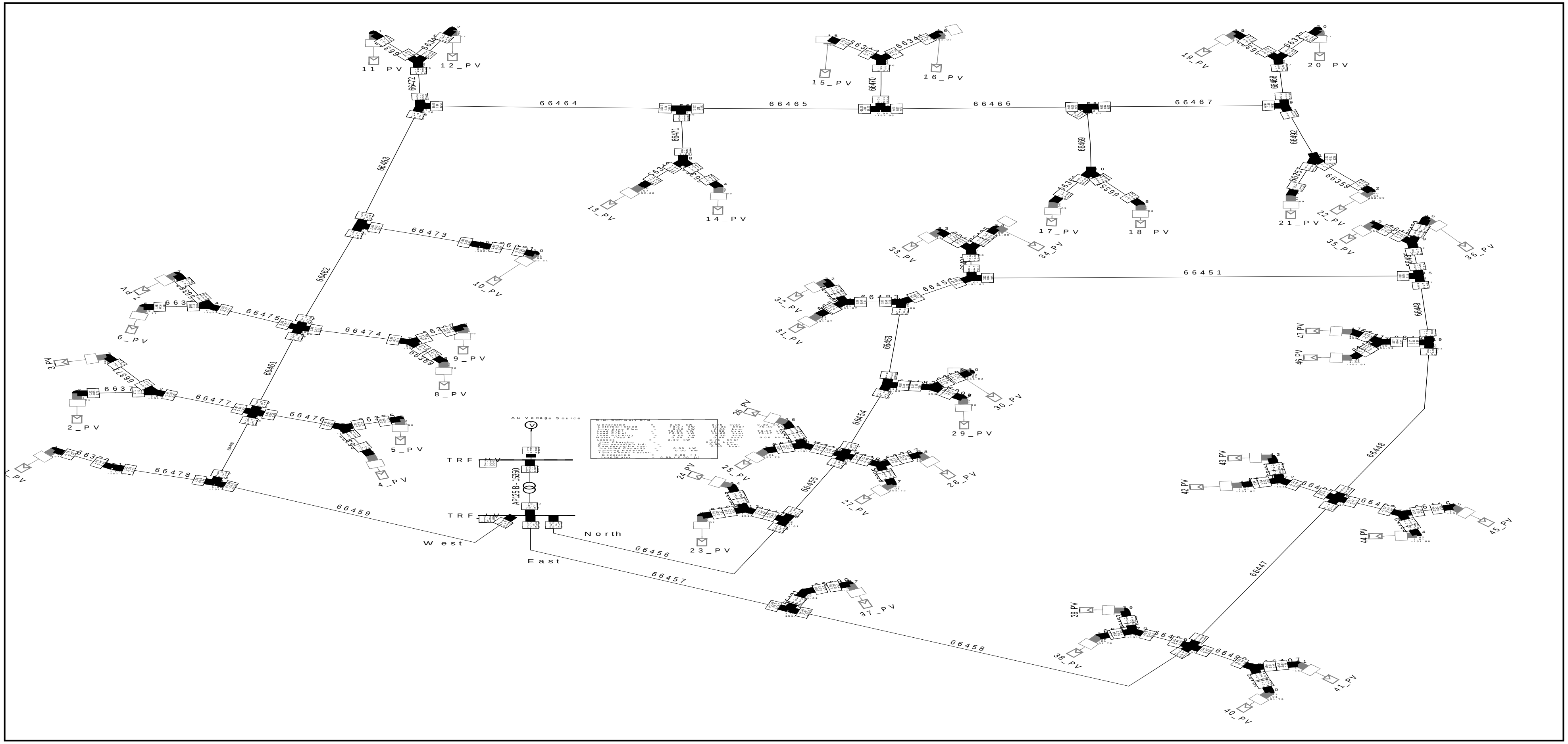


Figure 3-1 : PowerFactory test model: AP125B-15350

3.2.2 Assumptions

To determine the distribution of customers on a feeder, it was assumed that 30% of the customers were three-phase and 70% single-phase. This assumption was based on the general composition of typical feeders in the SA Power Networks system. From the total number of customers on a feeder, the numbers of customers per phase was then calculated from this assumption as well as from the actual percentage load balance across each of the phases (see 3.1.2). Where metering data was available for individual distribution legs on a feeder, the number of customers per phase was calculated from the total number of customers on that leg as well as the percentage load balance of phases on that leg. The same process was followed for each leg on that feeder, where metering data was available. For feeders with only one meter, the numbers of customers per phase was calculated from the total number of customers on the feeder and the percentage load balance across the phases, regardless of the number of distribution legs on the feeder. This process was used since the customer phasing data was not available.

Table 3-2 and Table 3-3 show the data and process used to determine the breakdown of customers across each of the feeders, based on the example of AP125B-15350.

Table 3-2: Percentage load balance feeder AP125B-15350 (as per peak demand data)

	Phase A	Phase B	Phase C
Leg 1	7.6 %	52.6 %	39.8 %
Leg 2	26 %	27 %	47 %

Table 3-3: Distribution of customers across feeder AP125B-15350

	Leg 1	Leg 2
Customers in %	53.2 %	46.8 %
Customers	25	22
3-Phase Customers	7	7
1-Phase Customers	18	15
1-Phase A	1	4
1-Phase B	10	4
1-Phase C	7	7

The distribution of customers and feeder phase balance used for the other representative feeders can be found in the summaries for each of the feeders in Appendix B.

3.3 DER scenario construction

Following construction of the PowerFactory model of each LV and SWER feeder, the DER scenarios were implemented as per Table 3-4.

The existing number of customers with PV and controllable load on each of the feeders is given in Appendix A.

Table 3-4: Implementation of DER scenarios

DER	ID	% Customers	DER rating per installation	DER implementation
PV	P0	0	N/A	N/A
	P1	Present level	Present level of PV installed	As per P2 (adjusted up or down depending on actual numbers)
	P2	25%	2.5 kW	PV placed at every 4th customer along the feeder
	P3	50%	2.5 kW	PV placed at every 2nd customer along the feeder
	P4	75%	2.5 kW	PV placed at every 3 out of 4 customers along the feeder
	P5	100%	2.5 kW	PV placed at every customer along the feeder
	P6	50%	5 kW	As per P3, with 5 kW inverters
EV	E0	No EV	N/A	N/A
	E1	5%	0.8 kW	EV load placed close to or at the end of the feeder as this would result in the worst case voltage profile
	E2	10%	0.8 kW	
	E3	15%	0.8 kW	
CL	L0	0	N/A	N/A
	L1	Existing	2.5 kW	Controllable load distributed evenly across the feeder (the existing numbers of customers – but not locations of those customers – with controllable load were provided per feeder; controllable load in the models has been distributed using the same principle as the distribution of PV)
ST	S0	No storage	N/A	N/A
	S1	5%	2.5 kW – charging (load)	Distributed according to the PV distribution, starting from P1
	S2	10%	2.5 kW – charging (load)	Distributed according to the PV distribution, starting from P1
	S3	5%	2.5 kW – discharging (generation)	Per S1
	S4	10%	2.5 kW – discharging (generation)	Per S2

3.4 Feeder load scaling

The final step to prepare the models for analysis was to perform feeder load scaling to represent both the peak and minimum demand scenarios. A representation of a peak demand scenario was required to understand the behaviour of the network without the presence of PV or other DER and to assess the implications the connection of CL, EV and ST (discharging) would have on the network. A representation of the minimum demand scenario was necessary to understand the behaviour of the network under the scenario when maximum PV penetration would exist and further to assess the impact the connection of additional PV has on the network.

Each of the feeders was firstly scaled according to the peak demand data. This was achieved by firstly calculating the kVA per customer from the total kVA value, the percentage feeder load balance (Table 3-2 example) and the breakdown of customers per feeder (Table 3-3 example). An example of the data used to scale the feeder to the peak demand is shown in Table 3-5.

The minimum demand case was scaled similarly to the peak demand case for each feeder. The minimum demand kVA value was determined from the minimum load data and the existing PV penetration on the feeder. An example of the data used to scale the feeder to the minimum demand is shown in Table 3-6.

The peak and minimum load data used for the other representative feeders is given in the feeder summaries in Appendix B.

Table 3-5: Peak demand kVA per customer breakdown - AP125B-15350

	Leg 1 [kVA / customer]	Leg 2 [kVA / customer]
3-Phase Customers	1.83	2.14
1-Phase A	0.00[11]	1.82
1-Phase B	1.98	1.94
1-Phase C	1.99	2.45

Table 3-6: Minimum demand kVA per customer breakdown - AP125B-15350

	Leg 1 [kVA / customer]	Leg 2 [kVA / customer]
3-Phase Customers	0.26	0.30
1-Phase A	0.00	0.26
1-Phase B	0.28	0.28
1-Phase C	0.28	0.35

3.5 Mitigation measures

Evaluation of the efficacy of mitigation measures has been carried out for a subset of the representative feeders selected by SA Power Networks. Three representative feeders were selected for further analysis, with the mitigation measures assessed listed in Table 3-7.

Table 3-7: Mitigation measures studied for three representative feeders

Feeder	LV feeders: HH341A-81 (old overhead) and EL14-TC54743 (old underground)	SWER feeder: M-23
Mitigation Measures	• Transformer tap setting changes • Reconductoring feeder backbone • Dynamic VAr control • Controllable load and storage • Feeder load balancing	• Transformer tap setting changes • MV voltage regulation • Dynamic VAr control • LV voltage regulation • Controllable load and storage

[11] This number is zero since Phase A of Leg 1 is only 7% loaded, which is entirely accounted for within the 3-phase customers.

4. Quantitative impact of DER penetration on QoS parameters

4.1 Voltage regulation

Figure 4-1 presents an overview of the voltage regulation results for each of the test cases. The per unit values in the table show the highest (for overvoltage) or lowest (for undervoltage) value recorded on each of the phases for all the feeder distribution legs. For the LV networks, the per unit limit is based on a voltage base of 400/230 V (nominal)[12]. For the SWER networks, the HV steady-state voltage limit is based on a 19.1 kV nominal voltage as per AS 61000.3.100-2011 – Table 4.

Six LV feeders were found to have overvoltage issues and one SWER feeder exhibits undervoltage issues.

		Overvoltage (limit 1.02pu)			Undervoltage (limit 0.87pu)		
		Phase A	Phase B	Phase C	Phase A	Phase B	Phase B
Old Overhead	HH341A 81	1.038	1.025	1.028	0.889	0.924	0.936
	AP351B 2034	1.004	1.004	1.007	0.994	0.997	0.994
	AP344D 15	1.022	1.024	1.016	0.94	0.927	0.976
New Overhead	SM126A 159	1.01	1.002	1.017	0.977	0.998	0.98
	EL13 57	1.022	1.016	1.023	0.918	0.945	0.921
	HH177F 253	1.022	1.03	1.03	0.971	0.976	0.965
Old Underground	EL14 TC54743	1.046	1.071	1.054	0.94	0.969	0.973
	AP125B 15350	1.015	1.028	1.01	0.975	0.973	0.962
	AP529E 30156	1.003	1.002	1	0.979	0.99	0.988
New Underground	HH496C 26079	1.017	1.019	1.014	0.986	0.969	0.974
	HH121B TC46352	1.013	1.012	1.009	0.991	0.995	0.992
	HH409F 29068	1.015	1.018	1.017	0.949	0.964	0.963
		Overvoltage (limit 1.06pu)			Undervoltage (limit 0.90pu)		
		Phase A			Phase A		
SWER	GU37	1.016			0.941		
	MTB82	1.028			0.947		
	M23	1.048			0.855		

Figure 4-1 : Overview of greatest voltage regulation violations for the 15 representative feeders studied

Several feeders[13] in the old and new overhead categories show similar results since these are largely comprised of the same overhead conductors that have higher impedance compared to the rest of the feeders in these categories, which do not show any issues. The higher overvoltages at points of DER connection can appear to be attributable to the higher conductor impedances back to the grid.

[12] Refer to Table 2-3.

[13] HH341A-81, AP344D-15, EL13-57 and HH177F-253.

The networks in the newer underground areas (primarily XLPE insulated aluminium conductor cable) did not show any voltage regulation issues, whereas overvoltage issues were seen in the old underground areas which consist largely of higher impedance copper cables.

Only one SWER feeder, M-23, showed undervoltage issues, attributable to the length of the feeder and to transformer overloading. An increase in feeder voltage has been observed with increasing PV penetrations but no breach of the overvoltage limits was seen.

Old overhead feeder AP344D-15 is in breach of the overvoltage limit on all phases. Since AP344D-15 is a pole mounted transformer, the operating voltage is 7600/445 V. Considering the 400/230 V voltage limits of +10% and -6%, at an operating voltage of 445 V, this implies that the voltage limits will be 0.98 pu and 0.83 pu. Therefore at the nominal voltage of 445 V, the feeder is already in breach of the voltage limits according to the standard and this breach is only exacerbated with the addition of any amount of PV. Possible mitigation for this issue would be a review of the approach to the existing AS 61000.3.100 standard to accommodate operating voltages other than the 400/230 V specified or changing the operating voltages of the old networks.

Figure 4-2 shows the boundary points at which an increase in DER penetration first results in breach of the undervoltage and overvoltage limits. Figure 4-2 also shows the effect that storage and controllable load have on mitigating the overvoltage issues. This table shows that introducing controllable load allows increased levels of PV penetration but is dependent on the amount of controllable load on a particular phase. In all cases, the addition of storage as a load has negligible impact on the voltage regulation; the addition of both storage and controllable load offers minimal improvement over the addition of controllable load only. Since the overvoltage issues occur during a minimum load scenario, storage is not expected to be discharged at this time; therefore, it has only been considered as a load for the purposes of the results in Figure 4-2. The addition of both controllable load and storage has been deliberately used as a mitigation strategy to understand the impact it has on the feeders concerned.

Furthermore, it was also noted that the boundary points vary across the three phases due to the unbalanced load across the phases of most feeders. The maximum amount of PV that may be connected to a feeder will be restricted by the phase with the lowest boundary point so as to avoid any voltage regulation issues.

		Overvoltage Boundary Point			New overvoltage boundary point with addition of:								
					STORAGE (S2)			CONTROLLABLE LOAD (L1)			BOTH (S2 & L1)		
		Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
Old Overhead	HH341A 81	P3	P4	P4	P3	P4	P4	P6	P5	P4	P6	P5	P4
New Overhead	EL13 57	P4	-	P4	P6	-	P5	P6	-	P6	P6	-	P6
	HH177F 253	P5	P3	P4	P6	P4	P5	P6	P6	P5	P6	P6	P6
Old Underground	EL14 TC54743	P3	P2	P2	P3	P2	P2	P6	P5	P5	P6	P5	P5
	AP125B 15350	-	P5	-	-	P5	-	-	P5	-	-	P5	-
		Undervoltage Boundary Point			New undervoltage boundary point with addition of:								
					STORAGE (S2) - discharging								
		Phase A	Phase B	Phase C	Phase A	Phase B	Phase C						
SWER	M23	P0	-	-	P0	-	-						

Figure 4-2 : Boundary points for feeders with quality of supply issues

For the old overhead feeder HH341A-81, considering the phase with the worst overvoltage (Phase A), the boundary point is at P3, i.e. when 50 % of the customers on the feeder have a 2.5 kW PV inverter. The addition of storage has no impact on the voltage profile; however, the addition of only controllable load could shift this boundary point to P5 or P6 (100% of customers with PV at 2.5 kW or 50% of customers with PV at 5 kW). The boundary point of P4 for Phase C however is unchanged with the addition of both controllable load and storage (Figure 4-3).

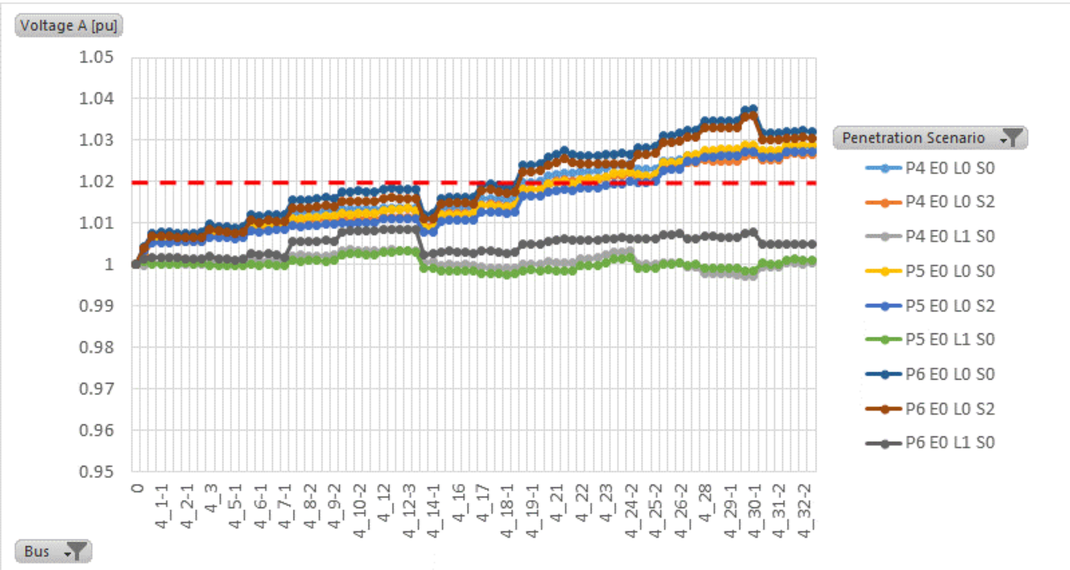


Figure 4-3 : Effect of storage and controllable load on Phase A of HH341A-81

For the new overhead feeder EL13-57, the boundary point for both phases A and C are at P4 (75% of customers with PV at 2.5 kW). Storage alone will shift this boundary point to P6 for Phase A and P5 for Phase C whilst controllable load alone will shift the boundary point to P6 for both phases (see Figure 4-9).

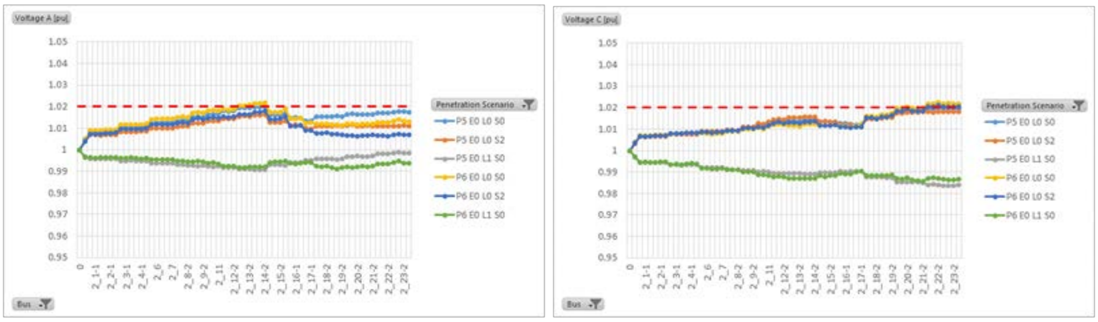


Figure 4-4 : Effect of storage and controllable load on Phase A & Phase C of EL13-57

For the new overhead feeder HH177F-253, considering the phase with the worst overvoltage (Phase B), the boundary point is at P3. The addition of storage only will change this boundary to P4 and the addition of controllable load will shift it to P6 (see Figure 4-5).

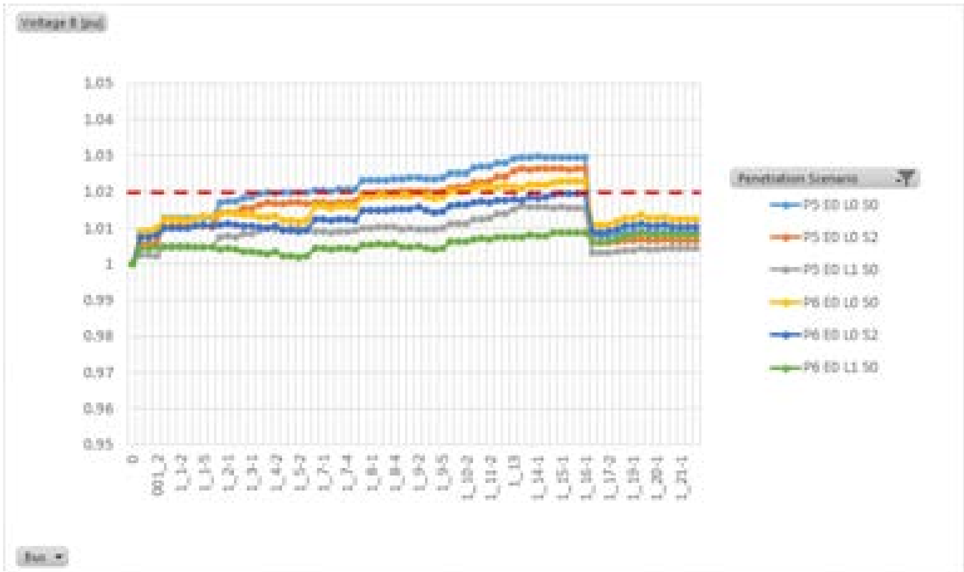


Figure 4-5 : Effect of storage and controllable load on Phase B of HH177F-253

For the old underground feeder EL14-TC54743 considering the phase with the worst overvoltage (Phase B), the boundary point is at P2. The addition of storage only will not change this boundary point; however, the addition of controllable load will shift it to P5 (see Figure 4-6).

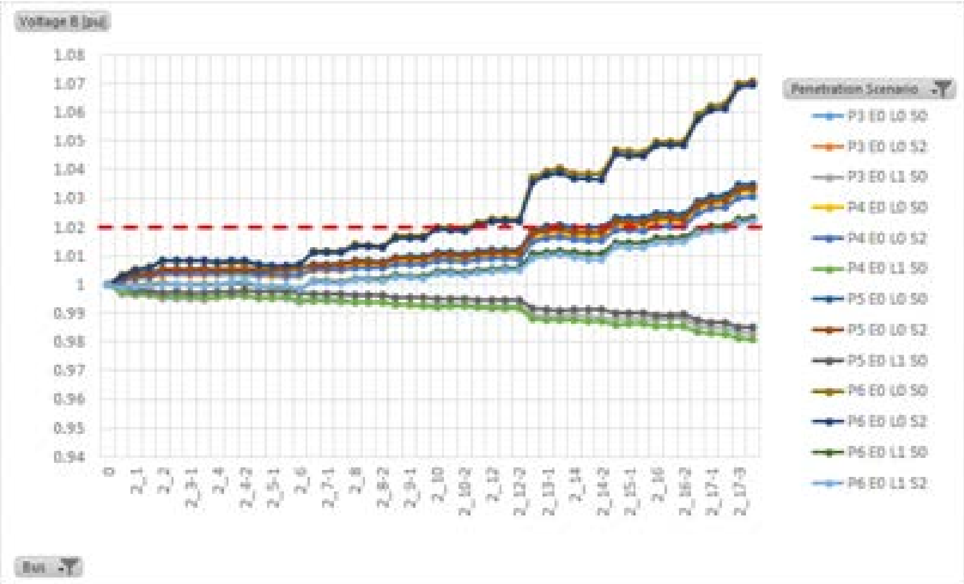


Figure 4-6 : Effect of storage and controllable load on Phase B of EL14-TC54743

For the old underground feeder AP125B-15350, an overvoltage was recorded only on phase B and has a boundary point of P5, i.e. 100% of customers with PV at 2.5 kW. The boundary point remains unchanged with the addition of storage, controllable load or both and therefore the P6 scenario where 50% of the customers have PV at 5 kW would not be an option for this feeder (see Figure 4-7).

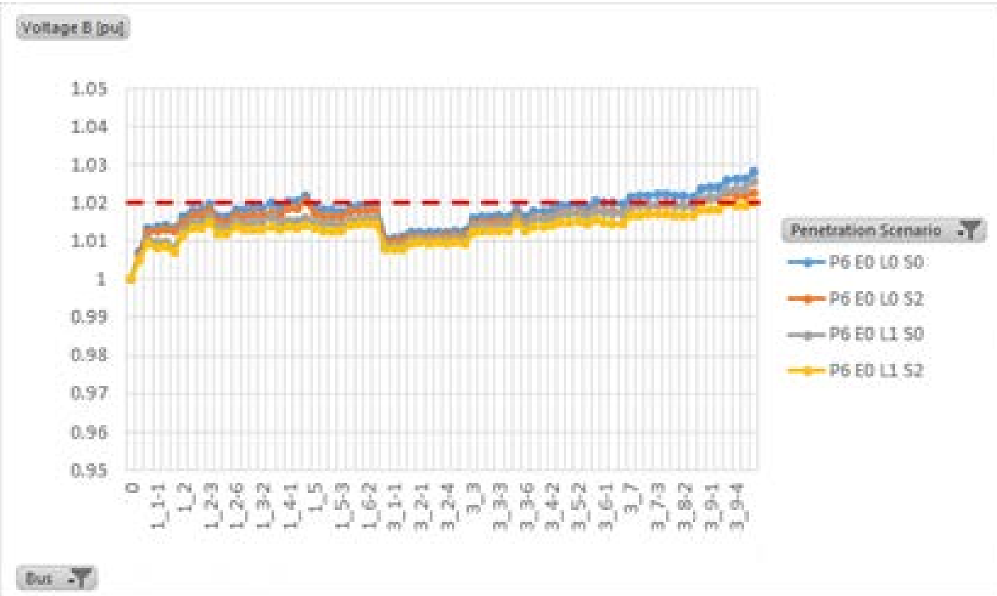


Figure 4-7 : Effect of storage and controllable load on Phase B of AP125B-15350

4.2 Voltage fluctuation

Figure 4-8 presents an overview of the voltage fluctuation results for each of the test cases. As shown, only EL14-TC54743 violates the voltage fluctuation limit of 3-5%. However, EL14-TC54743 only breaches the voltage fluctuation limit under a P6 scenario (50% of customers with 5 kW PV systems), which is the upper bound on PV penetration scenarios studied.

With increasing DER on the feeders, an increase in the percentage voltage fluctuation is observed.

		Highest voltage fluctuation observed (%)
Old Overhead	HH341A 81	3.3%
	AP351B 2034	0.5%
	AP344D 15	3.1%
New Overhead	SM126A 159	1.3%
	EL13 57	1.9%
	HH177F 253	3.1%
Old Underground	EL14 TC54743	**5.6%**
	AP125B 15350	1.8%
	AP529E 30156	1.0%
New Underground	HH496C 26079	1.6%
	HH121B TC46352	0.9%
	HH409F 29068	1.4%
SWER	GU37	2.5%
	MTB82	3.7%
	M23	4.5%

Figure 4-8: Overview of voltage fluctuation results for 15 test cases

4.3 Voltage unbalance

Figure 4-9 presents an overview of the voltage unbalance results for each of the test cases. The maximum voltage unbalance percentage under each of the peak and minimum demand cases has been recorded as well as the unbalance percentage under the no DER scenario. Only EL14-TC54743, in the old underground area category, exceeds the 2% unbalance limit. Comparison of unbalance results against those without any DER on the feeders indicates an increase when DER is added.

		Max. Vneg/Vpos (%) observed		Max. Vneg/Vpos (%) observed (No DERs)	
		Peak demand case	Minimum demand case	Peak demand case	Minimum demand case
Old Overhead	HH341A 81	1.26%	1.01%	0.44%	0.07%
	AP351B 2034	0.14%	0.29%	0.11%	0.03%
	AP344D 15	1.44%	0.94%	1.28%	0.29%
New Overhead	SM126A 159	0.89%	0.79%	0.40%	0.00%
	EL13 57	1.12%	0.77%	0.46%	0.05%
	HH177F 253	0.56%	0.97%	0.28%	0.04%
Old Underground	EL14 TC54743	**3.89%**	**2.26%**	1.43%	0.07%
	AP125B 15350	0.88%	0.84%	0.63%	0.07%
	AP529E 30156	0.42%	0.36%	0.34%	0.16%
New Underground	HH496C 26079	0.61%	0.53%	0.47%	0.04%
	HH121B TC46352	0.23%	0.31%	0.22%	0.00%
	HH409F 29068	0.60%	0.32%	0.54%	0.03%

Figure 4-9: Overview of voltage unbalance results for 15 test cases

5. Mitigation measures

The three feeders selected for mitigation analysis, in collaboration with SA Power Networks, were LV feeders HH341A-81 (old overhead) and EL14-TC54743 (old underground) and SWER feeder M-23.

5.1 Representative old overhead and old underground feeders

The mitigation measures considered for the LV feeders were:

- tap setting changes;
- reconductoring of the feeder backbone;
- dynamic VAr control;
- load control; and
- feeder load balancing.

These mitigation measures were investigated under the original assumption of unity HV voltage as well as at the upper and lower HV voltage fluctuation levels for each of these feeders: ±2.5% for HH341A-81 and ±3.5% for EL14-TC54743.

Full results of the mitigation investigation for the two LV feeders are given in Appendix A. Table 5-1 provides a summary of these results, with each scenario listed being the maximum level of PV penetration able to be tolerated before a voltage regulation limit is breached.

Table 5-1: Overview of mitigation results for LV feeders

MITIGATION MEASURE	HH341A-81 (Old Overhead)			EL14-TC54743 (Old Underground)		
	Unity	Upper	Lower	Unity	Upper	Lower
	1.00 pu	1.025 pu	0.975 pu	1.00 pu	1.035 pu	0.965 pu
Tap setting changes	•Tap 4: P6 •Tap 5: P6 •UV violations - peak demand with DERs (Tap 4 & Tap 5)	•Tap 4: P4 •Tap 5: P6	•Tap 4: P6 •Tap 5: P6	•Tap 4: P5 •Tap 5: P6 •UV violations – peak demand & with DERs (Tap 4 & Tap 5)	•Tap 4: P1 •Tap 5 P5	•Tap 4: P6 •Tap 5: P6
Reconductor backbone	•P6	•P4	•P6	•P5	•P3	•P6
Dynamic Var control	•P6	•P6	•P6	•P6	•P6	•P6
Load control	•P3	•P0	•P6	•P5	•P0	•P6
Feeder load balancing	•P3	•P0	•P6	•P2	•P0	•P5

For the old overhead feeder HH341A-81, the results in Table 5-1 imply that:

1. Provided that the HV voltage is maintained at or below nominal, either changing the transformer tap setting to Tap 4 or Tap 5, or reconductoring the feeder backbone, is sufficient for voltage regulation to be acceptable when up to 100% of customers have 2.5 kW PV systems (P5), or when up to 50% of customers have 5 kW PV systems (P6).
2. If the HV system is operated at 1.025 pu voltage then the mitigations studied, other than dynamic VAr control (which requires additional capital investment), are not able to maintain overvoltages within limits. Operating the HV system at or below nominal would need to constitute part of the mitigation.
3. Operating the HV system at 0.975 pu is sufficient for voltage regulation to be acceptable when up to 50% of customers have 5 kW PV systems (P6). The voltage regulation range of the LV network should however be known before operating the LV network at a lower setpoint.
4. Feeder load balancing and controllable load are more effective if the HV voltage is kept in the lower half of its usual range and managed during peak demand periods. Since only 38% of customers have controllable load, it is not effective on its own.

For the old underground feeder EL4-TC54743:

1. Other than dynamic VAr control (which requires additional capital investment), no single mitigation is sufficient to control overvoltage issues when up to 50% of customers have 5 kW PV systems (P6).
2. If the HV voltage is operated at 1.035 pu then the mitigations considered are not able to control overvoltages. Operating the HV system at or below nominal would need to constitute part of the mitigation.
3. Operating the HV system at 0.965 pu is sufficient for voltage regulation to be acceptable when up to100% of customers have 2.5 kW PV systems (P5). The voltage regulation range of the LV network should however be known before operating the LV network at a lower setpoint. Changing transformer tap settings can resolve overvoltages, but introduces undervoltages under peak demand with DER.
4. Reconductoring the feeder backbone will maintain undervoltages within limits, and yield marginal overvoltages.
5. Feeder load balancing will allow connection of additional DER, but is less effective than the other mitigations studied. However it could be more effective if the HV voltage is kept in the lower half of its usual range and managed during peak demand periods.
6. Controllable load alone allows connection of up to 100% of customers with 2.5 kW PV systems (P5), since all customers on this feeder has controllable load.

5.2 Representative SWER feeder

The mitigation measures considered for the SWER network M-23 were:

- tap setting changes;
- HV voltage regulation;
- LV voltage regulation;
- dynamic VAr control; and
- load control.

Table 5-2 summarises the mitigation results for M- 23.

Table 5-2: Overview of mitigation results for M-23 (SWER)

MITIGATION MEASURE	M-23
• Tap setting changes	• Tap 1 – no undervoltage violations but overvoltage limit violated •Tap 2 – violates undervoltage and overvoltage limits
• MV voltage regulation	•VR at maximum tap with no undervoltage violations, except for 1 customer immediately before VR (TF 26)
• LV voltage regulation	•Required for 66 customers (50%) with VR tap fixed •Required for 1 customer with VR at maximum tap
• Dynamic Var control	•Approximately 271 kVAr required with VR at fixed tap
• Load control	•Storage does not reduce the undervoltage violation

The mitigation results for M-23 indicate:

1. The voltage regulator on the maximum tap setting enables control of undervoltages under the peak demand scenario, except for one customer. Addition of an LV voltage regulator or repositioning of the existing HV voltage regulator could remove the violation for this customer.
2. M-23 is not able to support additional DER, due to insufficient taps being available on the HV voltage regulator. Replacement of the existing voltage regulator would be required to overcome this.
3. Changing transformer taps to control undervoltages introduces overvoltage issues during minimum demand period.
4. Storage (discharging) does not reduce the undervoltage violation and is therefore not an effective mitigation.

6. Conclusions

6.1 Voltage regulation

Certain feeders in both the old and new overhead categories show similar results since these are largely comprised of the same overhead conductors that have higher impedance compared to the rest of the feeders in these categories, which do not show any issues.

The networks in the newer underground areas (comprised mainly of XLPE AL cable) do not show any voltage regulation issues whereas the overvoltage issues were seen in the old underground areas which are comprised largely of old copper cables, which have much higher impedances and therefore high voltages at the point of DER connection.

Only one SWER network, M-23, showed undervoltage issues, attributable to the length of the feeder and to transformer overloading. An increase in feeder voltage has been observed with increasing PV penetrations on the SWER networks but no breach on the overvoltage limits has been evident.

For the overhead networks, the lowest boundary point is P3. That is, up to 50% of customers with PV (at 2.5 kW) on the feeder did not result in any voltage regulation issues. The addition of storage load on these feeders at maximum PV penetration largely does not change this boundary point. The addition of controllable load, however, will in most cases shift this boundary point to P5 and P6, i.e. 100% of customers with PV at 2.5 kW and 50% of customers with PV at 5 kW respectively.

For the old underground networks, the lowest boundary point is P2, i.e. up to 25% of customers with PV (at 2.5 kW) on the feeder did not result in any voltage regulation issues. The addition of storage load on these feeders during maximum PV penetration largely does not change this boundary point. The addition of controllable load, however, will in most cases shift this boundary point to P5, i.e. 100% of customers with PV at 2.5 kW.

It was also noted that the boundary points vary across the three phases due to the unbalanced load across the phases of most feeders. This is an issue for concern as the maximum amount of PV that may be connected to a feeder will be restricted by the phase with the lowest boundary point so as to avoid any voltage regulation issues.

Furthermore, AS 61000.3.100 provides steady state voltage limits for 230/400 V systems (1.1 pu and 0.94 pu); however, the low voltage networks assessed in the study are predominantly 433/248 V which results in limits of 1.02 pu and 0.87 pu for these networks, which are difficult to meet in the SA Power Networks areas with higher transformer secondary voltages.

6.2 Voltage fluctuation

Only the old underground feeder EL14-TC54743 violated the voltage fluctuation limit of 3-5% but the breach was only observed under a P6 scenario.

Whilst an increase in the percentage voltage fluctuation was observed with increasing DER penetration levels, the increase was not sufficient to breach the limits for the remaining representative feeders studied.

6.3 Voltage unbalance

Only EL14-TC54743, in the old underground area category, exceeds the 2% unbalance limit. These results were compared against unbalance results without any DER on the feeders. The addition of DER such as electric vehicles and controllable load increases the unbalance percentage on the network. Whilst DER in isolation is not sufficient to cause the unbalance limit to be exceeded, DER can thus exacerbate a situation where other factors lead to a violation.

Appendix A. Supplementary data

A.1 Transformer data used in models

Feeder / Transformer	Voltage [V]	Rating [kVA]	R [pu]	X [pu]	R [pu]	R [pu]	No. of taps	Step	Neutral Tap
			100 MVA base		Machine base				
HH341A 81	11000/433	315	3.49	12.06	0.01099	0.03799	5	2.5	3
AP351B 2034	7600/433	500	2.00	8.20	0.01	0.041	5	2.5	3
AP344D 15	7600/445	150	8.33	22.67	0.0125	0.03401	No tap changer		
SM126A 159	11000/433	50	32.00	56.00	0.016	0.028	No tap changer		
EL13 57	11000/433	200	6.00	18.00	0.012	0.036	5	2.5	3
HH177F 253	11000/433	100	14.00	31.00	0.014	0.031	5	2.5	3
EL14 TC54743	11000/433	300	3.83	12.33	0.01149	0.03699	5	2.5	3
AP125B 15350	7600/433	200	6.00	18.00	0.012	0.036	5	2.5	3
AP529E 30156	7600/433	500	2.00	8.20	0.01	0.041	5	2.5	3
HH496C 26079	11000/433	150	8.33	22.67	0.0125	0.03401	5	2.5	3
HH121B TC46352	11000/433	300	3.83	12.33	0.01149	0.03699	5	2.5	3
HH409F 29068	11000/433	300	3.83	12.33	0.01149	0.03699	5	2.5	3
GU37	11/19 kV	150	8.33	21.67	0.0125	0.03251	5	2.5	3
MTB82	11/19 kV	200	5.25	16.75	0.0105	0.0335	5	2.5	3
M23	11/19 kV	200	5.25	16.75	0.0105	0.0335	5	2.5	3

A.2 Voltage regulator data used for SWER feeders GU-37 and M-23

Rating 19kV 50A

Tap range - 32 taps (tap -16 through to tap +16)

Buck/Boost Range -10%, +10%

Tap step - 0.625% per tap

Neutral Tap – tap 0

A.3 Existing customers with solar and controllable load on each representative feeder studied

Feeder / Transformer	No. of customers with solar	No. of customers with controllable load
HH341A 81	32	16
AP351B 2034	0	0
AP344D 15	11	15
SM126A 159	5	5
EL13 57	50	6
HH177F 253	11	9
EL14 TC54743	53	7
AP125B 15350	13	19
AP529E 30156	3	2
HH496C 26079	5	22
HH121B TC46352	2	36
HH409F 29068	4	8
GU37	31	15
MTB82	40	19
M23	67	31

Appendix B. Feeder Result Summaries

FEEDER HH341A - 81 (OLD OVERHEAD)

1. Details

- Norwood – Kensington 11 kV feeder
- 11000/433 V 315 kVA transformer
- Comprised of the following underground cable:
  - 7 / 4.75 AAC (81 m / 2.8%)
  - 7 / 3.75 AAC (473 m / 16.5%)
  - 7 / 16 Cu (44 m / 1.5%)
  - 7/14 Cu (680 m / 23.7%)
  - 4 x 95 ABC (913 m / 31.8%)
  - 0.2 Cu (459 m / 16%)
  - 0.1 Cu (219 m / 7.6%)
- Has one meter point to four distribution legs:
  Leg 1 – 113 m
  Leg 2 – 157 m
  Leg 3 – 297 m
  Leg 4 – 933 m
- 85 customers
- Feeder phase balance (as per load data)
  - Leg 1: Phase A = 35.3% Phase B = 31.1% Phase C = 33.6%
- Distribution of customers across feeder:

	Leg 1 to 4
Customers in %	100 %
Customers	85
3-Phase Customers	25
1-Phase Customers	60
1-Phase A	21
1-Phase B	19
1-Phase C	20

- Max. consumer load assumed = 213.2 kVA (obtained from actual data)

	Leg 1 to 4 [kVA / customer]
3-Phase Customers	2.51
1-Phase A	2.59
1-Phase B	2.39
1-Phase C	2.54

- Min. consumer load = 38.7 kVA (obtained from actual data assuming existing PV utilisation factor of 80%)

	Leg 1 to 4 [kVA / customer]
3-Phase Customers	0.46
1-Phase A	0.47
1-Phase B	0.43
1-Phase C	0.46

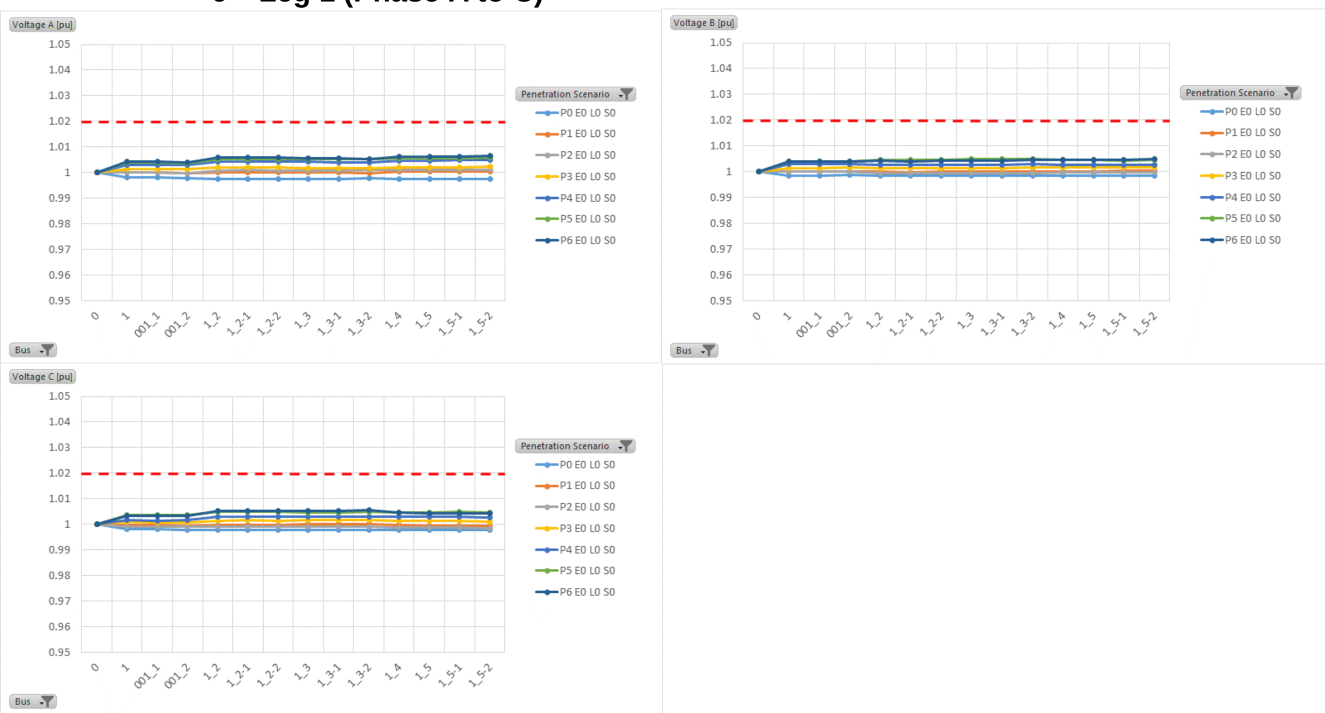
- Existing PV penetration = 18.05% or 56.86 kW rated, i.e. 23 customers (assuming a 2.5 kW inverter size)
- Existing customers with controllable load = 32 (38 %)

2. Overvoltage check

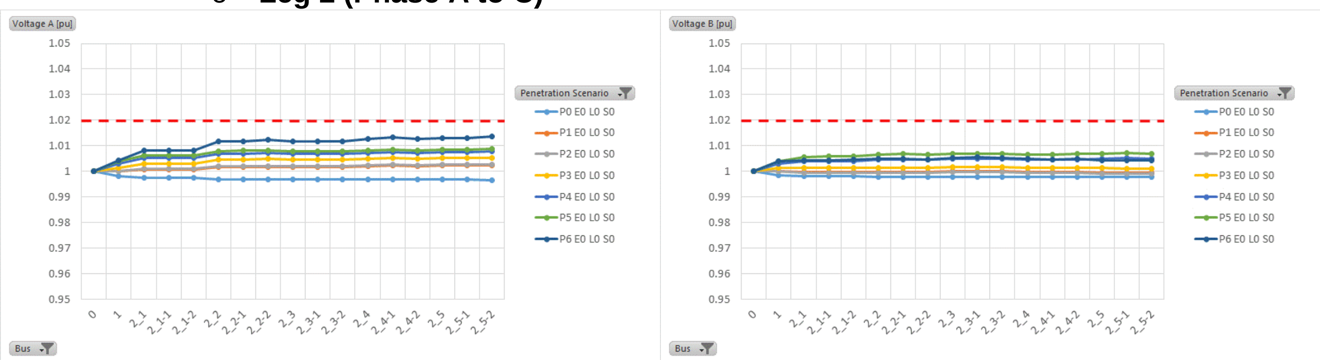
- To check the worst overvoltage – consider the min. consumer load with the highest PV utilisation factor of 80% for the PV only DERs penetration scenarios. The PV only DERs penetration scenarios are most onerous to overvoltage issues.
- Overvoltages (>1.02 pu) were observed in distribution Leg 4 on this feeder. Voltages on other distribution legs are within limit.
- Highest overvoltages observed:
  Leg 4 – Phase A: 1.038 pu (P6E0L0S0)
  Phase B: 1.025 pu (P5E0L0S0)
  Phase C: 1.028 pu (P5E0L0S0)
    - In Leg 4, the Phase A boundary penetration scenario before overvoltages occur is P3. The controllable loads (L1) could be switched on to increase PV penetration to P4, P5 or P6 while maintaining voltage. Connecting the storage loads (S2) alone is insufficient to keep the voltage within range.
    - In Leg 4, the Phase B overvoltages occur under the P5 penetration scenario. The controllable loads (L1) could be switched on to resolve the issues. Connecting the storage loads (S2) alone is insufficient to keep the voltage within limit.
    - In Leg 4, the Phase C boundary penetration scenario before overvoltages occur is P4. Both the controllable loads (L1) and storage (S2) are required to be switched on to increase PV penetration to P5 or P6, resulting in only marginal overvoltages. The overvoltages cannot be resolved completely in this phase.

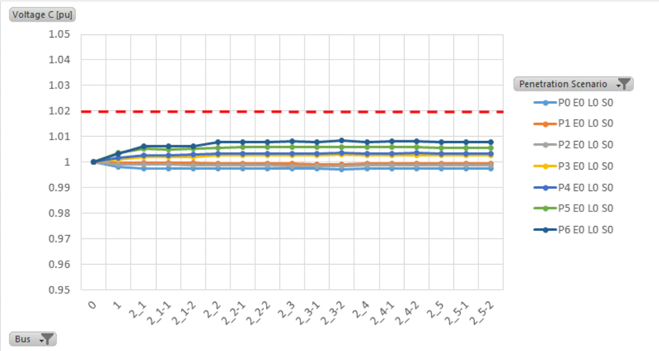
a) Min. consumer load with 80% PV utilisation factor

- **Leg 1 (Phase A to C)**

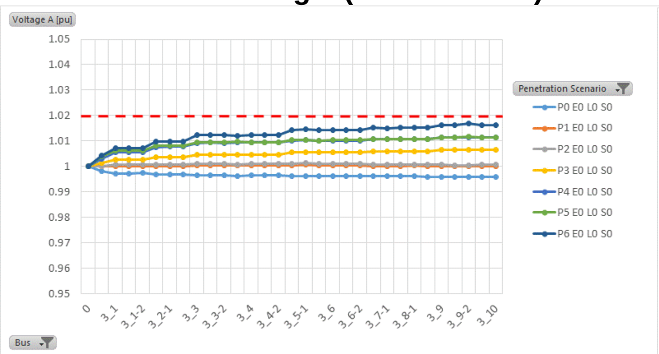


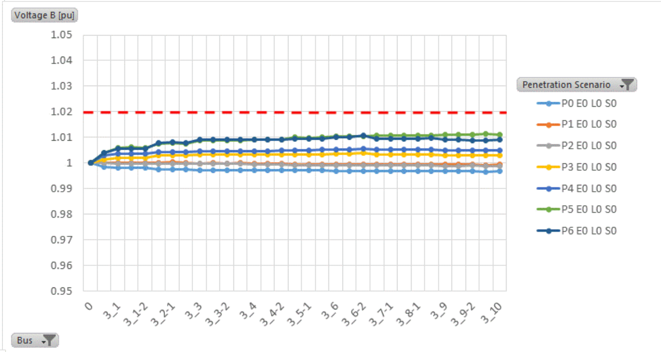
- **Leg 2 (Phase A to C)**

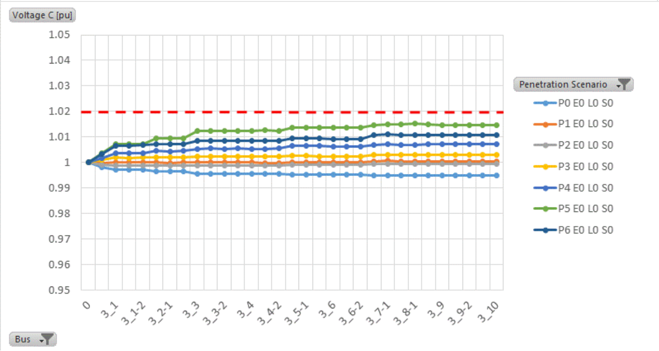




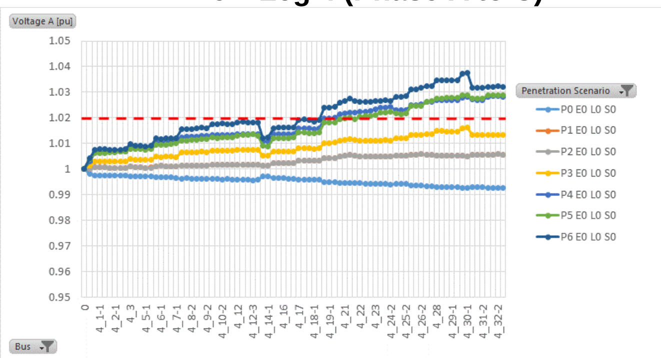
- **Leg 3 (Phase A to C)**

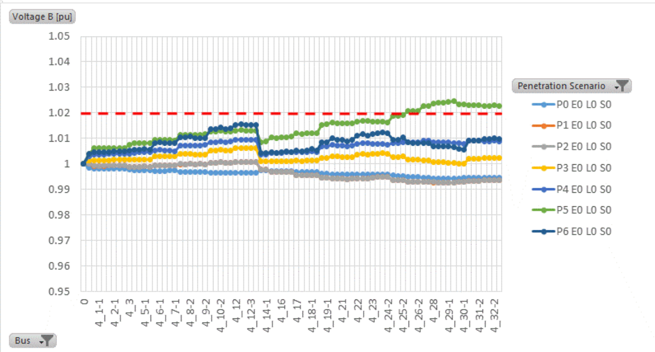


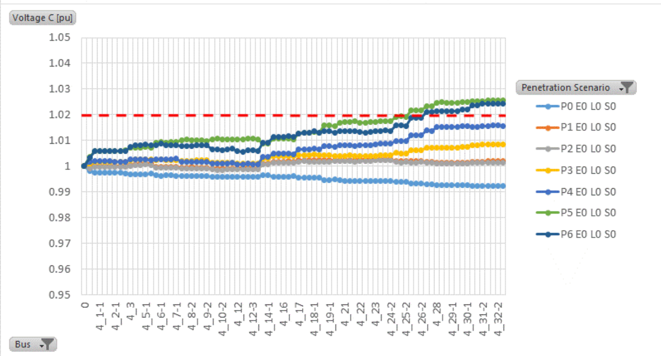




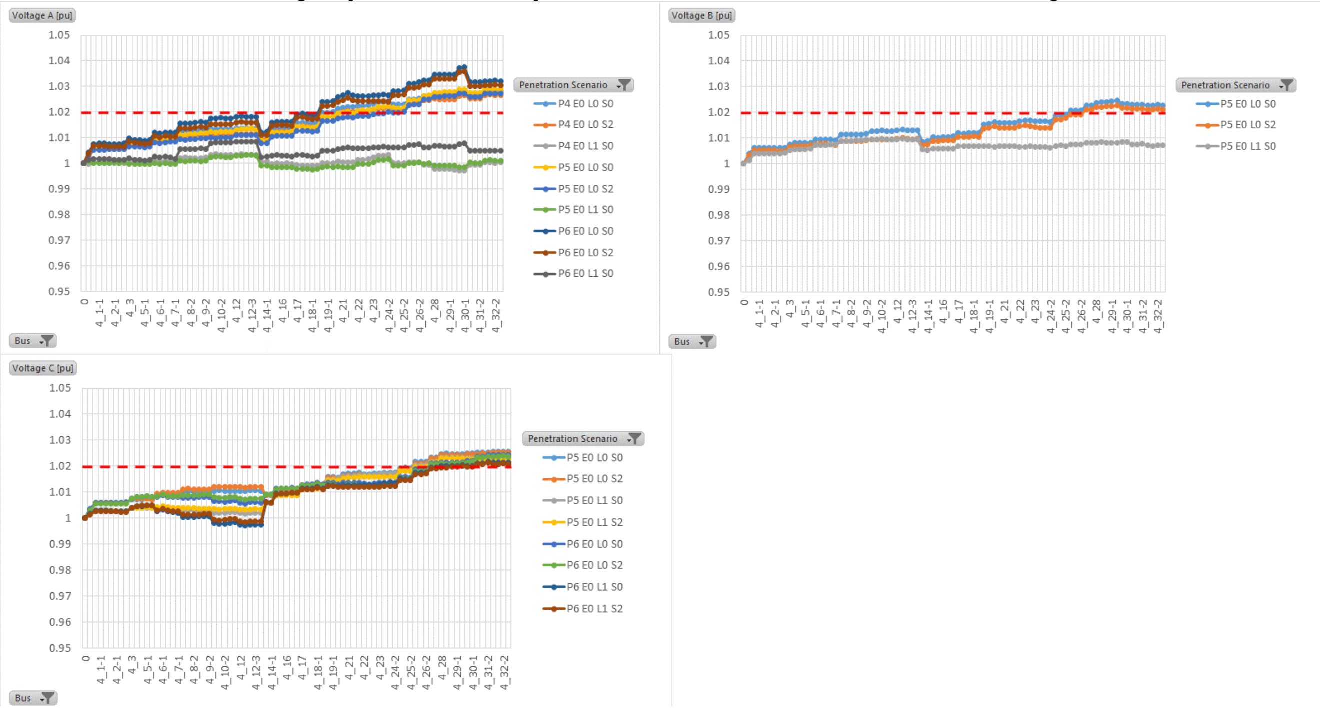
- **Leg 4 (Phase A to C)**







- Leg 4 (Phase A to C) with CL and ST to control overvoltages



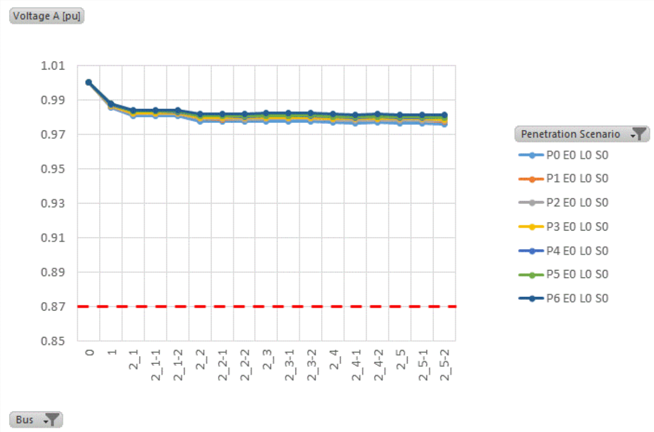
3. Undervoltage check

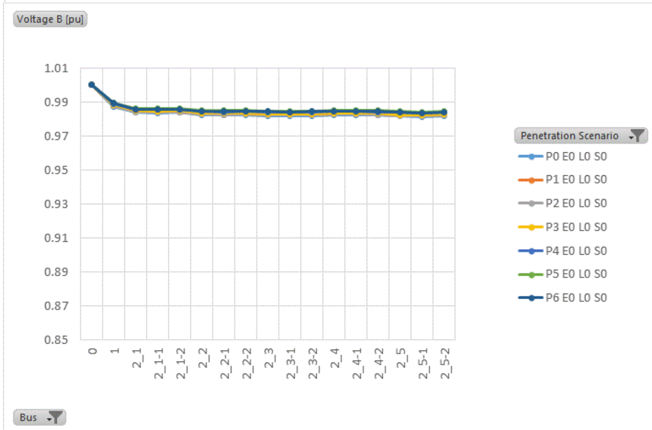
- To check the worst undervoltage – consider the max. consumer load with the lowest PV utilisation factor of 20%.
- The PV only DERs penetration scenarios were considered; and a more onerous scenario with only the power sinking DERs was tested.
- No undervoltages (<0.87pu) were observed in this feeder.

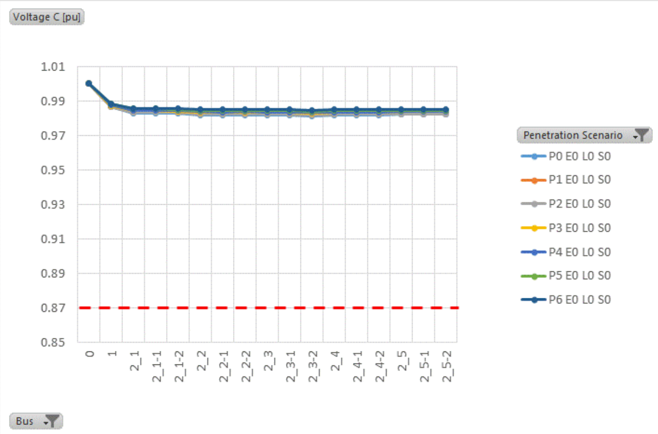
b) Max. consumer load with 20% PV utilisation factor

- **Leg 1 (Phase A to C)**

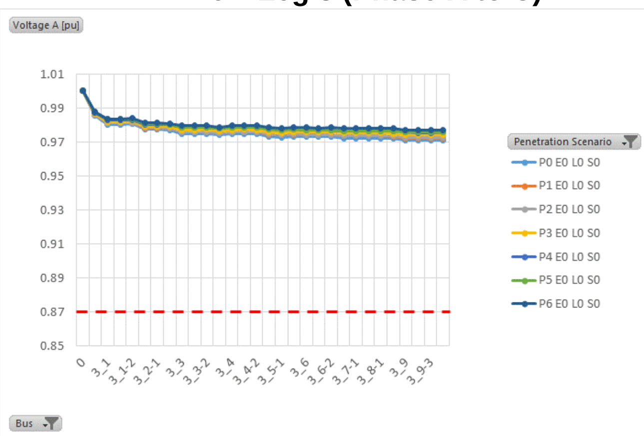
- o **Leg 2 (Phase A to C)**

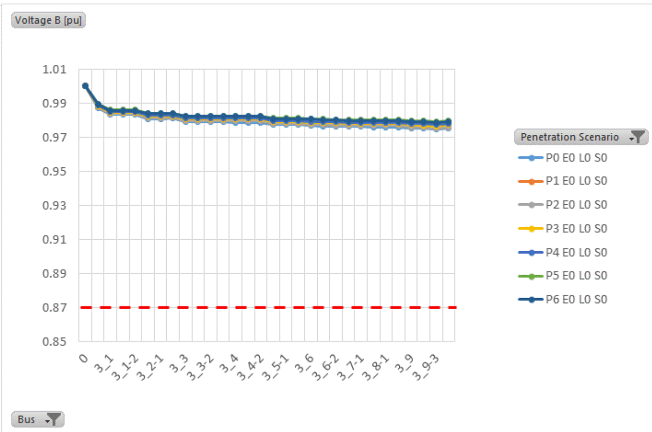


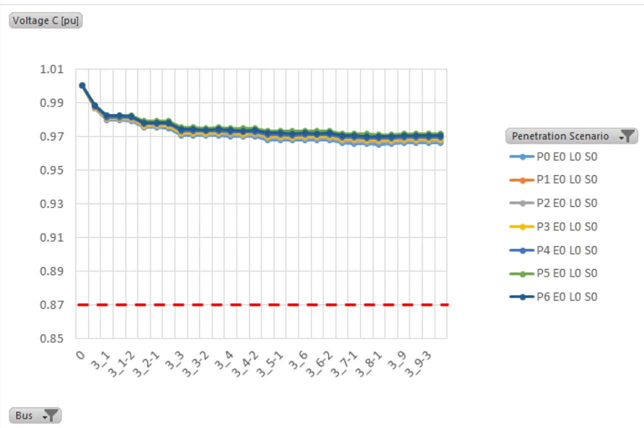




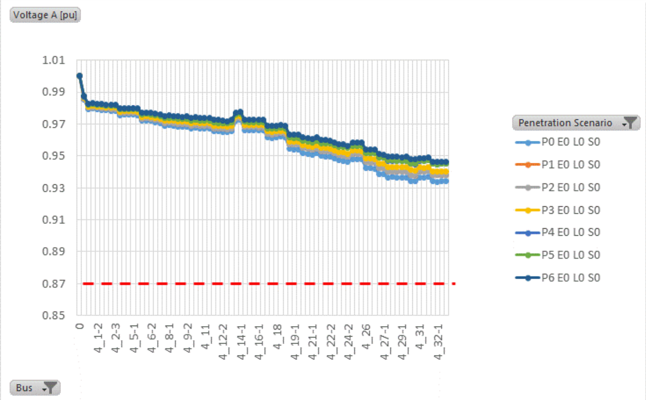
- o **Leg 3 (Phase A to C)**

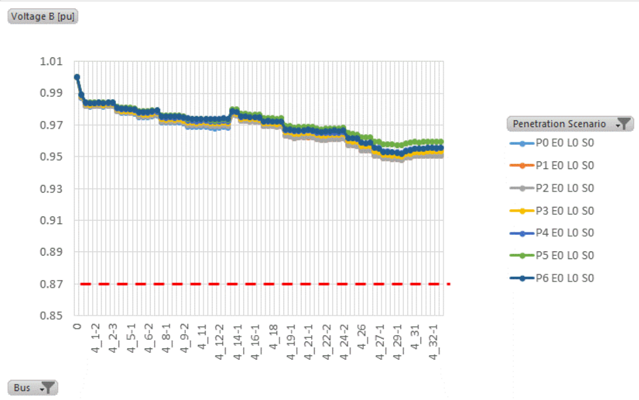


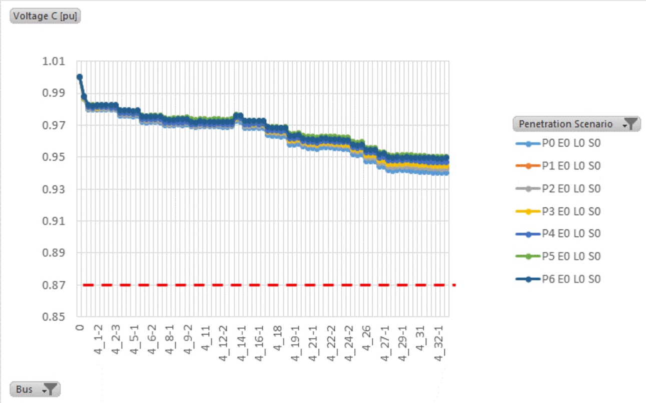




o **Leg 4 (Phase A to C)**

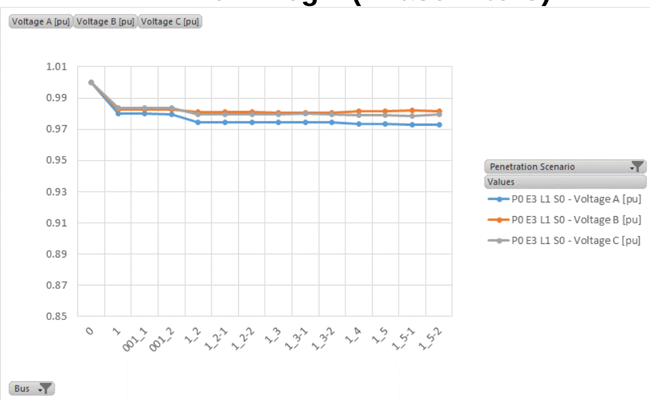


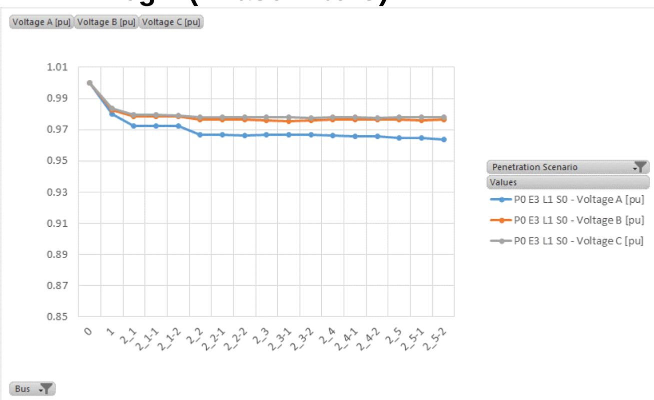




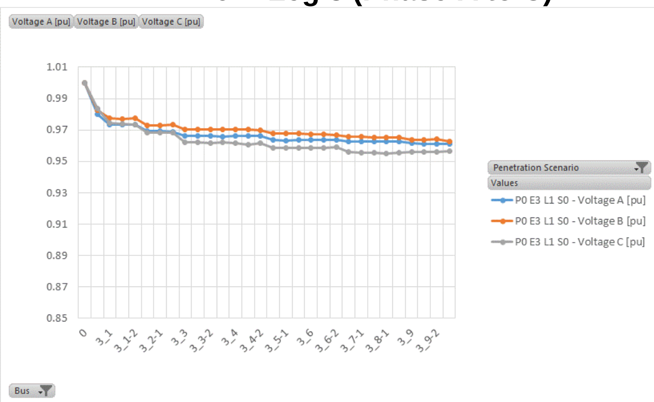
c) Max. consumer load with power sinking DERs

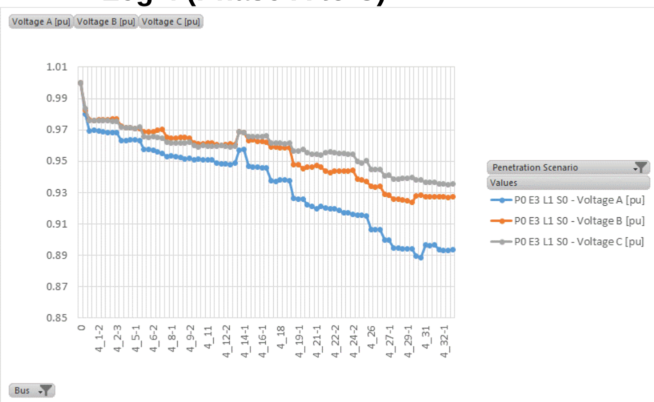
o **Leg 1 (Phase A to C)** **Leg 2 (Phase A to C)**





o **Leg 3 (Phase A to C)** **Leg 4 (Phase A to C)**



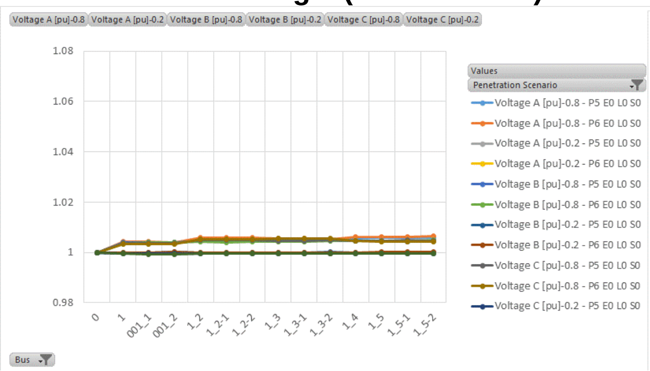


4. Voltage fluctuations

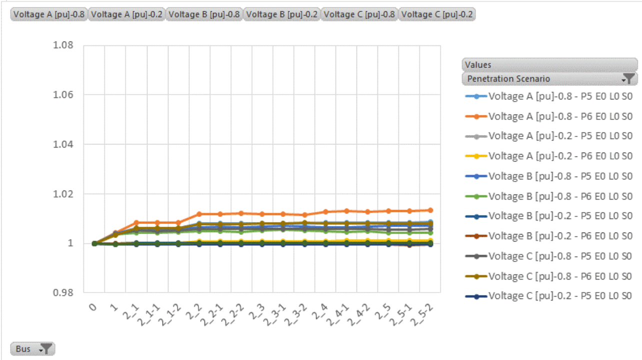
- The potential voltage fluctuation range is predicted by checking the step change in voltages from low PV utilisation factor (20%) to high PV utilisation factor (80%).
- The most onerous fluctuation would occur under the PV only DERs penetration scenarios. Based on the solar profile provided by SAPN the periods with high PV utilisation coincides with the min. load periods of the day (12-2PM). Hence, for this assessment a network with min. load is considered.
- From the voltage plots – the voltage fluctuation range for any particular point is not more than 0.05 pu (or 5%) within the criteria in IEC/TR 61000-3-7:2008 of 3-5%.

d) Potential voltage fluctuations

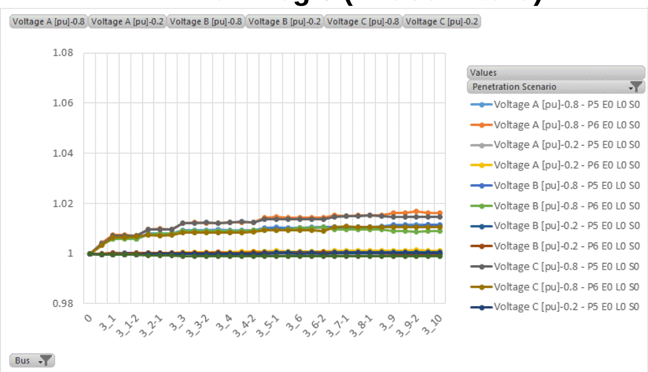
- **Leg 1 (Phase A to C)**



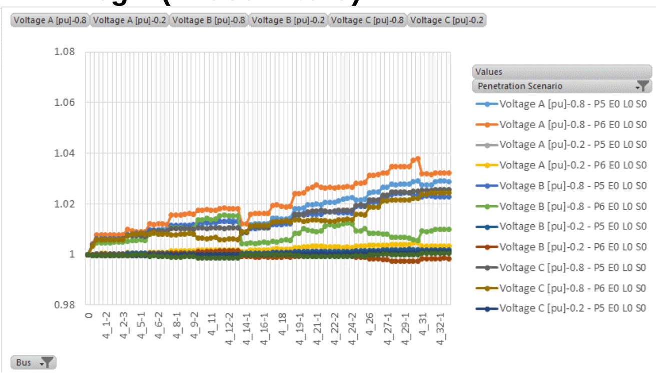
Leg 2 (Phase A to C)



- **Leg 3 (Phase A to C)**



Leg 4 (Phase A to C)



5. Voltage unbalance

- For max. consumer load - the highest voltage unbalance factor of 1.26% is observed under penetration scenario P0E1L1S2.
- For min. consumer load - the highest voltage unbalance factor of 1.01% is observed under penetration scenario P0E1L1S2.
- The continuous voltage unbalance factor limit is 2%; hence, the unbalance factor for this feeder is within the limit.

	Max. Vneg/Vpos (%) observed		Max. Vneg/Vpos (%) observed (No DERs)	
	Peak demand case	Minimum demand case	Peak demand case	Minimum demand case
HH341A 81	1.26%	1.01%	0.44%	0.07%

FEEDER AP351B - 2034 (OLD OVERHEAD)

1. Details

- Woodville – Cheltenham 7.6 kV feeder
- 7600/433 V 500 kVA transformer
- Comprised of the following underground cable:
  - 37/ XLPE (23 m / 5.4%)
  - 7 / 3.75 AAC (182 m / 42.8%)
  - 0.1 Cu (220 m / 51.8%)
- Has one metering point to two distribution legs
  Leg 1 – 126 m
  Leg 2 – 126 m
- 12 customers
- Feeder phase balance (as per load data)
  - Leg 1&2: Phase A = 34.1% Phase B = 43.3% Phase C = 22.7%
- Distribution of customers across feeder:

	Leg 1 & 2
Customers in %	100 %
Customers	12
3-Phase Customers	4
1-Phase Customers	8
1-Phase A	3
1-Phase B	3
1-Phase C	2

- Max. consumer load assumed = 25.2 kVA (obtained from actual data)

	Leg 1 & 2 [kVA / customer]
3-Phase Customers	2.11
1-Phase A	2.12
1-Phase B	2.30
1-Phase C	1.74

- Min. consumer load = 7.15 kVA (obtained from actual data assuming existing PV utilisation factor of 80%)

	Leg 1 & 2 [kVA / customer]
3-Phase Customers	0.60
1-Phase A	0.60
1-Phase B	0.65
1-Phase C	0.49

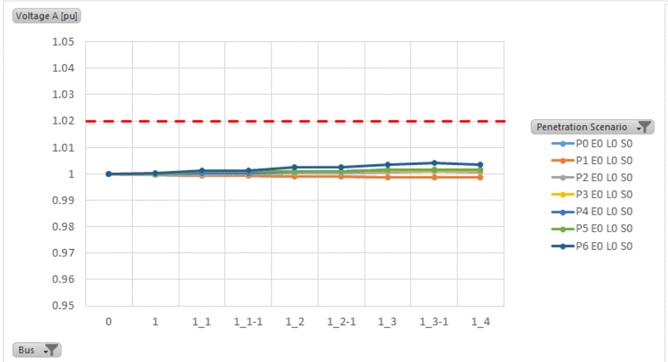
- Existing PV penetration = 0%
- Existing customers with controllable load = 0

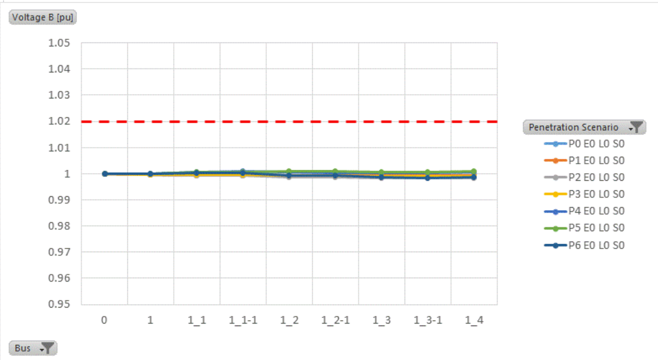
2. Overvoltage check

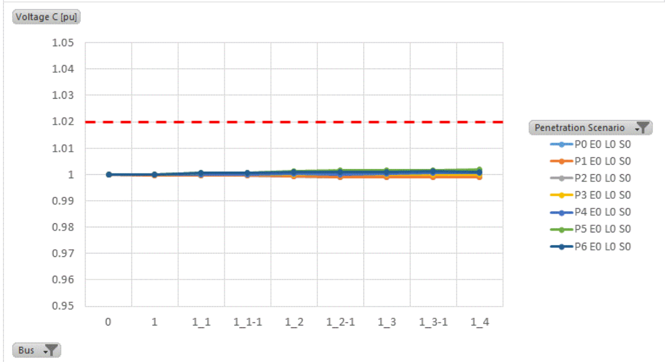
- To check the worst overvoltage – consider the min. consumer load with the highest PV utilisation factor of 80% for the PV only DERs penetration scenarios. The PV only DERs penetration scenarios are most onerous to overvoltage issues.
- No overvoltages (>1.02 pu) were observed in this feeder.
- An extreme case was tested where the consumer load is assumed to be at 10% of the max. No overvoltages were observed in this extreme case even under the most onerous penetration scenarios of *P5E0L0S0* and *P6E0L0S0*.

a) Min. consumer load with 80% PV utilisation factor

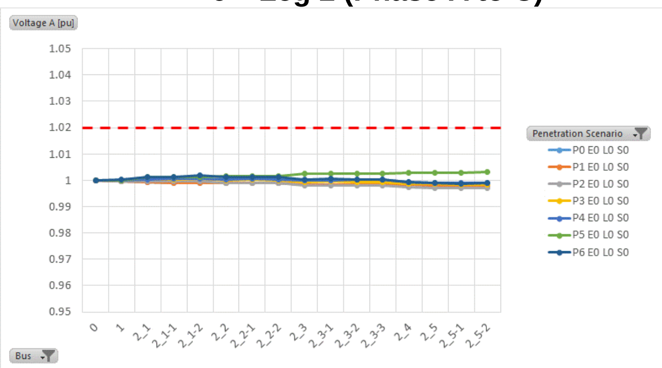
- **Leg 1 (Phase A to C)**

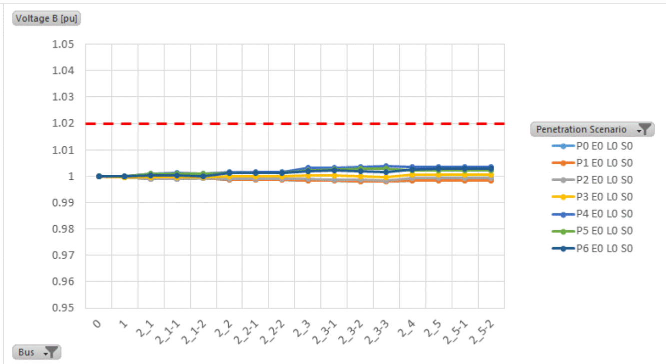


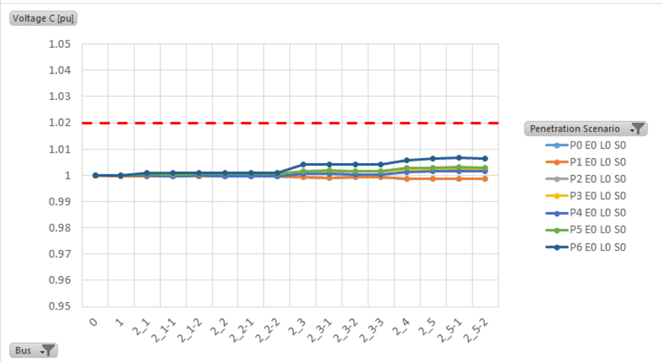




- **Leg 2 (Phase A to C)**

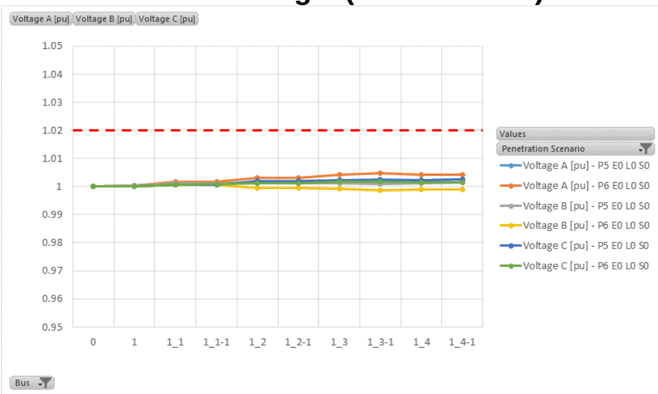


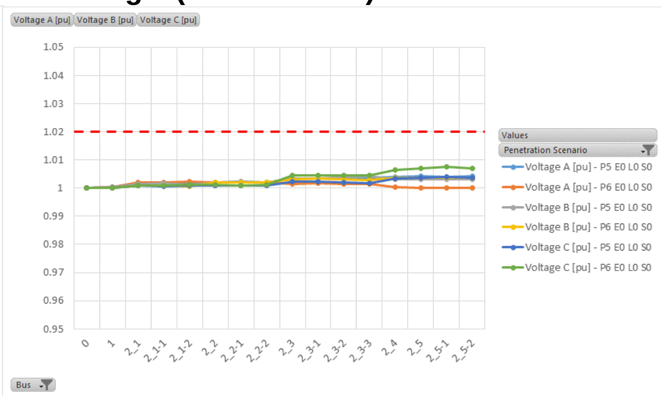




b) Extreme case with consumer load at 10% of the max.

- o **Leg 1 (Phase A to C)** **Leg 1 (Phase A to C)**



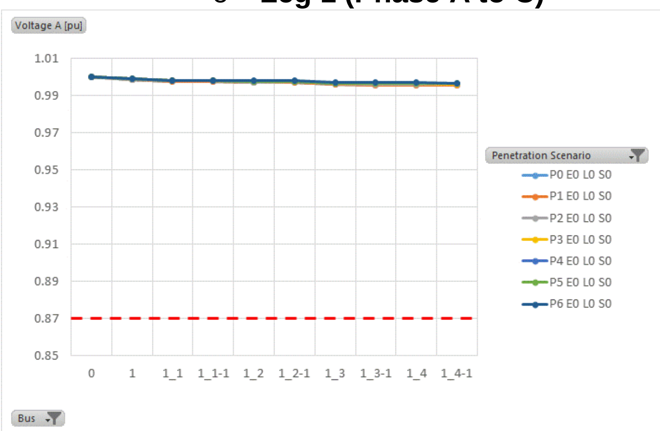


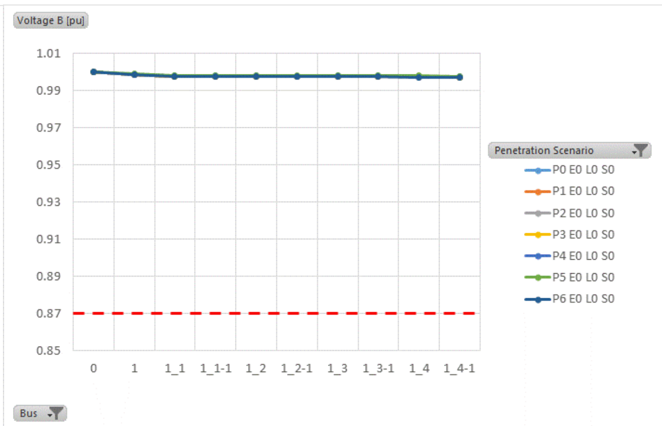
3. Undervoltage check

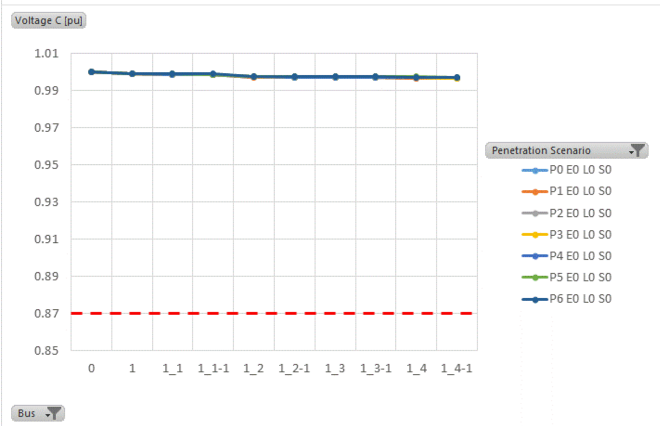
- To check the worst undervoltage – consider the max. consumer load with the lowest PV utilisation factor of 20%.
- The PV only DERs penetration scenarios were considered; and a more onerous scenario with only the power sinking DERs was tested.
- No undervoltages (<0.87pu) were observed in this feeder under all the scenarios considered.

c) Max. consumer load with 20% PV utilisation factor

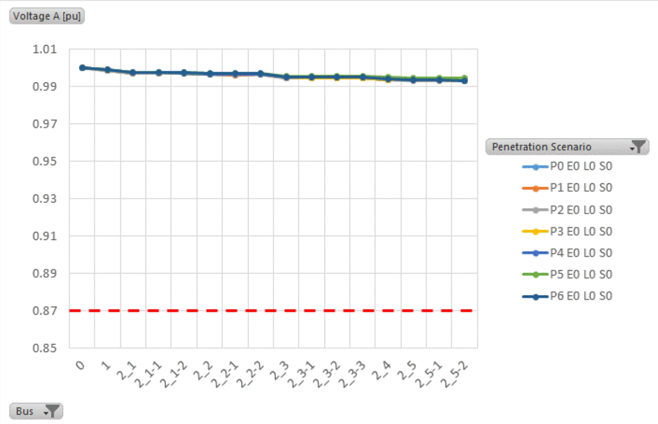
- o **Leg 1 (Phase A to C)**

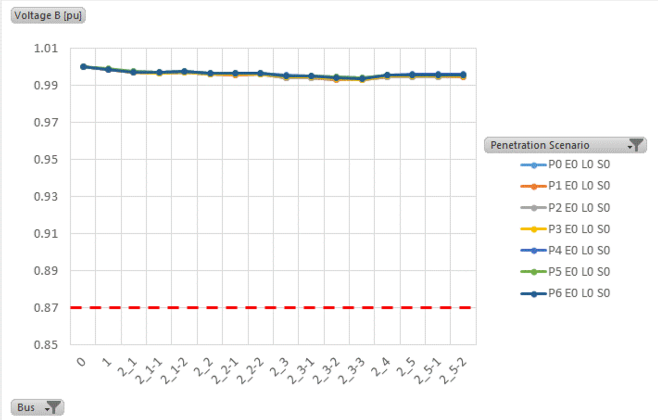


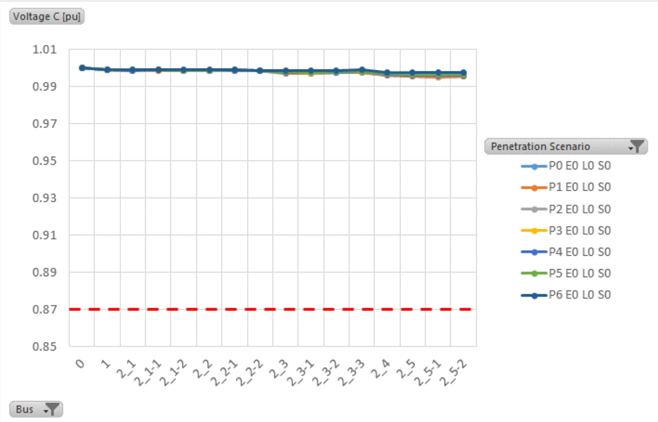




- Leg 2 (Phase A to C)

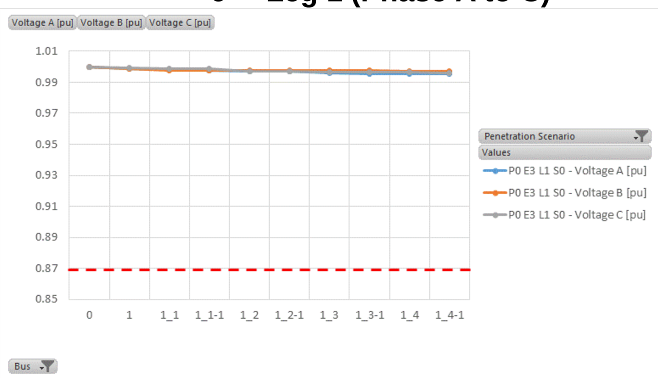


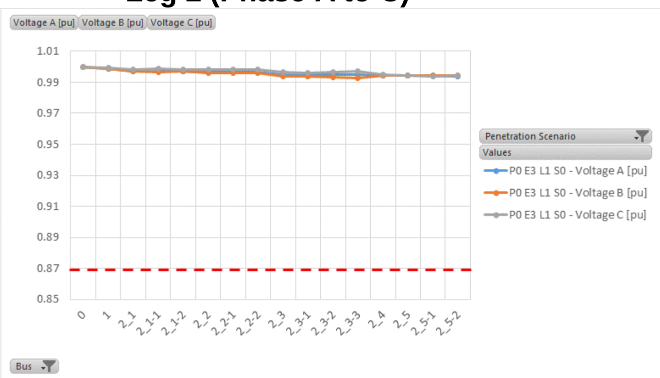




d) Max. consumer load with power sinking DERs

- Leg 1 (Phase A to C) Leg 2 (Phase A to C)



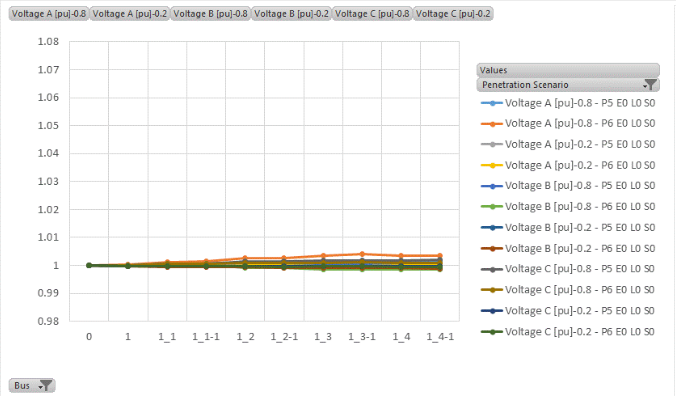


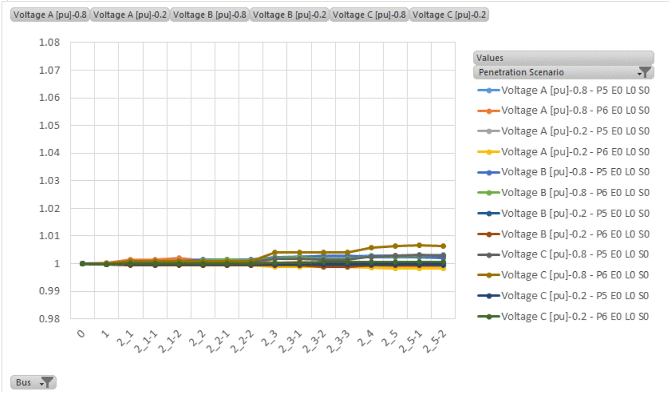
4. Voltage fluctuations

- The potential voltage fluctuation range is predicted by checking the voltages at the distribution legs from low PV utilisation factor (0.2) to high PV utilisation factor (0.8).
- The onerous fluctuation would occur should the cloud cover vary the PV factor from 0.2 to 0.8, or vice-versa, under the highest PV penetration scenario. Cloud cover reducing the PV output to zero is not considered here.
- Based on the voltage plots for both the distribution legs – the voltage fluctuation range for any particular point is not more than 0.05 pu (or 5%) within the criteria in IEC/TR 61000-3-7:2008 of 3-5%.

e) Potential voltage fluctuations

- **Leg 1 (Phase A to C)** **Leg 2 (Phase A to C)**





5. Voltage unbalance

- For max. consumer load - the highest voltage unbalance factor of 0.14% is observed under penetration scenario P2E0L0S4.
- For min. consumer load - the highest voltage unbalance factor of 0.29% is observed under penetration scenario P6E0L0S4.
- The continuous voltage unbalance factor limit is 2% hence, the unbalance factor for this feeder is within the limit.

	Max. Vneg/Vpos (%) observed		Max. Vneg/Vpos (%) observed (No DERs)	
	Peak demand case	Minimum demand case	Peak demand case	Minimum demand case
AP351B 2034	0.14%	0.29%	0.11%	0.03%

FEEDER AP344D - 15 (OLD OVERHEAD)

1. Details

- Port Adelaide – Alberton 7.6 kV feeder
- 7600/455 V 150 kVA transformer (pole mounted)
- Comprised of the following overhead conductor:
  - 7 / 4.75 AAC (378 m / 23.4%)
  - 7 / 3.75 AAC (653 m / 40.5%)
  - 0.1 Cu (581 m / 36%)
- Has one meter point to two distribution legs:
  Leg 1 – 353 m
  Leg 2 – 394 m
- 46 customers
- Feeder phase balance (as per load data)
  - Phase A = 34.1% Phase B = 42.3% Phase C = 22.7%
- Distribution of customers across feeder:

	Leg 1 & 2
Customers in %	100 %
Customers	46
3-Phase Customers	14
1-Phase Customers	32
1-Phase A	11
1-Phase B	14
1-Phase C	7

- Max. consumer load assumed = 97.3 kVA (obtained from actual data)

	Leg 1 & 2 [kVA / customer]
3-Phase Customers	2.11
1-Phase A	2.11
1-Phase B	2.30
1-Phase C	1.74

- Min. consumer load = 27.6 kVA (obtained from actual data assuming existing PV utilisation factor of 80%)

	Leg 1 & 2 [kVA / customer]
3-Phase Customers	0.60
1-Phase A	0.60
1-Phase B	0.26
1-Phase C	0.20

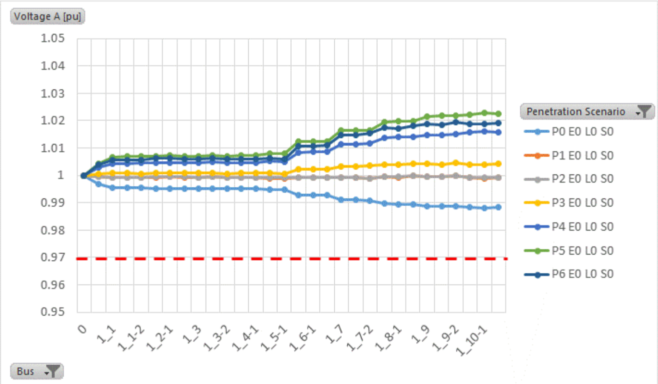
- Existing PV penetration = 25.27 % or 37.9 kW rated, i.e. 15 customers (assuming a 2.5 kW inverter size)
- Existing customers with controllable load = 11 (24 %)

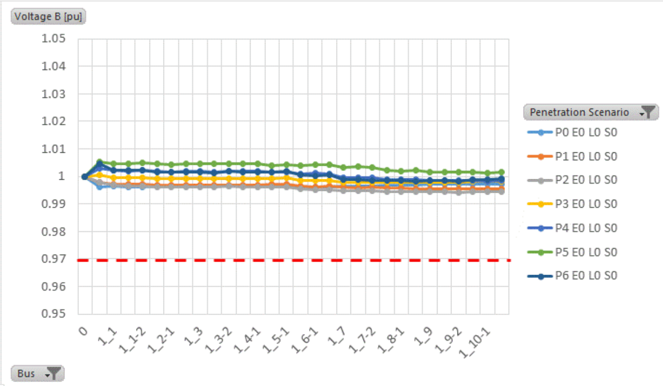
2. Overvoltage check

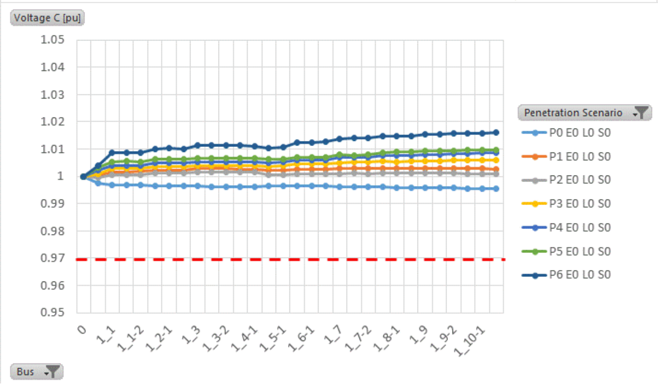
- To check the worst overvoltage – consider the min. consumer load with the highest PV utilisation factor of 80% for the PV only DERs penetration scenarios. The PV only DERs penetration scenarios are most onerous to overvoltage issues.
- Due to the higher LV rating of the transformer of 445 V, the overvoltage limit for this feeder is 0.98 pu if converted to a nominal of 400 V. Hence, the voltages on this feeder are observed to be above the limit regardless of the PV penetration levels.

a) Min. consumer load with 80% PV utilisation factor

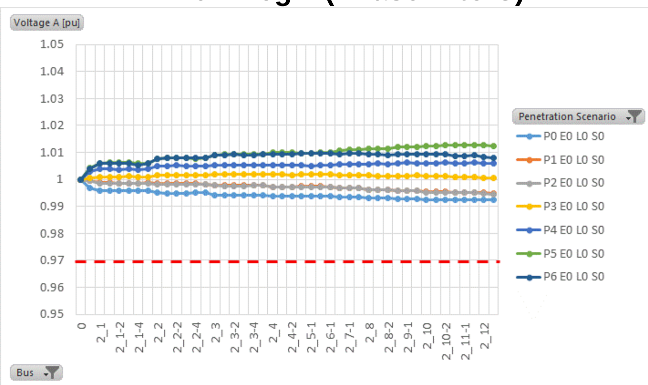
- **Leg 1 (Phase A to C)**

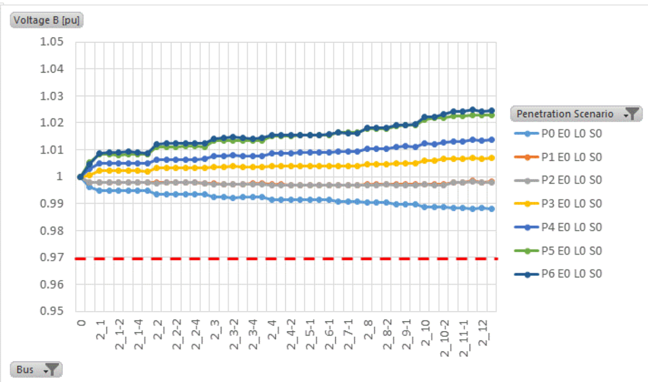


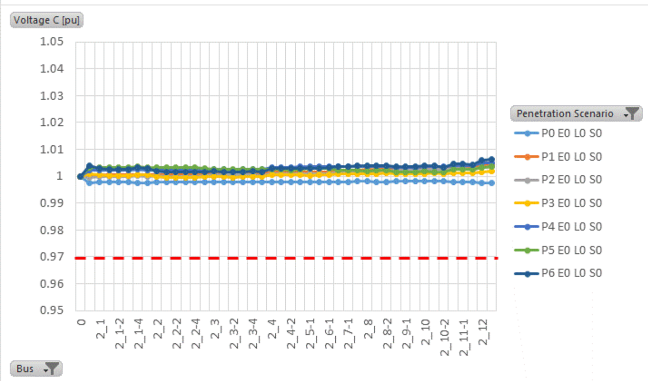




- **Leg 2 (Phase A to C)**





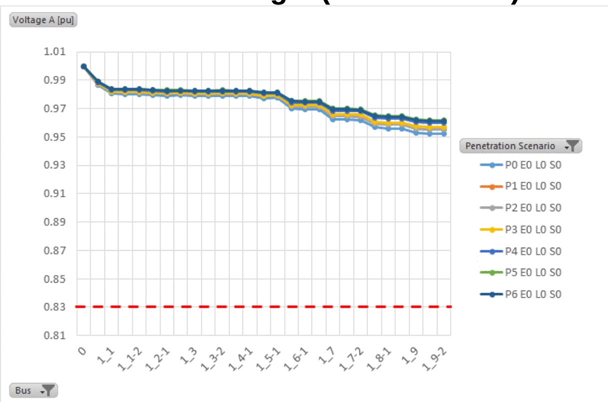


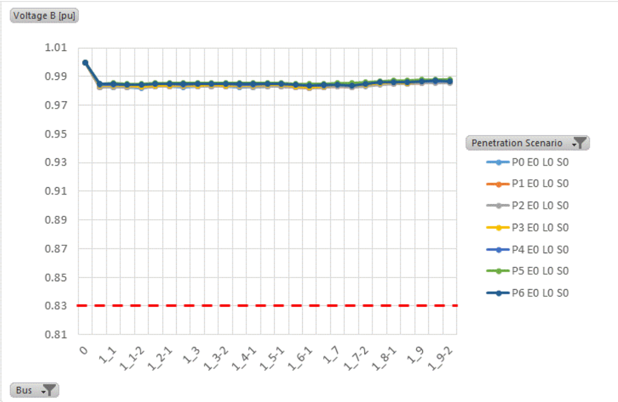
3. Undervoltage check

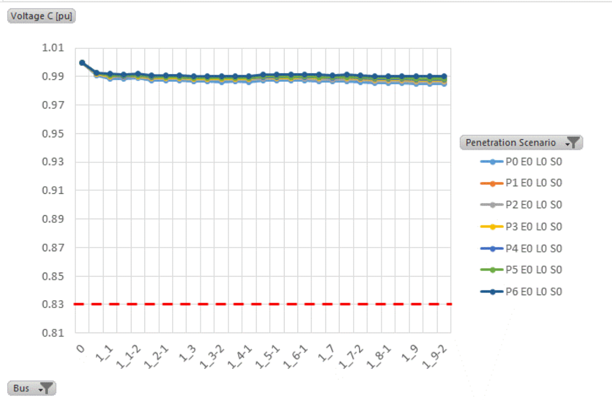
- To check the worst undervoltage – consider the max. consumer load with the lowest PV utilisation factor of 20%.
- The PV only DERs penetration scenarios were considered; and a more onerous scenario with only the power sinking DERs was tested.
- No undervoltages (<0.83pu) were observed in this feeder.

b) Max. consumer load with 20% PV utilisation factor

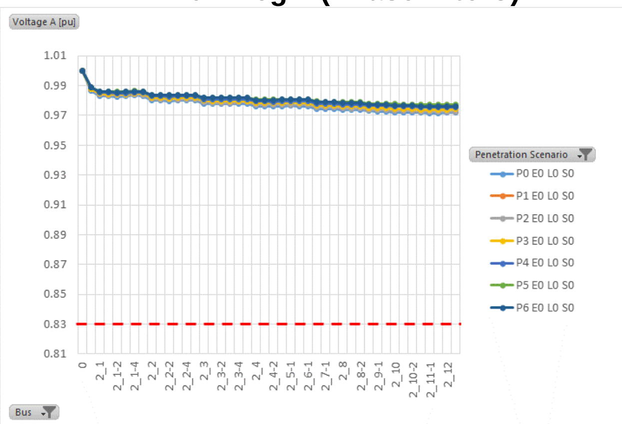
- **Leg 1 (Phase A to C)**

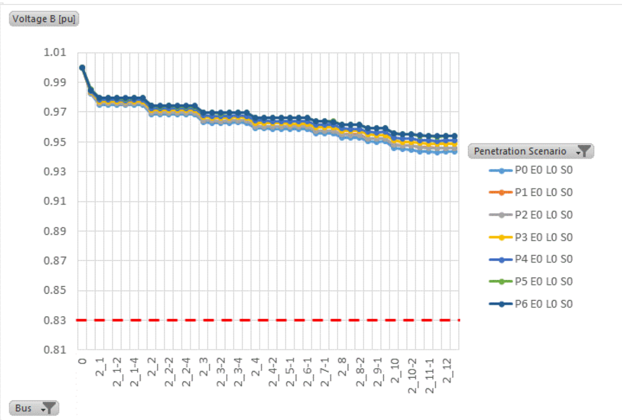


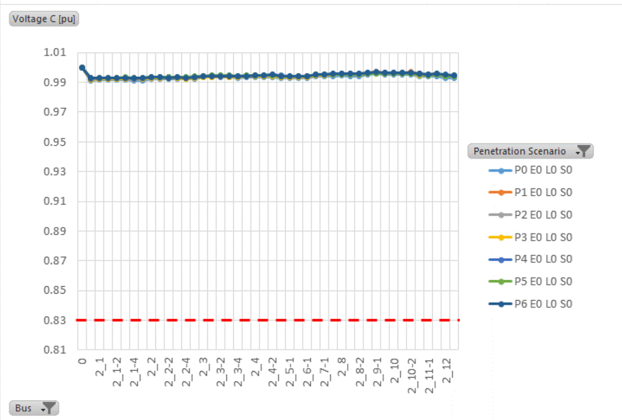




- **Leg 2 (Phase A to C)**

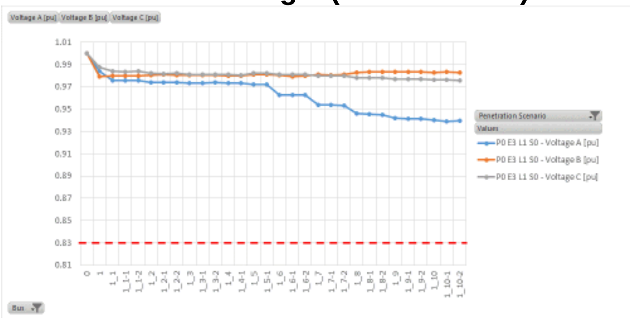


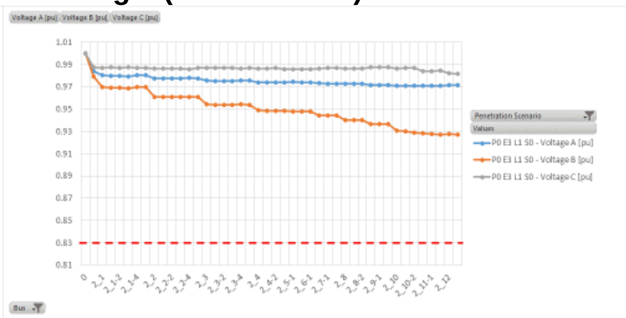




c) Max. consumer load with power sinking DERs

- Leg 1 (Phase A to C) Leg 2 (Phase A to C)



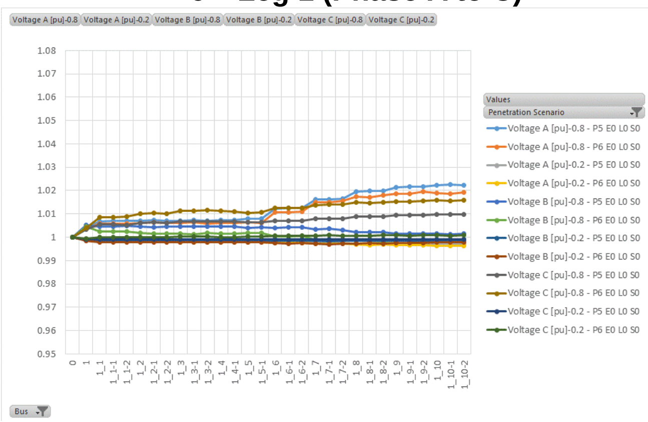


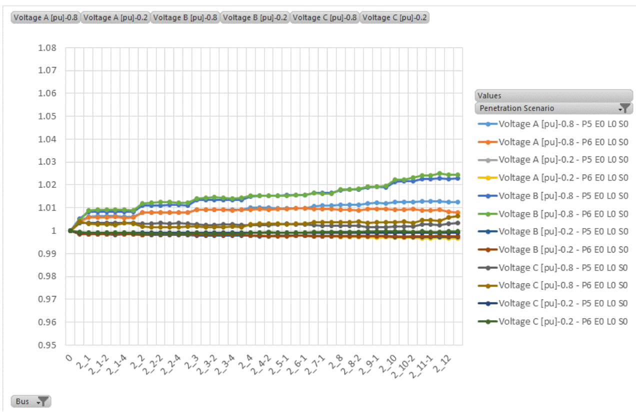
4. Voltage fluctuations

- The potential voltage fluctuation range is predicted by checking the voltages at the distribution legs from low PV utilisation factor (0.2) to high PV utilisation factor (0.8).
- The onerous fluctuation would occur should the cloud cover vary the PV utilisation factor from 0.2 to 0.8, or vice-versa, under the highest PV penetration scenario. Cloud cover reducing the PV output to zero is not considered here. Based on the solar profile provided by SAPN the periods with high solar intensity coincides with the low load periods of the day (12-2PM).
- From the voltage plots for both the distribution legs – the voltage fluctuation range for any particular point is not more than 0.05 pu (or 5%) within the criteria in IEC/TR 61000-3-7:2008 of 3-5%.

d) Potential voltage fluctuations

- Leg 1 (Phase A to C) Leg 2 (Phase A to C)





5. Voltage unbalance

- For max. consumer load - the highest voltage unbalance factor of 1.44% is observed under penetration scenario P0E1L0S2.
- For min. consumer load - the highest voltage unbalance factor of 0.94% is observed under penetration scenario P0E1L0S2.
- The continuous voltage unbalance factor limit is 2%, hence, the unbalance factor for this feeder under the max. consumer load has not exceeded the limit.

	Max. Vneg/Vpos (%) observed		Max. Vneg/Vpos (%) observed (No DERs)	
	Peak demand case	Minimum demand case	Peak demand case	Minimum demand case
AP344D 15	1.44%	0.94%	1.28%	0.29%

FEEDER SM126A - 159 (NEW OVERHEAD)

1. Details

- Blackwood – Glenalta 11 kV feeder
- 11000/433 V 50 kVA transformer
- Comprised of the following overhead conductor and underground cable:
  - XLPE AL 150 mm^2 (191 m / 35.7%)
  - 4 x 95 ABC (344 m / 64.4%)
- Has one meter point to two distribution legs:
  Leg 1 – 158 m
  Leg 2 – 191 m
- 7 customers
- Feeder phase balance (as per load data)
  - Phase A = 40.6% Phase B = 1.4% Phase C = 58%
- Distribution of customers across feeder:

	Leg 1 & 2
Customers in %	100 %
Customers	7
3-Phase Customers	2
1-Phase Customers	5
1-Phase A	2
1-Phase B	0
1-Phase C	3

- Max. consumer load assumed = 11.6 kVA (obtained from actual data)

	Leg 1 & 2 [kVA / customer]
3-Phase Customers	1.66
1-Phase A	1.80
1-Phase B	0
1-Phase C	1.88

- Min. consumer load = 0 kVA (obtained from actual data assuming existing PV utilisation factor of 80%)

	Leg 1 & 2 [kVA / customer]
3-Phase Customers	0
1-Phase A	0
1-Phase B	0
1-Phase C	0

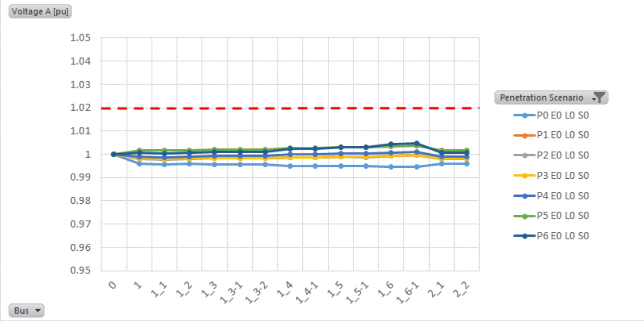
- Existing PV penetration = 20.94 % or 10.5 kW rated, i.e. 4 customers (assuming a 2.5 kW inverter size)
- Existing customers with controllable load = 5 (71 %)

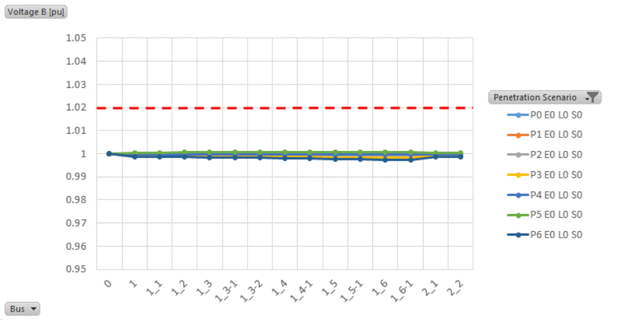
2. Overvoltage check

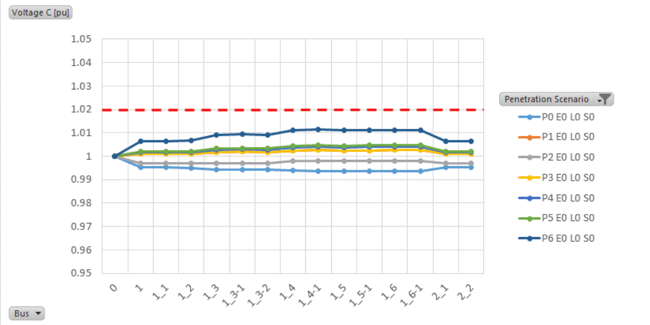
- To check the worst overvoltage – consider the min. consumer load with the highest PV utilisation factor of 80% for the PV only DERs penetration scenarios. The PV only DERs penetration scenarios are most onerous to overvoltage issues.
- No overvoltages (>1.02 pu) were observed in this feeder.

a) Min. consumer load with 80% PV utilisation factor

- **Leg 1 & 2 (Phase A to C)**





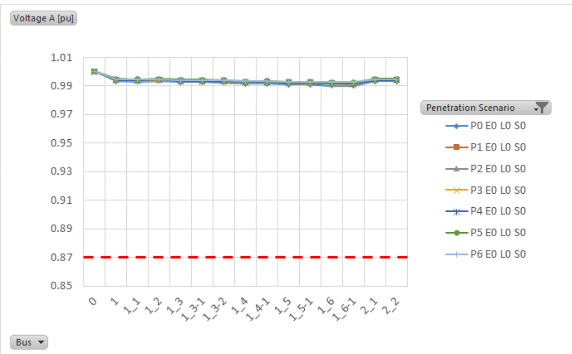


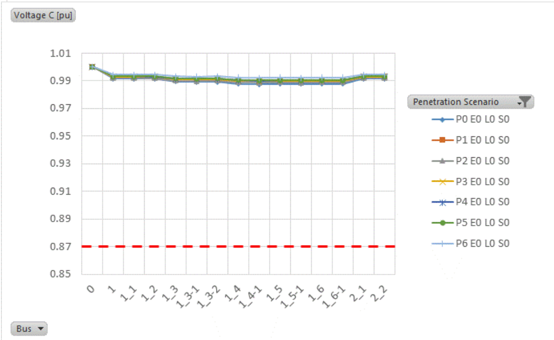
3. Undervoltage check

- To check the worst undervoltage – consider the max. consumer load with the lowest PV utilisation factor of 20%.
- The PV only DERs penetration scenarios were considered; and a more onerous scenario with only the power sinking DERs was tested.
- No undervoltages (<0.87pu) were observed in this feeder under all the scenarios considered.

b) Max. consumer load with 20% PV utilisation factor

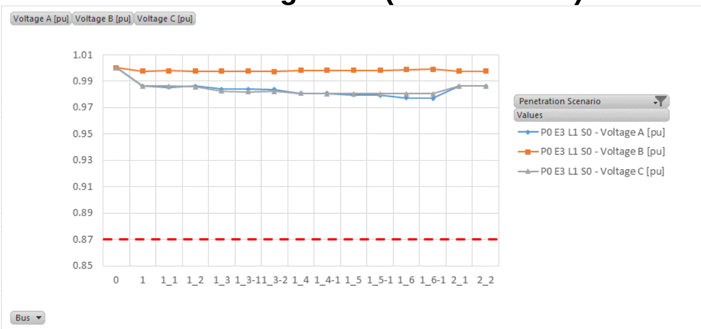
- **Leg 1 & 2 (Phase A to C)**





c) Max. consumer load with power sinking DERs

- Leg 1 & 2 (Phase A to C)

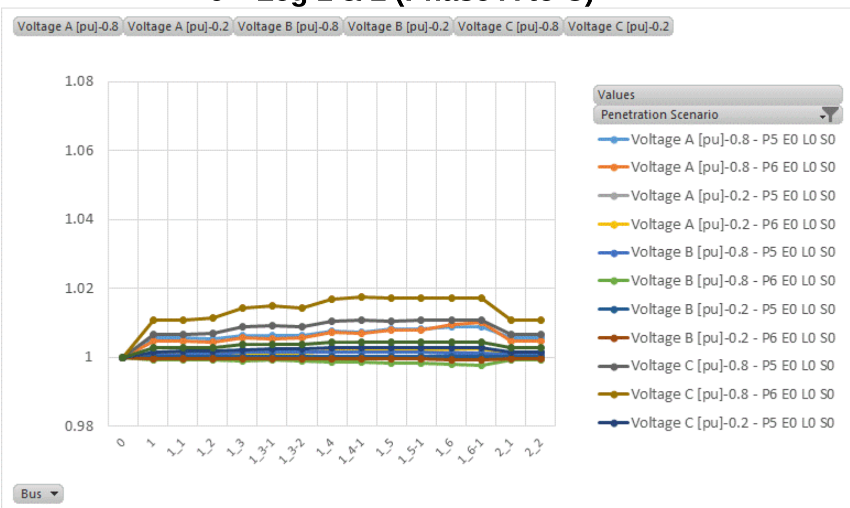


4. Voltage fluctuations

- The potential voltage fluctuation range is predicted by checking the step change in voltages from low PV utilisation factor (20%) to high PV utilisation factor (80%).
- The most onerous fluctuation would occur under the PV only DERs penetration scenarios. Based on the solar profile provided by SAPN the periods with high PV utilisation coincides with the min. load periods of the day (12-2PM). Hence, for this assessment a network with min. load is considered.
- From the voltage plots – the voltage fluctuation range for any particular point is not more than 0.05 pu (or 5%) within the criteria in IEC/TR 61000-3-7:2008 of 3-5%.

d) Potential voltage fluctuations

- Leg 1 & 2 (Phase A to C)



5. Voltage unbalance

- For max. consumer load - the highest voltage unbalance factor of 0.89% is observed under penetration scenario P0E2L1S2.
- For min. consumer load - the highest voltage unbalance factor of 0.79% is observed under penetration scenario P0E1L0S2.
- The continuous voltage unbalance factor limit is 2% hence; the unbalance factor for this feeder is within the limit.

	Max. Vneg/Vpos (%) observed		Max. Vneg/Vpos (%) observed (No DERs)	
	Peak demand case	Minimum demand case	Peak demand case	Minimum demand case
SM126A 159	0.89%	0.79%	0.40%	0.00%

FEEDER EL13 - 57 (NEW OVERHEAD)

1. Details

- Elizabeth Downs – Anderson Walk 11 kV feeder
- 11000/433 V 200 kVA transformer
- Comprised of the following overhead conductor:
  - 7 / 4.75 AAC (528 m / 30.7%)
  - 7 / 3.75 AAC (589 m / 34.2%)
  - 7 / 2.75 AAC (604 m / 35.1%)
- Has one metering point to two distribution legs:
  Leg 1 – 133 m
  Leg 2 – 860 m
- 49 customers
- Feeder phase balance (as per load data)
  - Phase A = 37.7% Phase B = 32.7% Phase C = 29.7%
- Distribution of customers across feeder:

	Leg 1 & 2
Customers in %	100 %
Customers	49
3-Phase Customers	15
1-Phase Customers	34
1-Phase A	13
1-Phase B	11
1-Phase C	10

- Max. consumer load assumed = 112.9 kVA (obtained from actual data)

	Leg 1 & 2 [kVA / customer]
3-Phase Customers	2.30
1-Phase A	2.38
1-Phase B	2.30
1-Phase C	2.20

- Min. consumer load = 18.3 kVA (obtained from actual data assuming existing PV utilisation factor of 80%)

	Leg 1 & 2 [kVA / customer]
3-Phase Customers	0.37
1-Phase A	0.39
1-Phase B	0.37
1-Phase C	0.36

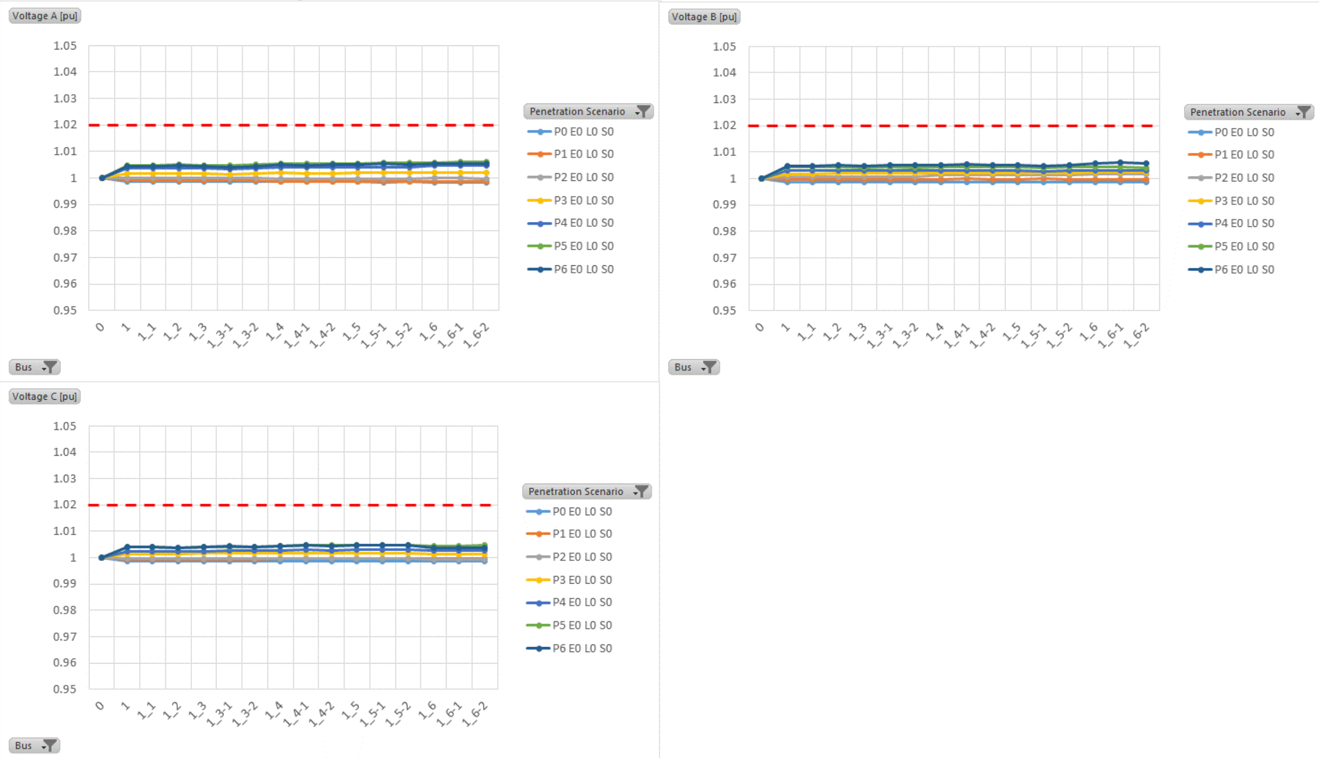
- Existing PV penetration = 5.94 % or 11.9 kW rated, i.e. 5 customers (assuming a 2.5 kW inverter size)
- Existing customers with controllable load = 49 (100 %)

2. Overvoltage check

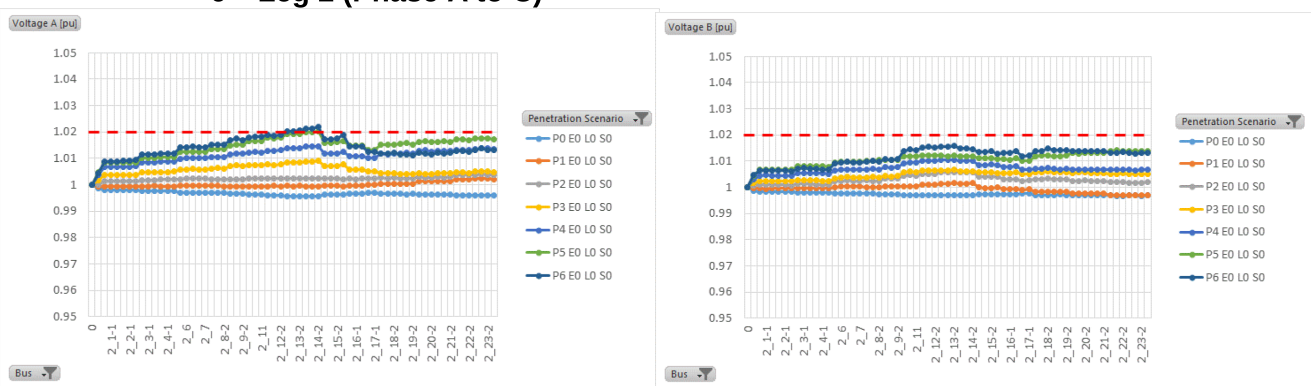
- To check the worst overvoltage – consider the min. consumer load with the highest PV utilisation factor of 80% for the PV only DERs penetration scenarios. The PV only DERs penetration scenarios are most onerous to overvoltage issues.
- Overvoltages (>1.02 pu) were observed in Phase A and C of Leg 2.
- Highest overvoltages observed:
  Leg 2 – Phase A: 1.022 pu (P6E0L0S0)
  Phase C: 1.023 pu (P6E0L0S0)
  - In Leg 2, the Phase A boundary penetration scenario before overvoltages occur is P4. Either the controllable loads (L1) or storage (S2) could be switched on to increase PV penetration to P5 and P6 while maintaining the voltage limit. For the case where only storage loads are switched on the voltages are only marginally within the limit.
  - In Leg 2, the Phase C boundary penetration scenario before overvoltages occur is P4. Either the controllable loads (L1) or storage (S2) could be switched on to increase PV penetration to P5 and P6 while maintaining the voltage limit.

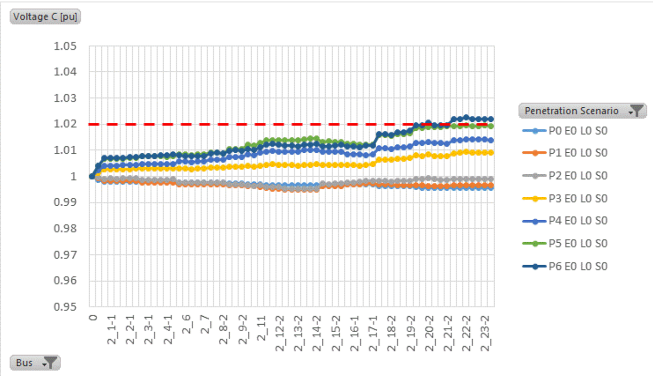
a) Min. consumer load with 80% PV utilisation factor

- **Leg 1 (Phase A to C)**

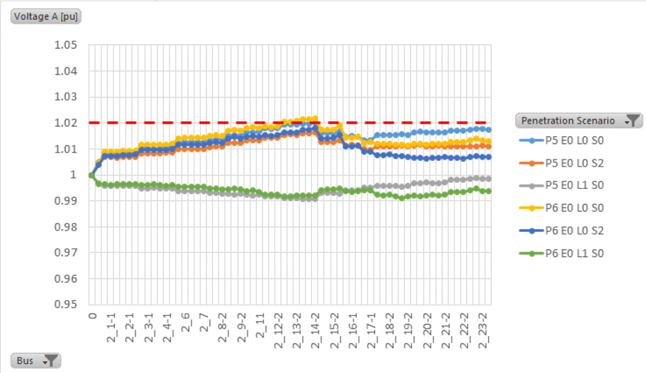


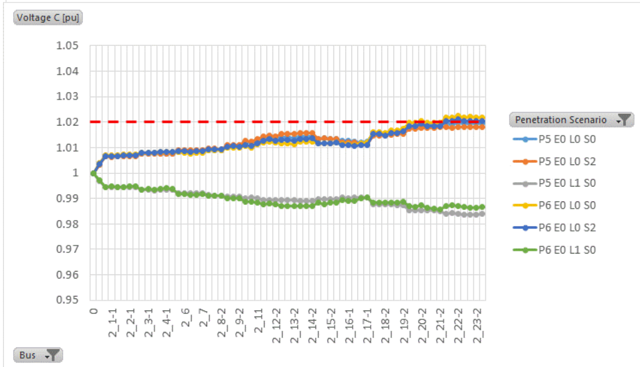
- **Leg 2 (Phase A to C)**





- **Leg 2 (Phase A) with CL and ST to control overvoltages**



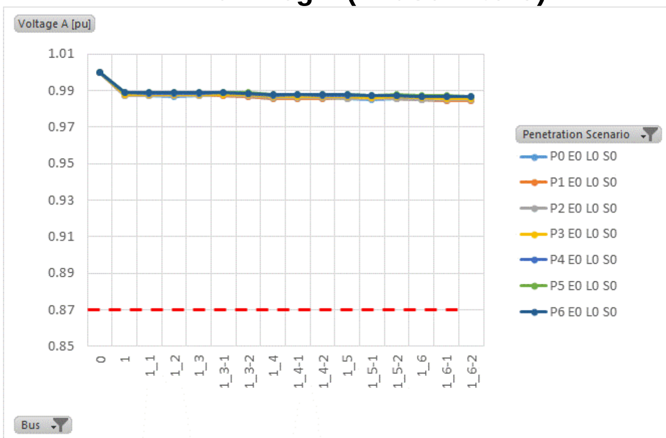


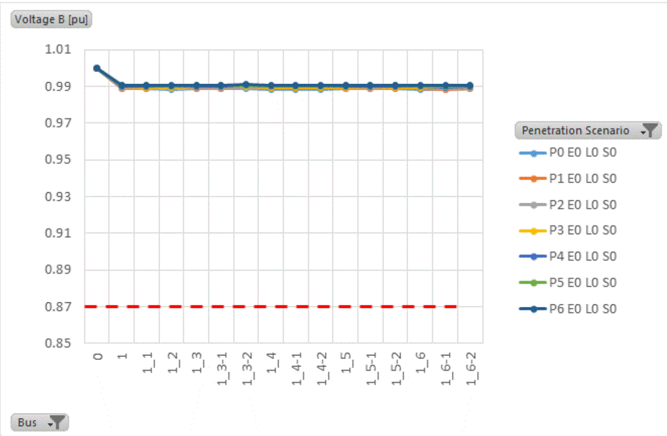
3. Undervoltage check

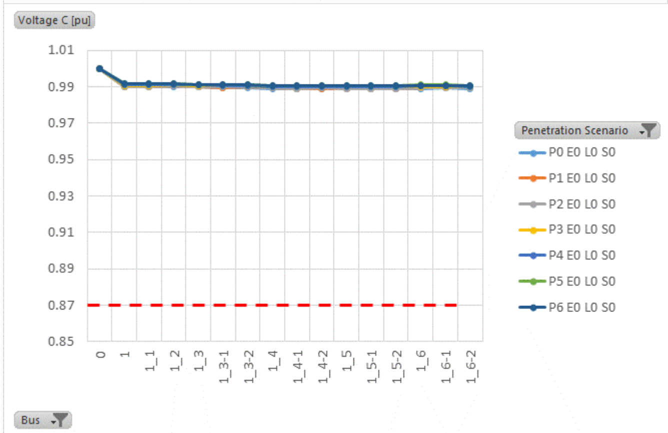
- To check the worst undervoltage – consider the max. consumer load with the lowest PV utilisation factor of 20%.
- The PV only DERs penetration scenarios were considered; and a more onerous scenario with only the power sinking DERs was tested.
- No undervoltages (<0.87pu) were observed in this feeder.

b) Max. consumer load with 20% PV utilisation factor

- **Leg 1 (Phase A to C)**



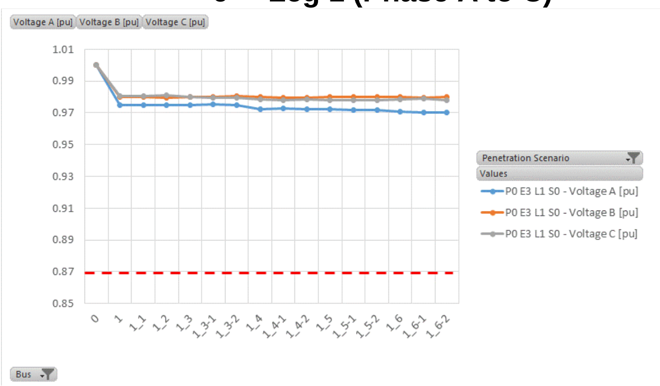


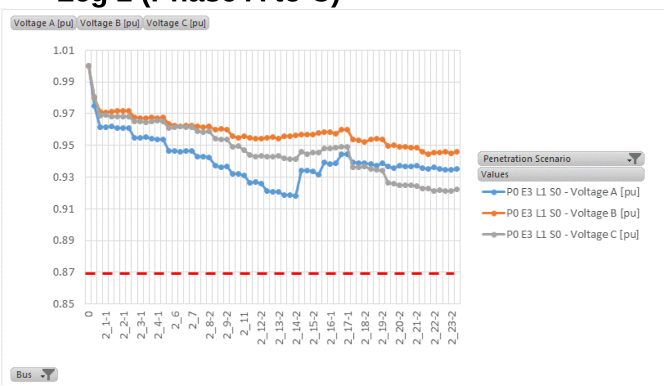


- o **Leg 2 (Phase A to C)**

c) Max. consumer load with power sinking DERs

- o **Leg 1 (Phase A to C)** **Leg 2 (Phase A to C)**



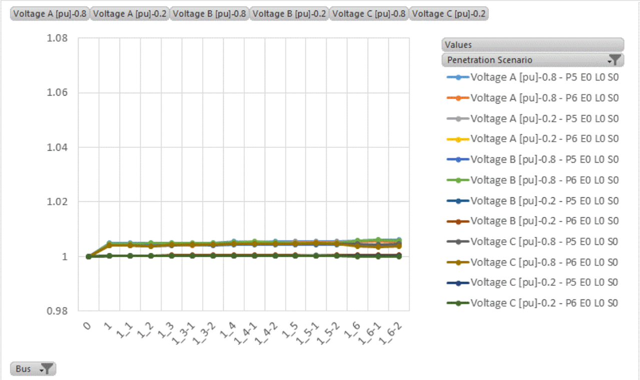


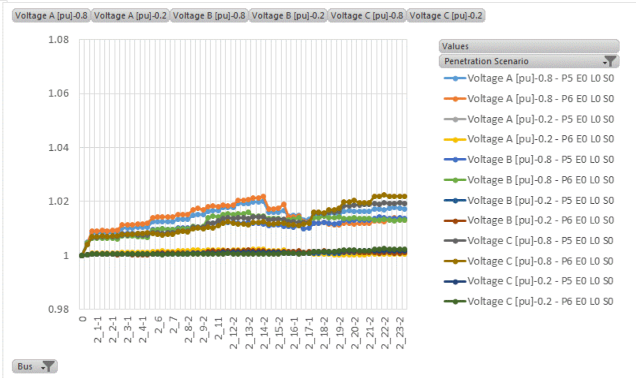
4. Voltage fluctuations

- The potential voltage fluctuation range is predicted by checking the step change in voltages from low PV utilisation factor (20%) to high PV utilisation factor (80%).
- The most onerous fluctuation would occur under the PV only DERs penetration scenarios. Based on the solar profile provided by SAPN the periods with high PV utilisation coincides with the min. load periods of the day (12-2PM). Hence, for this assessment a network with min. load is considered.
- From the voltage plots – the voltage fluctuation range for any particular point is not more than 0.05 pu (or 5%) within the criteria in IEC/TR 61000-3-7:2008 of 3-5%.

a) Potential voltage fluctuations

- **Leg 1 (Phase A to C)** **Leg 2 (Phase A to C)**





5. Voltage unbalance

- For max. consumer load - the highest voltage unbalance factor of 1.12% is observed under penetration scenario P2E3L1S4.
- For min. consumer load - the highest voltage unbalance factor of 0.77% is observed under penetration scenario P2E3L1S4.
- The continuous voltage unbalance factor limit is 2%, hence, the unbalance factor for this feeder does not exceed the limit.

	Max. Vneg/Vpos (%) observed		Max. Vneg/Vpos (%) observed (No DERs)	
	Peak demand case	Minimum demand case	Peak demand case	Minimum demand case
EL13 57	1.12%	0.77%	0.46%	0.05%

FEEDER HH177F - 253 (NEW OVERHEAD)

1. Details

- Ingle Farm – Montague Farm 11 kV feeder
- 11000/433 V 100 kVA transformer
- Comprised of the following overhead conductor and underground cable:
  - XLPE AL 150 mm^2 (355 / 20.7%)
  - 7 / 3.75 AAC (468 m / 27.3%)
  - 7 / 14 Cu (243 m / 14.2%)
  - 0.06 Cu (646 m / 37.7%)
- Has one meter point to two distribution legs:
  Leg 1 – 546 m
  Leg 2 – 225 m
- 43 customers
- Feeder phase balance (as per load data)
  - Phase A = 34.9% Phase B = 29.8% Phase C = 35.3%
- Distribution of customers across feeder:

	Leg 1 & 2
Customers in %	100 %
Customers	43
3-Phase Customers	13
1-Phase Customers	30
1-Phase A	10
1-Phase B	9
1-Phase C	11

- Max. consumer load assumed = 57.4 kVA (obtained from actual data)

	Leg 1 & 2 [kVA / customer]
3-Phase Customers	1.34
1-Phase A	1.42
1-Phase B	1.26
1-Phase C	1.32

- Min. consumer load = 11.5 kVA (obtained from actual data assuming existing PV utilisation factor of 80%)

	Leg 1 & 2 [kVA / customer]
3-Phase Customers	0.27
1-Phase A	0.28
1-Phase B	0.25
1-Phase C	0.26

- Existing PV penetration = 33.62 % or 33.6 kW rated, i.e. 13 customers (assuming a 2.5 kW inverter size)
- Existing customers with controllable load = 11 (26 %)

2. Overvoltage check

- To check the worst overvoltage – consider the min. consumer load with the highest PV utilisation factor of 80% for the PV only DERs penetration scenarios. The PV only DERs penetration scenarios are most onerous to overvoltage issues.
- Overvoltages (>1.02 pu) were observed in this feeder.
- Highest overvoltages observed:

  Leg 1 – Phase A: 1.022 pu (P6E0L0S0)

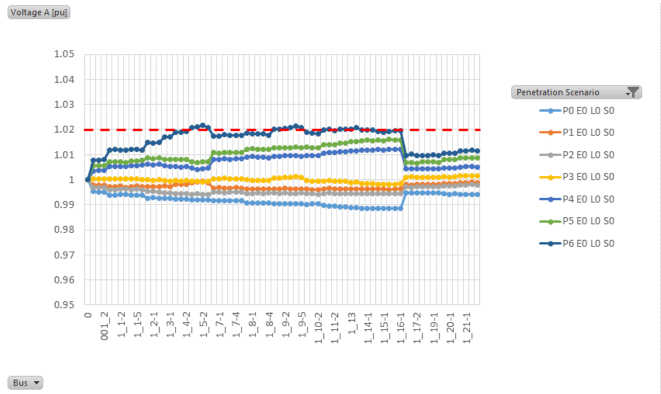
  Phase B: 1.030 pu (P5E0L0S0)

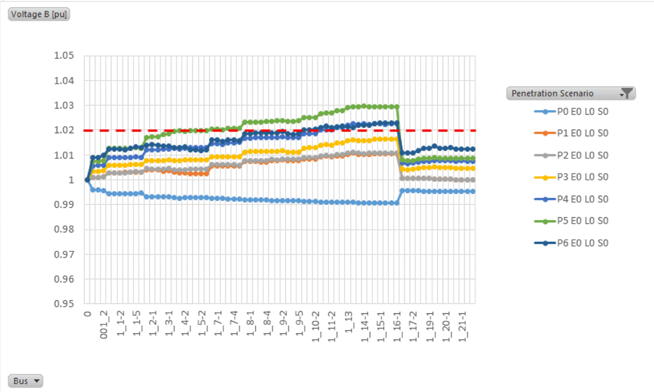
  Phase C: 1.030 pu (P6E0L0S0)

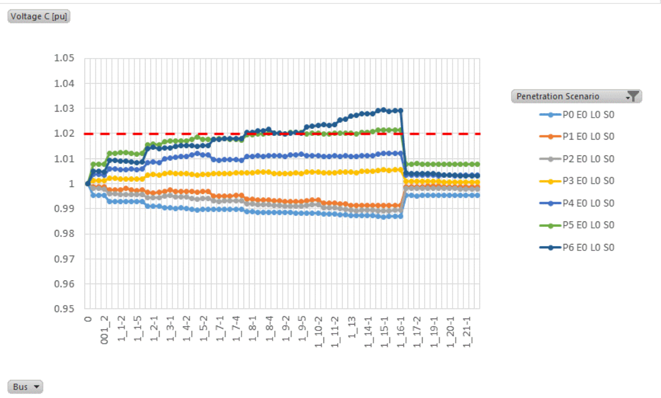
  - In Leg 1, the Phase A overvoltages occur under the P6 penetration scenario. Either the controllable loads (L1) or the storage loads (S2) could be switched on to resolve the issues.
  - In Leg 1, the Phase B boundary penetration scenario before overvoltages occur is P4. The controllable loads (L1) could be switched on to increase PV penetration to P5 or P6, while maintaining voltage. The storage loads (S2) is also sufficient to support P6; but the storage loads (S2) alone is insufficient to support P5.
  - In Leg 1, the Phase C boundary penetration scenario before overvoltages occur is P4. The controllable loads (L1) or storage loads (S2) could be switched on to increase PV penetration to P5 while maintaining voltage. However, both the controllable (L1) and storage (S2) loads are required to support P6.

a) Min. consumer load with 80% PV utilisation factor

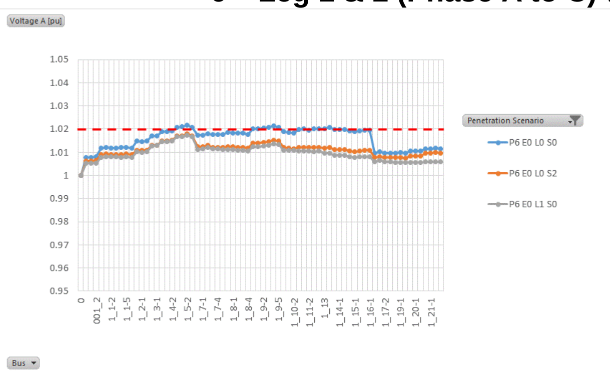
- **Leg 1 & 2 (Phase A to C)**

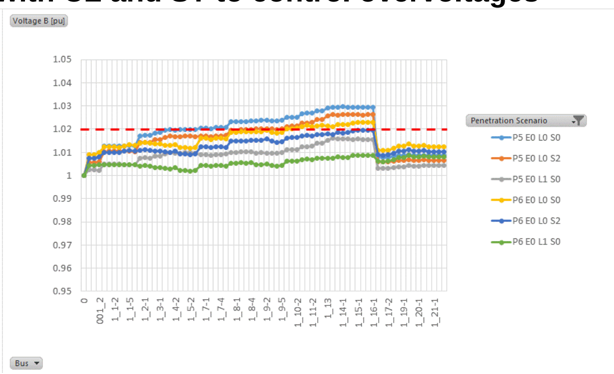


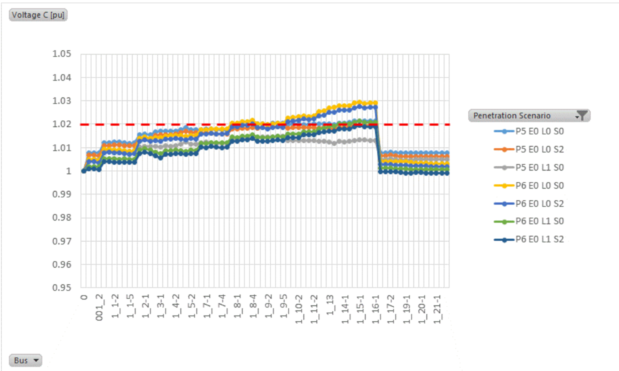




- **Leg 1 & 2 (Phase A to C) with CL and ST to control overvoltages**





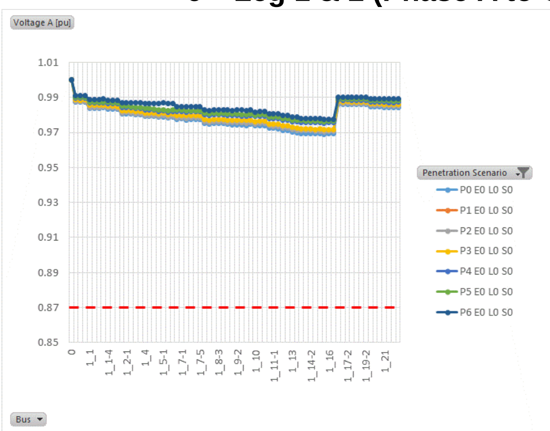


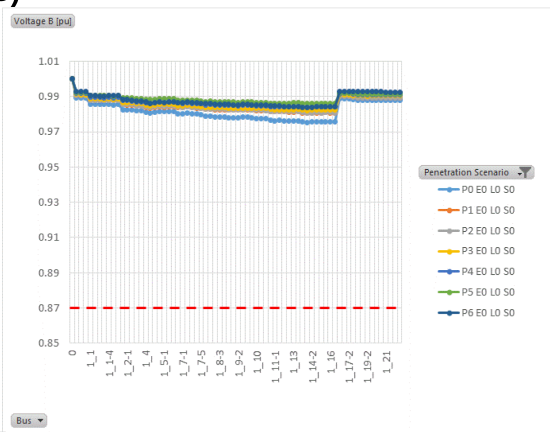
3. Undervoltage check

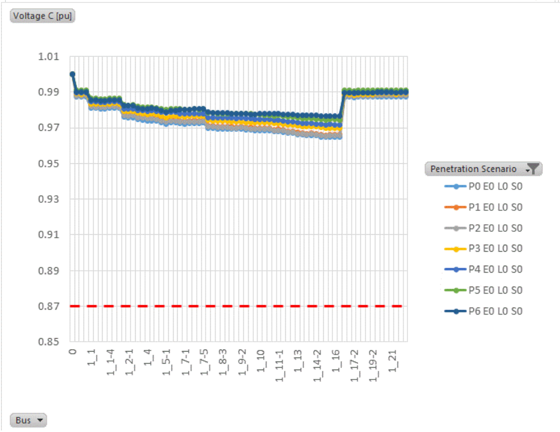
- To check the worst undervoltage – consider the max. consumer load with the lowest PV utilisation factor of 20%.
- The PV only DERs penetration scenarios were considered; and a more onerous scenario with only the power sinking DERs was tested.
- No undervoltages (<0.87pu) were observed in this feeder under all the scenarios considered.

b) Max. consumer load with 20% PV utilisation factor

- **Leg 1 & 2 (Phase A to C)**

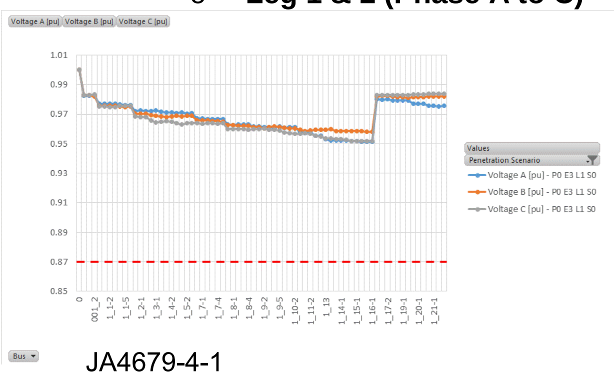






c) Max. consumer load with power sinking DERs

- **Leg 1 & 2 (Phase A to C)**

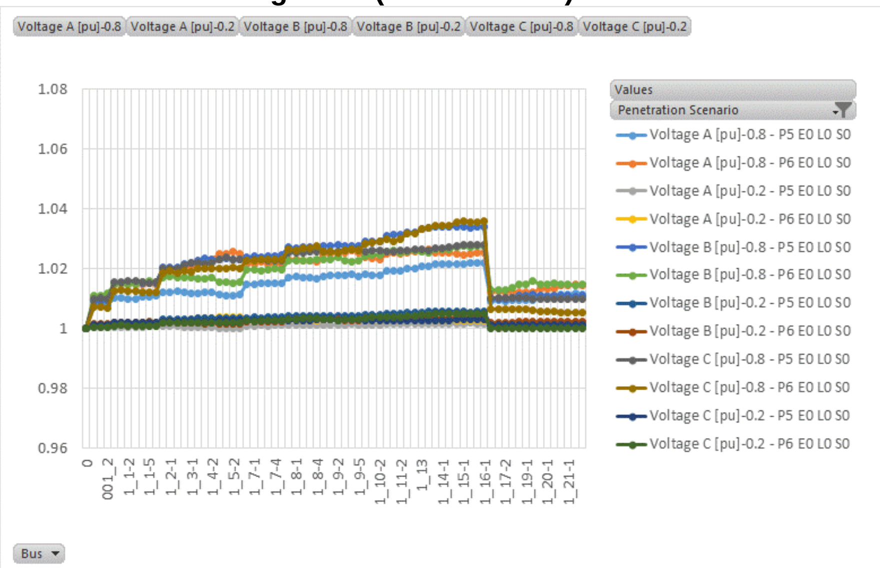


4. Voltage fluctuations

- The potential voltage fluctuation range is predicted by checking the step change in voltages from low PV utilisation factor (20%) to high PV utilisation factor (80%).
- The most onerous fluctuation would occur under the PV only DERs penetration scenarios. Based on the solar profile provided by SAPN the periods with high PV utilisation coincides with the min. load periods of the day (12-2PM). Hence, for this assessment a network with min. load is considered.
- From the voltage plots – the voltage fluctuation range for any particular point is not more than 0.05 pu (or 5%) within the criteria in IEC/TR 61000-3-7:2008 of 3-5%.

d) Potential voltage fluctuations

- **Leg 1 & 2 (Phase A to C)**



5. Voltage unbalance

- For max. consumer load - the highest voltage unbalance factor of 0.56% is observed under penetration scenario P2E3L0S1.
- For min. consumer load - the highest voltage unbalance factor of 0.97% is observed under penetration scenario P2E3L0S1.
- The continuous voltage unbalance factor limit is 2% hence; the unbalance factor for this feeder under the min. consumer load does not exceed the limit.

	Max. Vneg/Vpos (%) observed		Max. Vneg/Vpos (%) observed (No DERs)	
	Peak demand case	Minimum demand case	Peak demand case	Minimum demand case
HH177F 253	0.56%	0.97%	0.28%	0.04%

FEEDER EL14-TC54743 (OLD UNDERGROUND)

1. Details

- Elizabeth Downs – JK Cable Elizabeth Downs 11 kV feeder
- 11000/433 V 300 kVA transformer
- Comprised of the following underground cable:
  - XLPE AL 150 mm^2 OR 37 / 0.093 XLPE (218 m / 8.5%)
  - XLPE AL 35 mm^2 OR 19 / 0.064 XLPE (79 m / 3.1%)
  - Cable PVC Cu 0.06 sq inch (955 m / 37.5%)
  - Cable PVC Cu 0.0225 sq inch (1294 m / 83.5%)
- Has three metering points to three distribution legs:
  - Leg 1 – Pit East, Heath Court (575 m)
  - Leg 2 – No. 4 Brixton (349 m)
  - Leg 3 – No.14 Brixton (581 m)
- 48 customers
- Feeder phase balance (as per load data)
  - Leg 1: Phase A = 46.8% Phase B = 22.2% Phase C = 30.9%
  - Leg 2: Phase A = 37.6% Phase B = 33.2% Phase C = 29.3%
  - Leg 3: Phase A = 44.9% Phase B = 34% Phase C = 21.1%
- Distribution of customers across feeder:

	Leg 1	**Leg 2**	**Leg 3**
Customers in %	39.6 %	33.3 %	27.1 %
Customers	19	16	13
3-Phase Customers	6	5	4
1-Phase Customers	13	11	9
1-Phase A	6	4	4
1-Phase B	3	4	3
1-Phase C	4	3	2

- Max. consumer load assumed = 101 kVA (obtained from actual data)

	Leg 1 [kVA / customer]	**Leg 2 [kVA / customer]**	**Leg 3 [kVA / customer]**
3-Phase Customers	2.61	1.66	1.92
1-Phase A	2.99	1.80	2.17
1-Phase B	1.93	1.51	1.98
1-Phase C	2.53	1.67	1.35

- Min. consumer load = 16.9 kVA (obtained from actual data assuming existing PV utilisation factor of 80%)

	Leg 1 [kVA / customer]	**Leg 2 [kVA / customer]**	**Leg 3 [kVA / customer]**
3-Phase Customers	0.44	0.28	0.32
1-Phase A	0.50	0.30	0.36
1-Phase B	0.32	0.25	0.33
1-Phase C	0.42	0.28	0.23

- Existing PV penetration = 4.23 % or 12.7 kW rated, i.e 5 customers (assuming a 2.5 kW inverter size)
- Existing customers with controllable load = 48 (100 %)

2. Overvoltage check

- To check the worst overvoltage – consider the min. consumer load with the highest PV utilisation factor of 80% for the PV only DERs penetration scenarios. The PV only DERs penetration scenarios are most onerous to overvoltage issues.
- Overvoltages (>1.02 pu) were observed in Phase A and Phase C of distribution Leg 1, Phase B of distribution Leg 2 and all phases of distribution Leg 3.
- Highest overvoltages observed:
  Leg 1 – Phase A: 1.046 pu (P5E0L0S0)
  Phase C: 1.048 pu (P6E0L0S0)
  Leg 2 – Phase B: 1.071 pu (P6E0L0S0)
  Leg 3 – Phase A: 1.029 pu (P5E0L0S0)
  Phase B: 1.054 pu (P6E0L0S0)
  Phase C: 1.020 pu (P6E0L0S0)

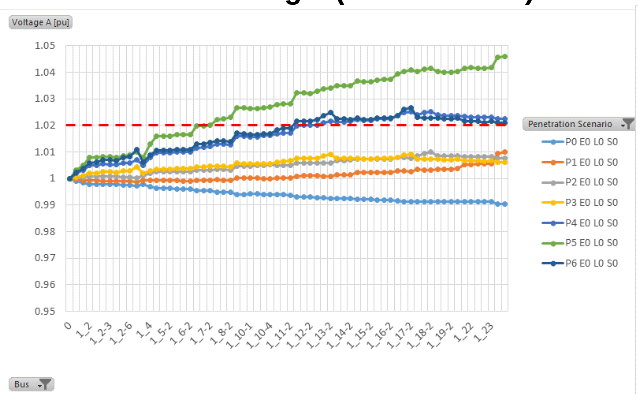
  - In Leg 1, the Phase A boundary penetration scenario before overvoltages occur is P3. The controllable loads (L1) could be switched on to increase the penetration to P4, P5 or P6. The storage loads (S2) alone is insufficient to keep the voltage within limit.
  - In Leg 1, the Phase C boundary penetration scenario before overvoltages occur is P3. The controllable loads (L1) could be switched on to increase the penetration to P4 or P5. The storage loads (S2) alone is insufficient to keep the voltage within limit. Penetration level P6 cannot be achieved within the voltage limit even with both the controllable loads (L1) and storage loads (S2) switched on.

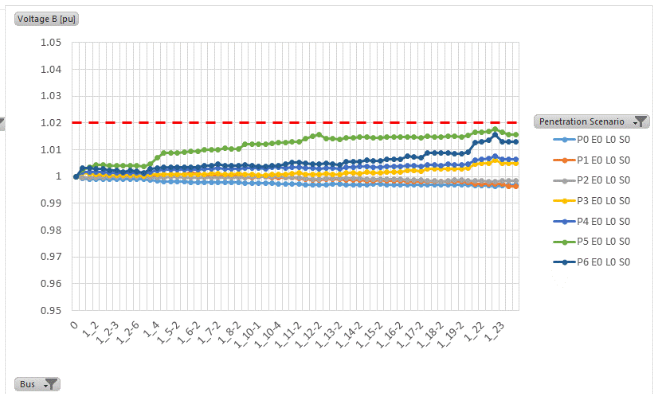
  - In Leg 2, the Phase B boundary penetration scenario before overvoltages occur is P2. The controllable loads (L1) could be switched on to increase the penetration to P3, P4 or P5. The storage loads (S2) alone is insufficient to keep the voltage within limit. Penetration level P6 cannot be achieved within the voltage limit even with both the controllable loads (L1) and storage loads (S2) switched on.

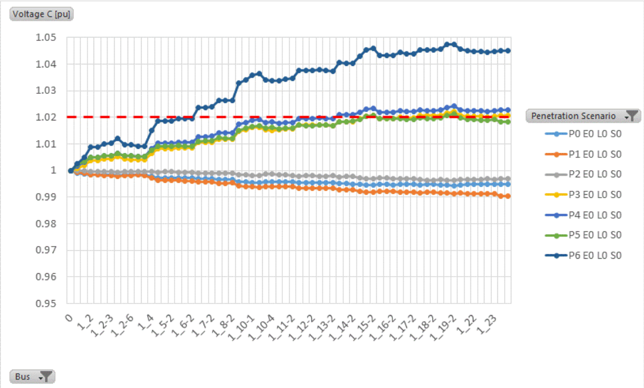
  - In Leg 3, the Phase A overvoltages occur under the P5 penetration scenario. The controllable loads (L1) could be switched on to resolve the issues. Connecting the storage loads (S2) alone is insufficient to keep the voltage within limit.
  - In Leg 3, the Phase B boundary penetration scenario before overvoltages occur is P2. The controllable loads (L1) could be switched on to increase the penetration to P3, P4, P5 or P6. The storage loads (S2) alone is insufficient to keep the voltage within limit.
  - In Leg 3, the Phase C overvoltages occur under the P6 penetration scenario. Either the controllable loads (L1) or storage loads could be switched on to resolve the issues.

a) Min. consumer load with 80% PV utilisation factor

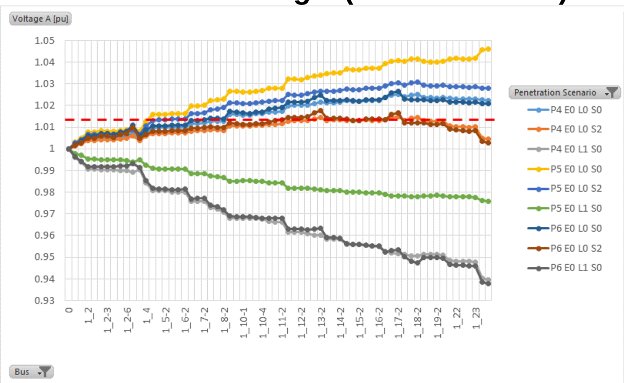
- **Leg 1 (Phase A to C)**

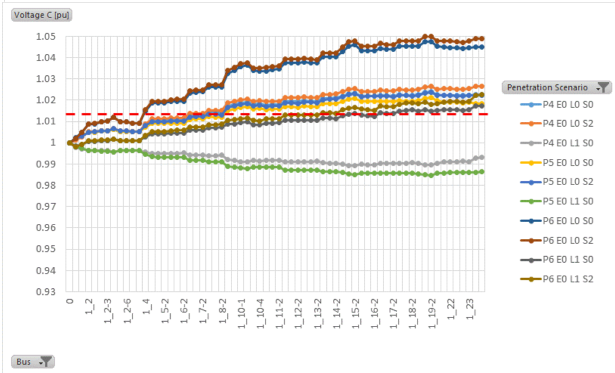




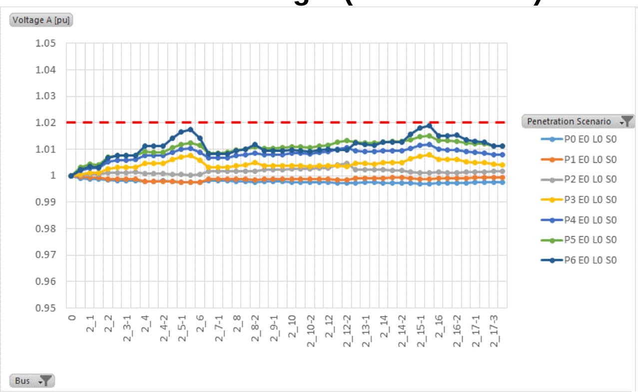


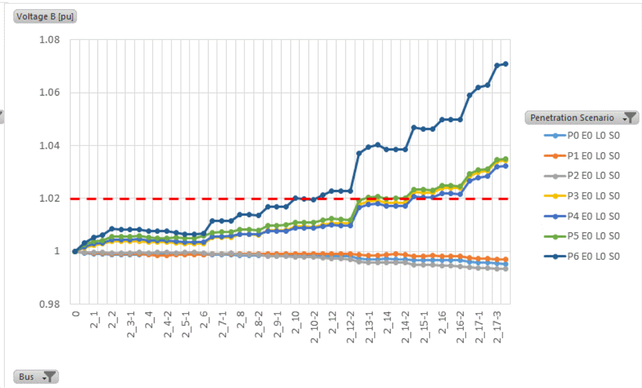
- Leg 1 (Phase A and C) - with CL and ST to control overvoltages

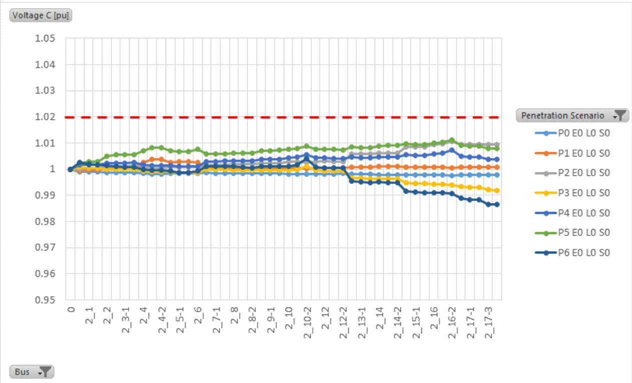




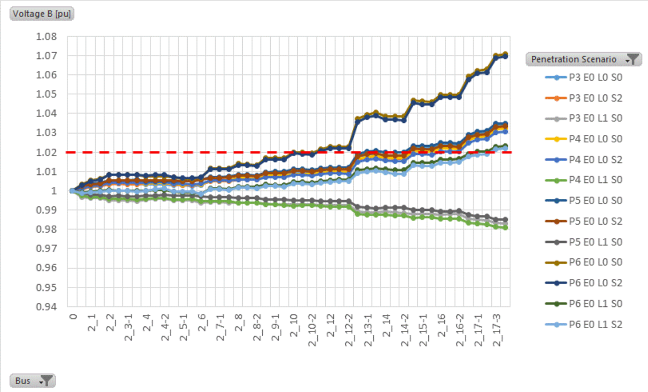
- Leg 2 (Phase A to C)



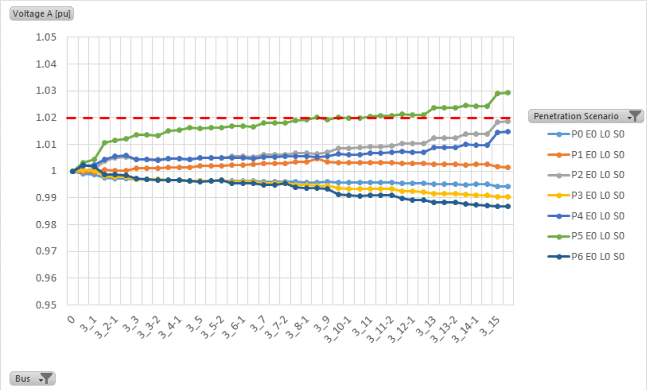


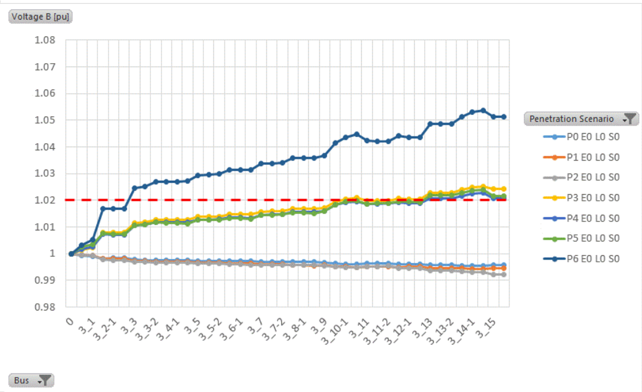


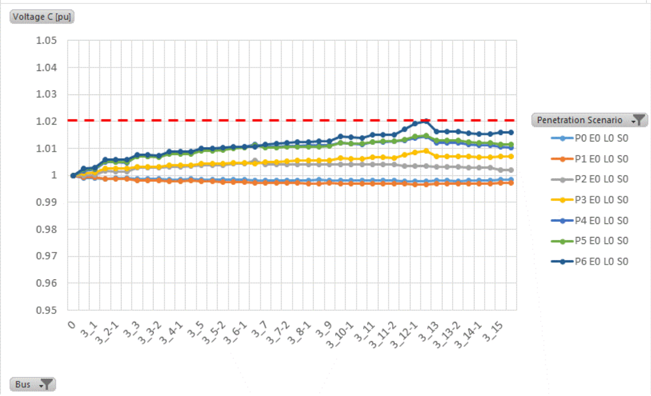
- Leg 2 (Phase B) - with CL and ST to control overvoltages



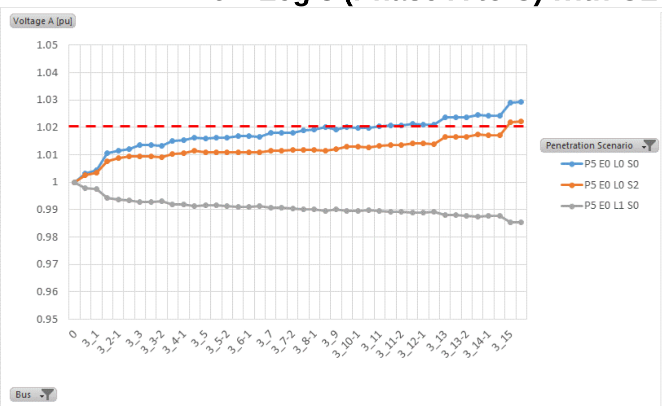
- Leg 3 (Phase A to C)

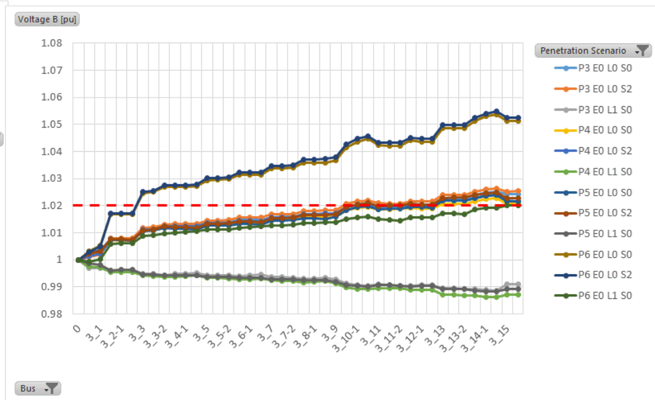


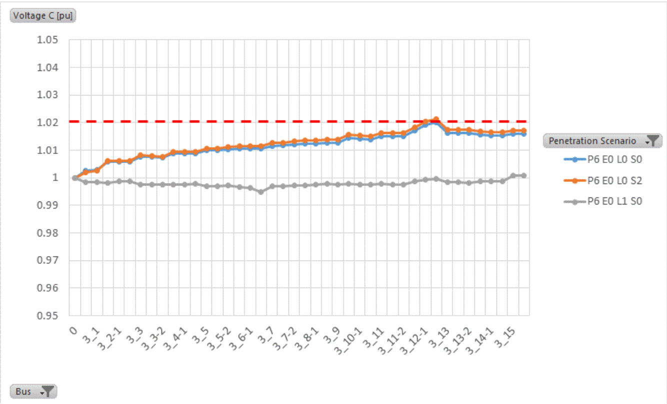




- Leg 3 (Phase A to C) with CL and ST to control overvoltages





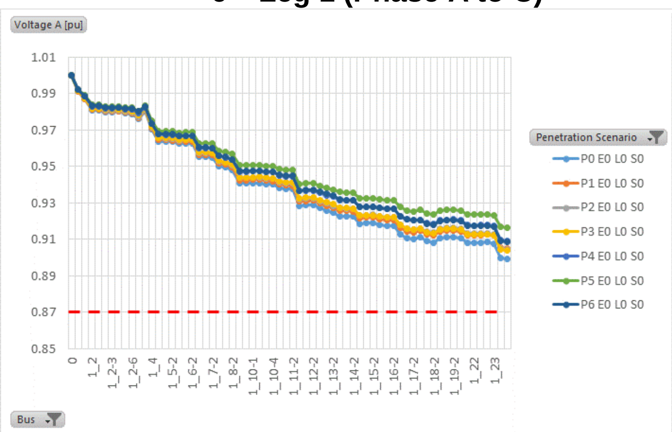


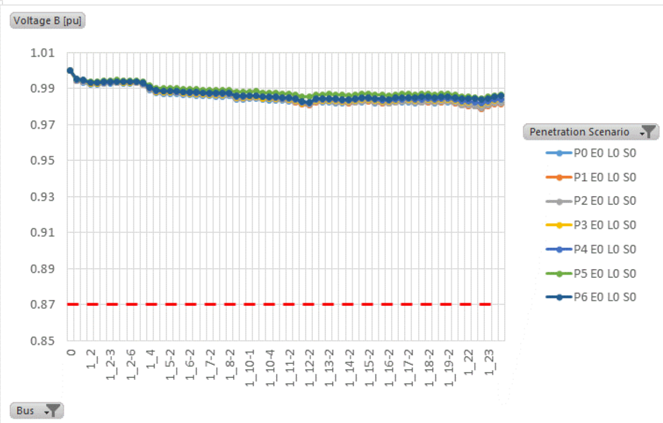
3. Undervoltage check

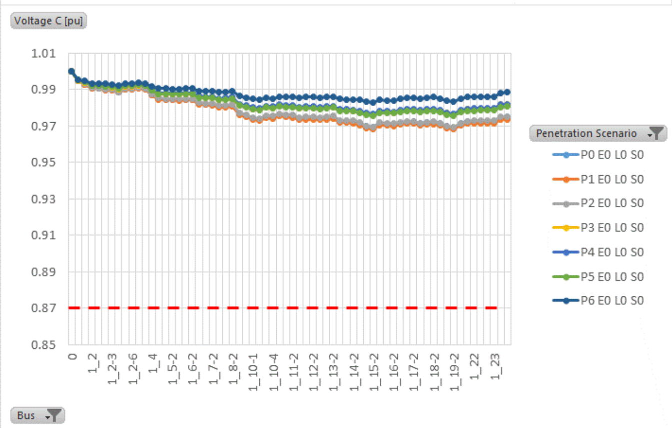
- To check the worst undervoltage – consider the max. consumer load with the lowest PV utilisation factor of 20%.
- The PV only DERs penetration scenarios were considered; and the most onerous for undervoltage with only the power sinking DERs.
- No undervoltages (<0.87pu) were observed in Phase A of distribution Leg 1.
- When subject to the most onerous DERs penetration scenarios undervoltages were observed in all the distribution legs.
- Mitigation to be tested:
    - Option A - Tap transformer to increase LV-side voltage of the feeder (ie bus 1 in the model)
    - Option B – Use storage as generation
    - Option C – Both Option A and B
- Using storage as generation is insufficient to support the low voltages in the distribution legs.

b) Max. consumer load with 20% PV utilisation factor

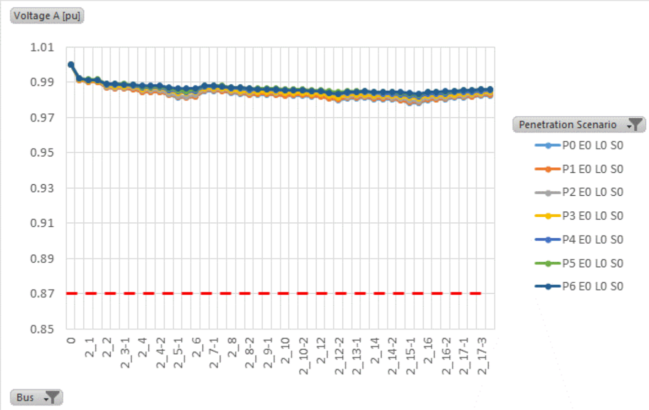
- **Leg 1 (Phase A to C)**

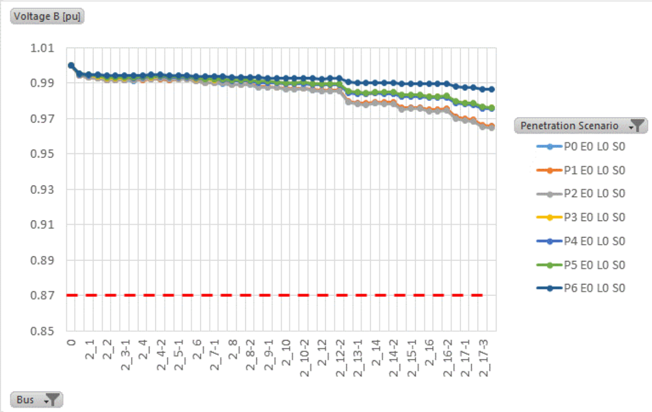


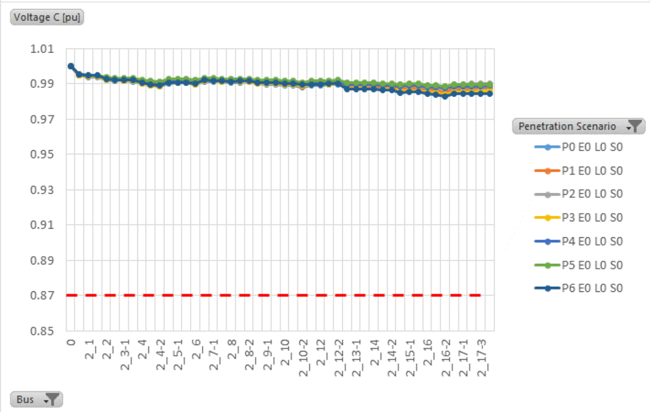




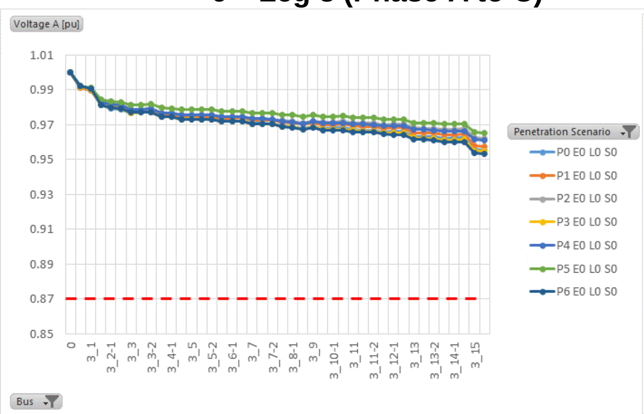
- Leg 2 (Phase A to C)

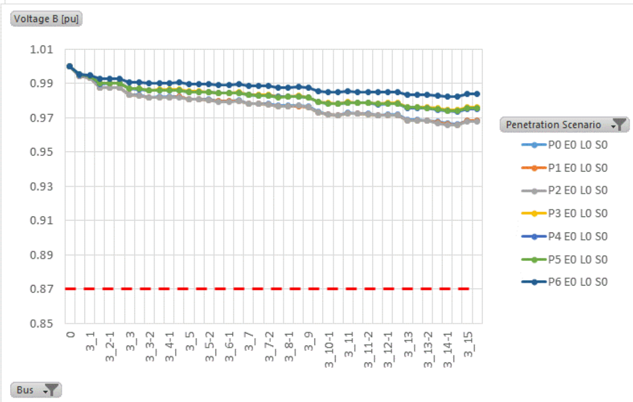


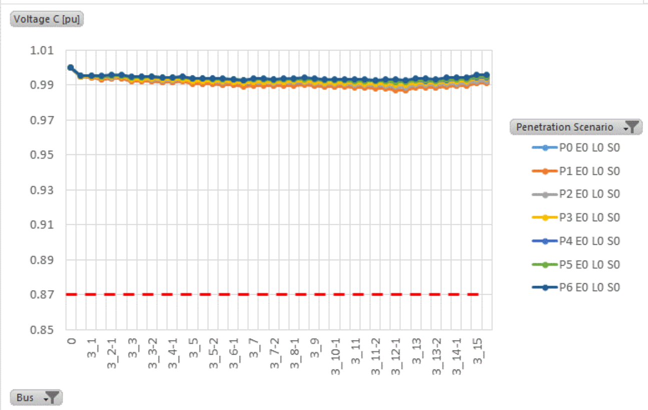




- Leg 3 (Phase A to C)

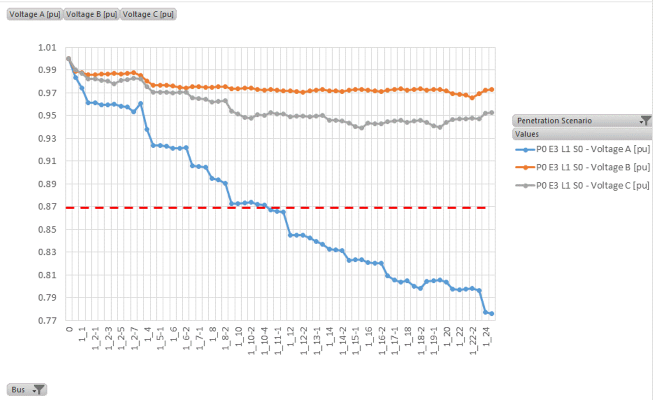




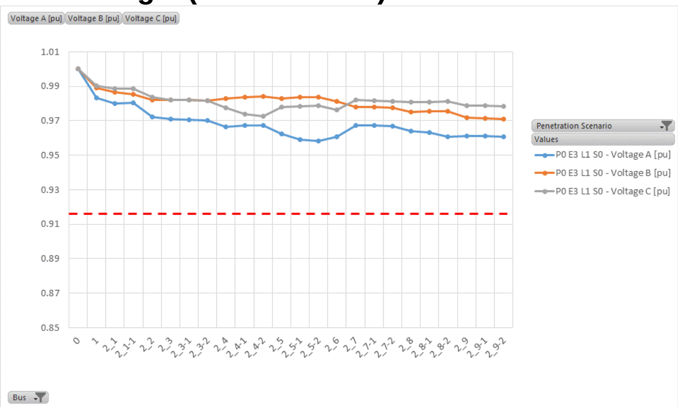


c) Max. consumer load with power sinking DERs

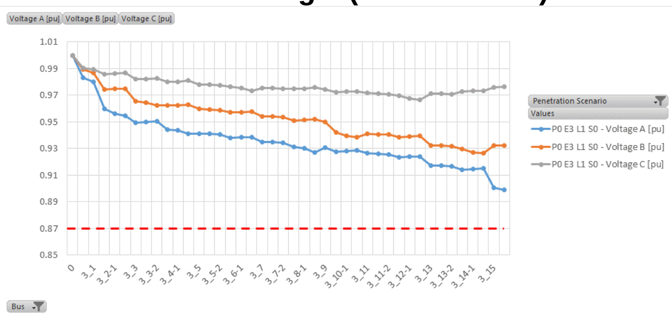
- Leg 1 (Phase A to C)



Leg 2 (Phase A to C)



- Leg 3 (Phase A to C)

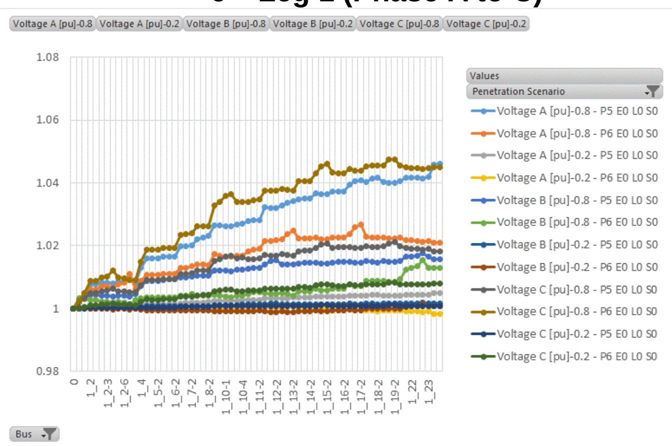


4. Voltage fluctuations

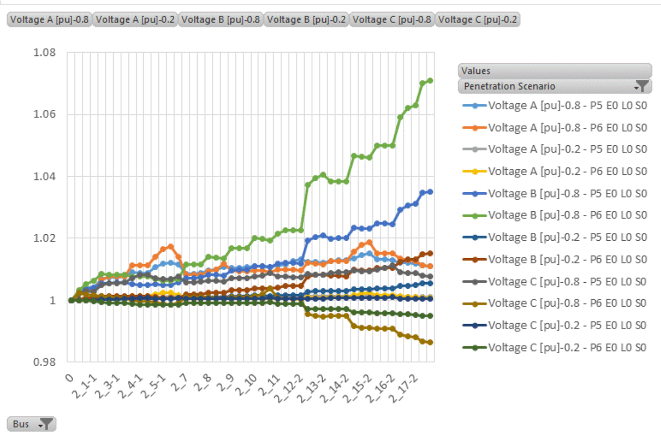
- The potential voltage fluctuation range is predicted by checking the step change in voltages from low PV utilisation factor (20%) to high PV utilisation factor (80%).
- The most onerous fluctuation would occur under the PV only DERs penetration scenarios. Based on the solar profile provided by SAPN the periods with high PV utilisation coincides with the min. load periods of the day (12-2PM). Hence, for this assessment a network with min. load is considered.
- From the voltage plots – the voltage fluctuation range for Leg 2 Phase B under the P6 scenario shows a voltage fluctuation of 0.0558 pu (or 5.58 %) which is in breach of the criteria in IEC/TR 61000-3-7:2008 of 3-5%.

d) Potential voltage fluctuations

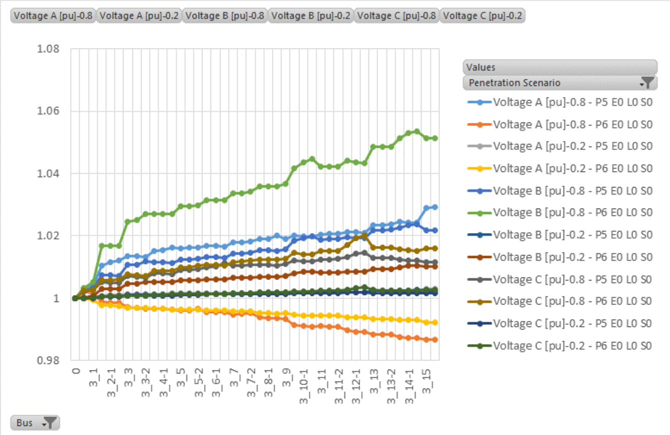
- Leg 1 (Phase A to C)



Leg 2 (Phase A to C)



- o **Leg 3 (Phase A to C)**



5. Voltage unbalance

- For max. consumer load - the highest voltage unbalance factor of 3.89% is observed under penetration scenario P0E3L1S1.
- For min. consumer load - the highest voltage unbalance factor of 2.26% is observed under penetration scenario P0E3L1S1.
- The continuous voltage unbalance factor limit is 2%, hence, the unbalance factor for this feeder exceeds the limit.

	Max. Vneg/Vpos (%) observed		Max. Vneg/Vpos (%) observed (No DERs)	
	Peak demand case	Minimum demand case	Peak demand case	Minimum demand case
EL14 TC54743	3.89%	2.26%	1.43%	0.07%

FEEDER AP125B-15350 (OLD UNDERGROUND)

1. Details

- Blackpool – Pelican Point 7.6 kV feeder
- 7600/433 V 200 kVA transformer
- Comprised of the following underground cable:
  - XLPE AL 150 mm^2 OR 37 / .093 XLPE (719 m / 44 %)
  - XLPE AL 35 mm^2 OR 19 / .064 XLPE (931 m / 56 %)
- 3 distribution legs (2 legs form a loop):
  - Leg 1 – Fraser Drive North (161 m)
  - Leg 3 – Fraser Drive East (278 m)
  - Leg 2 – Fraser Drive West (218 m)
- 47 customers
- Feeder phase balance (as per load data)
  - Leg 1: Phase A = 7.6% Phase B = 52.6% Phase C = 39.8%
  - Leg 2: Phase A = 26% Phase B = 27% Phase C = 47%
- Distribution of customers across feeder:

	Leg 1 & Leg 3	**Leg 2**
Customers in %	53.2 %	46.8 %
Customers	25	22
3-Phase Customers	7	7
1-Phase Customers	18	15
1-Phase A	1	4
1-Phase B	10	4
1-Phase C	7	7

- Max. consumer load assumed = 93.8 kVA (Leg 1 = 46.6 kVA, Leg 2 = 47.2 kVA)

	Leg 1 & Leg 3 [kVA / customer]	**Leg 2 [kVA / customer]**
3-Phase Customers	1.83	2.14
1-Phase A	0.00	1.82
1-Phase B	1.98	1.94
1-Phase C	1.99	2.45

- Min. consumer load = 13.92 kVA (obtained from actual data assuming PV penetration at 80%)

	Leg 1 & Leg 3 [kVA / customer]	**Leg 2 [kVA / customer]**
3-Phase Customers	0.26	0.30
1-Phase A	0.00	0.26
1-Phase B	0.28	0.28
1-Phase C	0.28	0.35

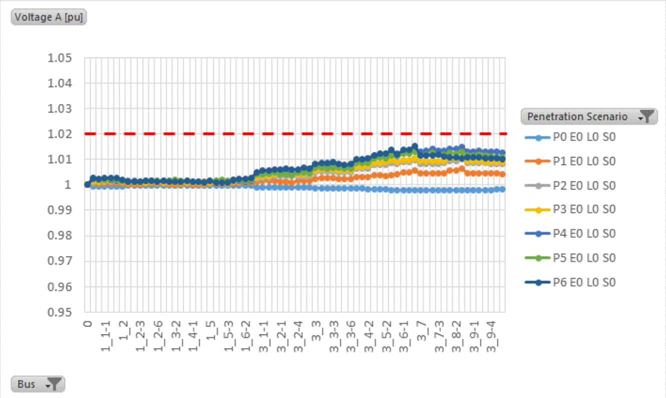
- Existing PV penetration = 18.72% or 37.44 kW rated, i.e. 15 customers (assuming a 2.5 kW inverter size)
- Existing customers with controllable load = 13 (28 %)

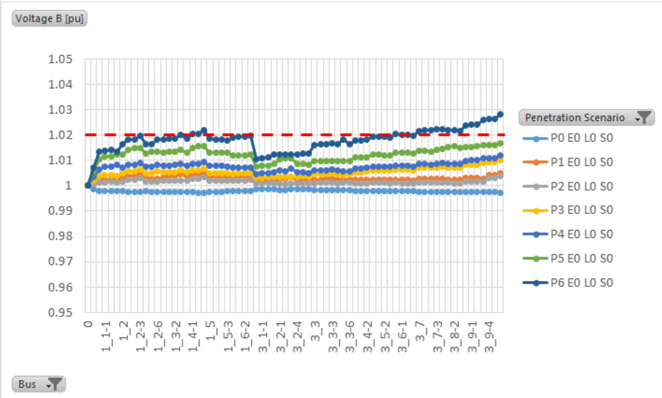
2. Overvoltage check

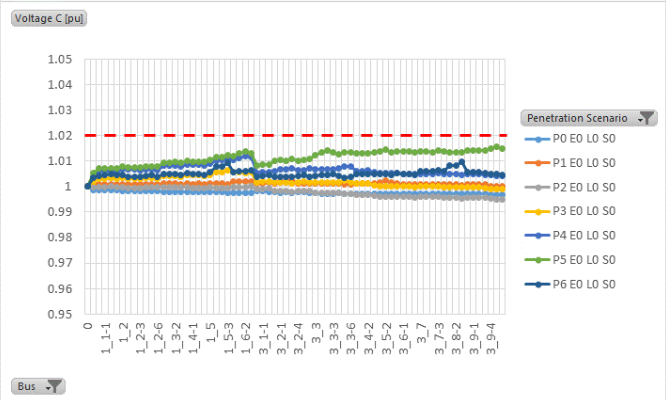
- To check the worst overvoltage – consider the min. consumer load with the highest PV utilisation factor of 80% for the PV only DERs penetration scenarios. The PV only DERs penetration scenarios are most onerous for overvoltage issues.
- Overvoltages (>1.02 pu) were observed in Phase B of distribution Leg 1 and 2 in this feeder.
- Highest overvoltages observed:
  Leg 1 – Phase B: 1.028 pu (P6E0L0S0)
  Leg 2 – Phase B: 1.021 pu (P6E0L0S0)
  - In Leg 1, the Phase B overvoltages occur under the P6 penetration level. The overvoltages at the far end of the distribution leg could not be resolved even with both the controllable (L1) and storage loads (S2) switched in.
  - In Leg 2, the Phase B overvoltages (marginal) occur under the P6 penetration level. The controllable loads (L1) could be switched on to resolve the issues. Connecting the storage loads (S2) alone is insufficient to keep the voltage within limit.

a) Min. consumer load with 80% PV utilisation factor

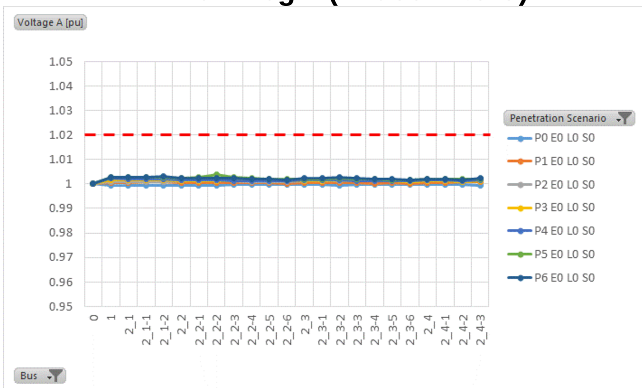
- **Leg 1 (Phase A to C)**

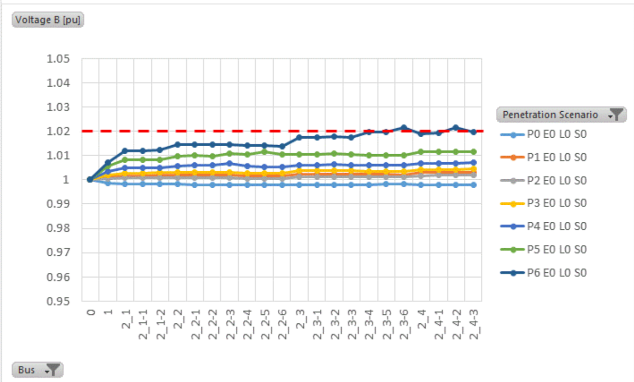


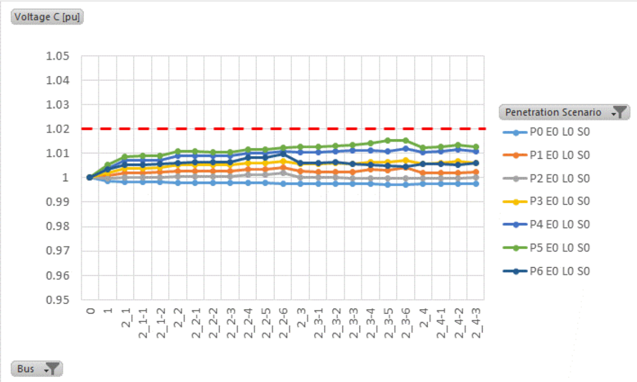




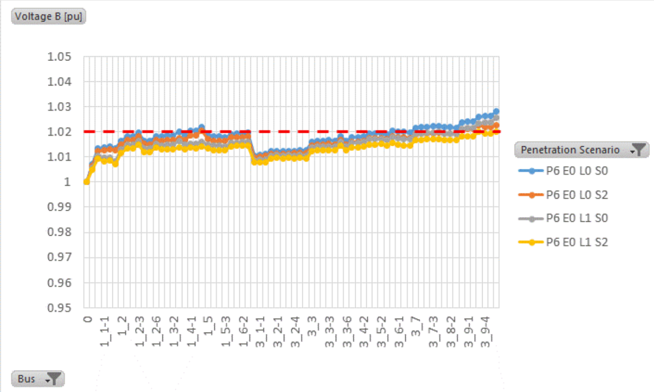
- **Leg 2 (Phase A to C)**

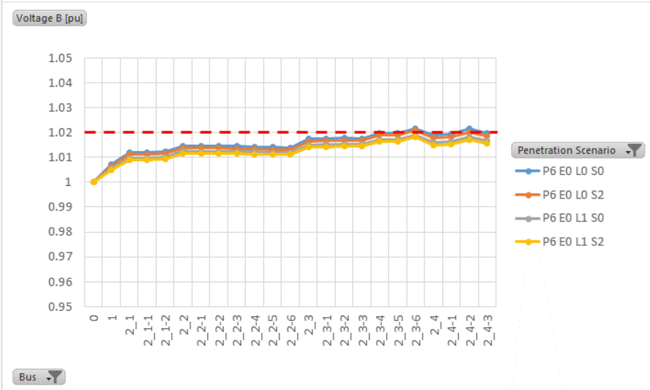






- Leg 1 and 2 (Phase B) with CL and ST to control overvoltages



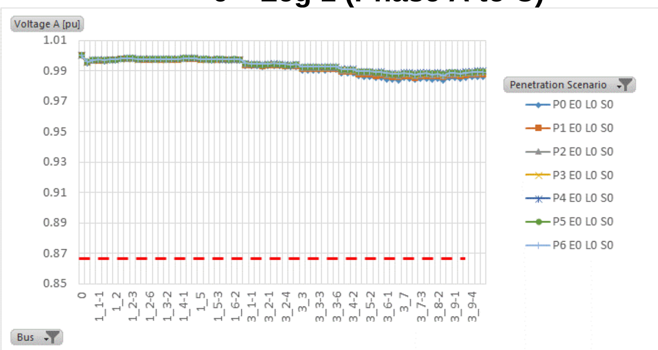


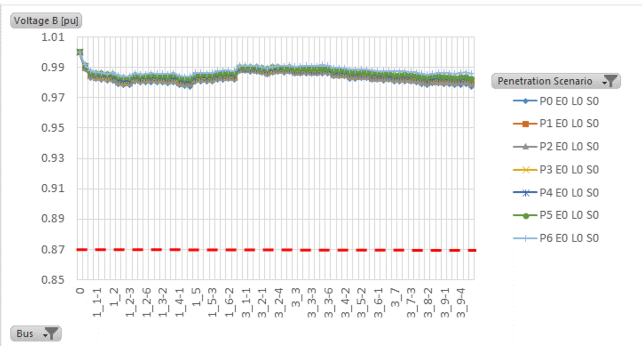
3. Undervoltage check

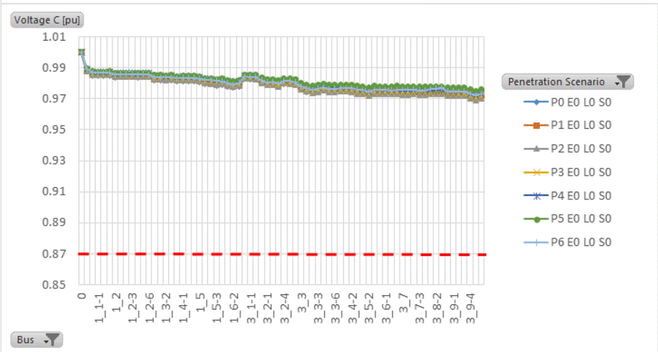
- To check the worst undervoltage – consider the max. consumer load with the lowest PV utilisation factor of 20%.
- The PV only DERs penetration scenarios were considered; and the most onerous for undervoltage with only the power sinking DERs.
- No undervoltages (<0.87pu) were observed in this feeder under all the scenarios considered.

b) Max. consumer load with 20% PV utilisation factor

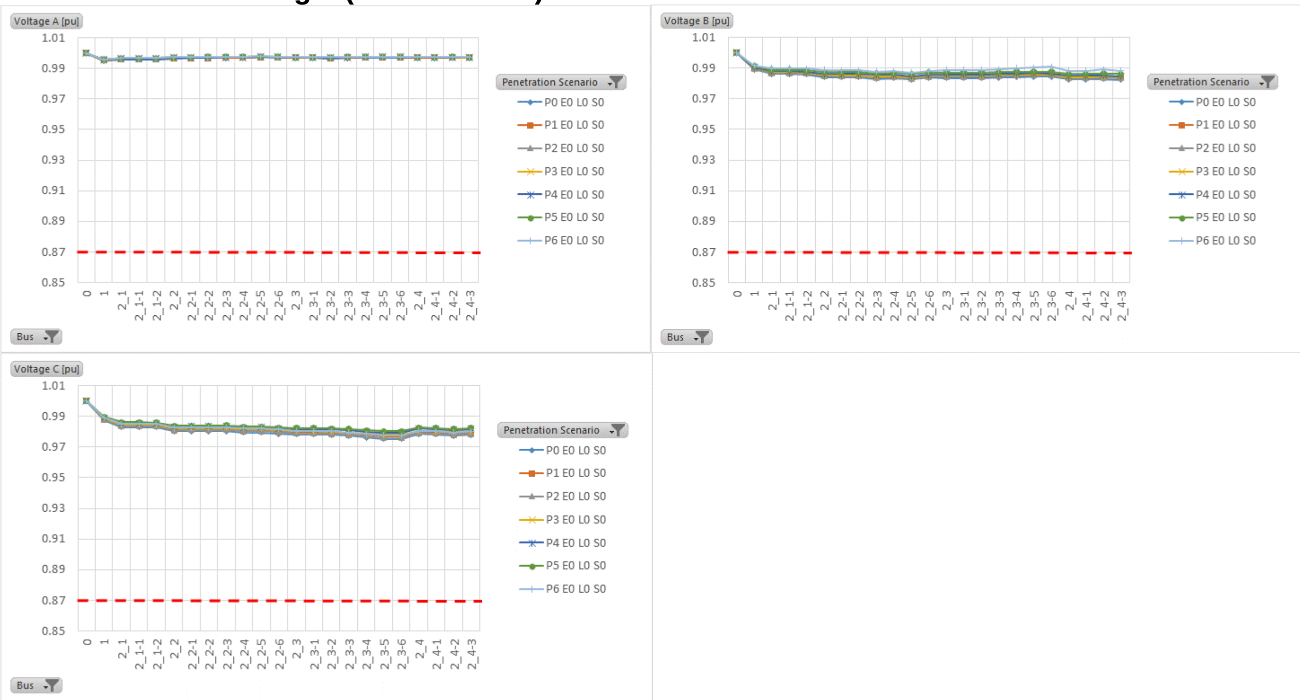
- Leg 1 (Phase A to C)





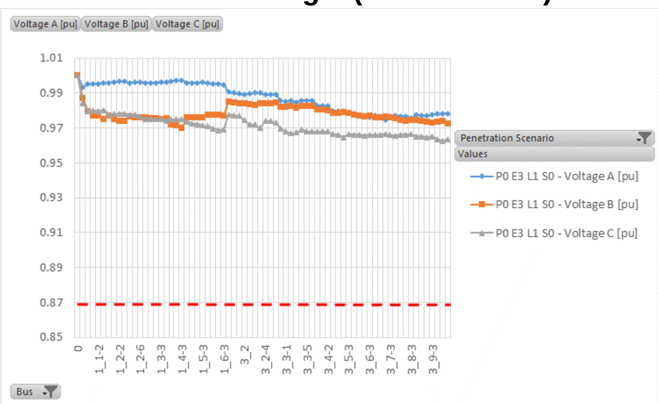


- Leg 2 (Phase A to C)

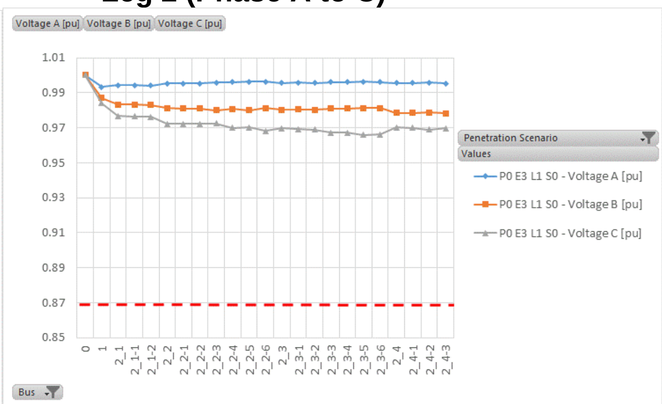


c) Max. consumer load with power sinking DERs

- Leg 1 (Phase A to C)



Leg 2 (Phase A to C)

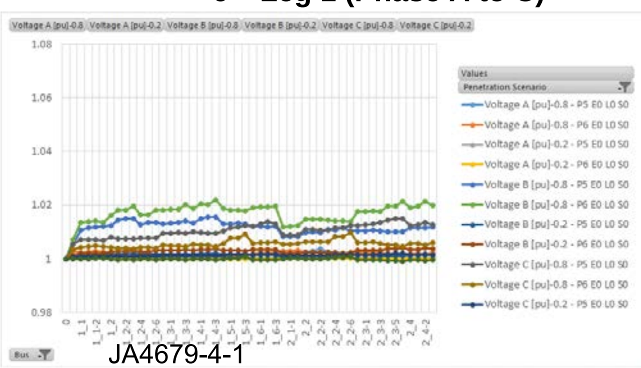


4. Voltage fluctuations

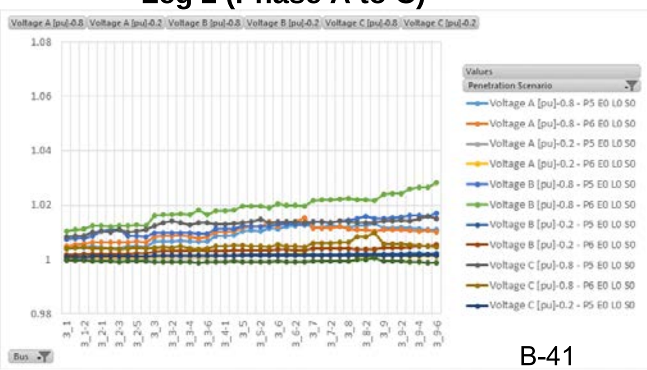
- The potential voltage fluctuation range is predicted by checking the step change in voltages from low PV utilisation factor (20%) to high PV utilisation factor (80%).
- The most onerous fluctuation would occur under the PV only DERs penetration scenarios. Based on the solar profile provided by SAPN the periods with high PV utilisation coincides with the min. load periods of the day (12-2PM). Hence, for this assessment a network with min. load is considered.
- From the voltage plots – the voltage fluctuation range for any particular point is not more than 0.05 pu (or 5%) within the criteria in IEC/TR 61000-3-7:2008 of 3-5%.

d) Potential voltage fluctuations

- Leg 1 (Phase A to C)



Leg 2 (Phase A to C)



5. Voltage unbalance

- For max. consumer load - the highest voltage unbalance factor of 0.88% is observed under penetration scenario P0E3L1S2.
- For min. consumer load - the highest voltage unbalance factor of 0.84% is observed under penetration scenario P6E0L1S3.
- The continuous voltage unbalance factor limit is 2%, hence, the unbalance factor for this feeder is within the limit.

	Max. Vneg/Vpos (%) observed		Max. Vneg/Vpos (%) observed (No DERs)	
	Peak demand case	Minimum demand case	Peak demand case	Minimum demand case
AP125B 15350	0.88%	0.84%	0.63%	0.07%

FEEDER AP529E (OLD UNDERGROUND)

1. Details

- Largs North – Military Road 7.6 kV feeder
- 7600/433 V 500 kVA transformer
- Comprised of the following underground cable and overhead conductor:
  - XLPE AL 150 mm^2 (619 m / 55.1%)
  - 7 / 4.75 AAC (192 m / 17.1%)
  - 0.1 Cu (284 m / 25.3%)
  - 0.2 Cu (27 m / 2.4%)
- Has one metering point to two distribution legs
  Leg 1 – 211 m
  Leg 2 – 583 m
- 24 customers
- Feeder phase balance (as per load data)
  - Leg 1: Phase A = 39.9% Phase B = 27.7% Phase C = 32.4%
- Distribution of customers across feeder:

	Leg 1 & 2
Customers in %	100 %
Customers	24
3-Phase Customers	7
1-Phase Customers	17
1-Phase A	7
1-Phase B	5
1-Phase C	5

- Max. consumer load assumed = 99.7kVA (obtained from actual data)

	Leg 1 & 2 kVA / customer
3-Phase Customers	4.15
1-Phase A	4.30
1-Phase B	3.58
1-Phase C	4.53

- Min. consumer load = 47.6 kVA (obtained from actual data assuming existing PV utilisation factor of 80%)

	Leg 1 & 2 [kVA / customer]
3-Phase Customers	1.98
1-Phase A	2.05
1-Phase B	1.71
1-Phase C	2.16

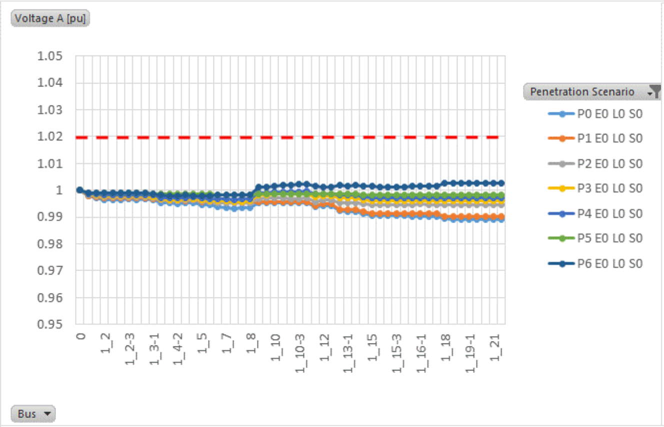
- Existing PV penetration = 0.98 % or 4.9 kW rated, i.e 2 customers (assuming a 2.5 kW inverter size)
- Existing customers with controllable load = 3 (12.5 %)

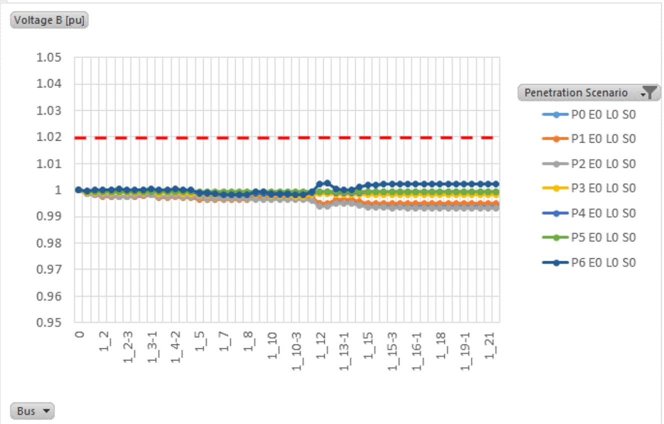
2. Overvoltage check

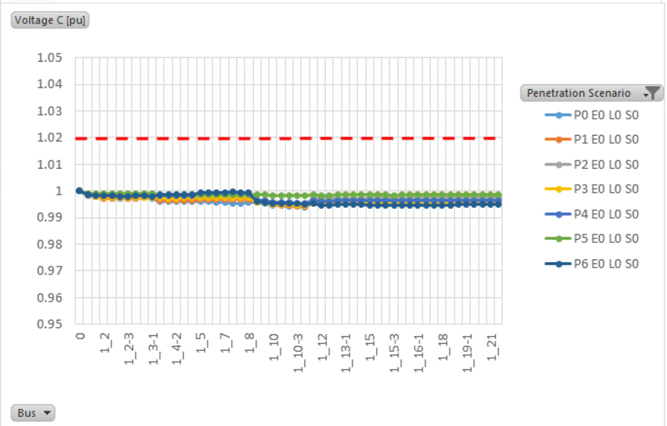
- To check the worst overvoltage – consider the min. consumer load with the highest PV utilisation factor of 80% for the PV only DERs penetration scenarios. The PV only DERs penetration scenarios are most onerous to overvoltage issues.
- No overvoltages (>1.02 pu) were observed in this feeder.
- An extreme case was tested where the consumer load is assumed to be at 10% of the max. No overvoltages were observed in this extreme case even under the most onerous penetration scenarios of *P5E0L0S0* and *P6E0L0S0*.

a) Min. consumer load with 80% PV utilisation factor

- o **Leg 1 & 2 (Phase A to C)**

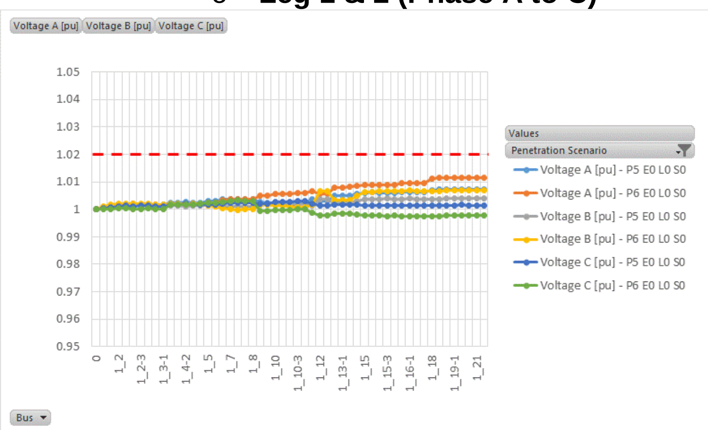






b) Extreme case with consumer load at 10% of the max.

- o **Leg 1 & 2 (Phase A to C)**

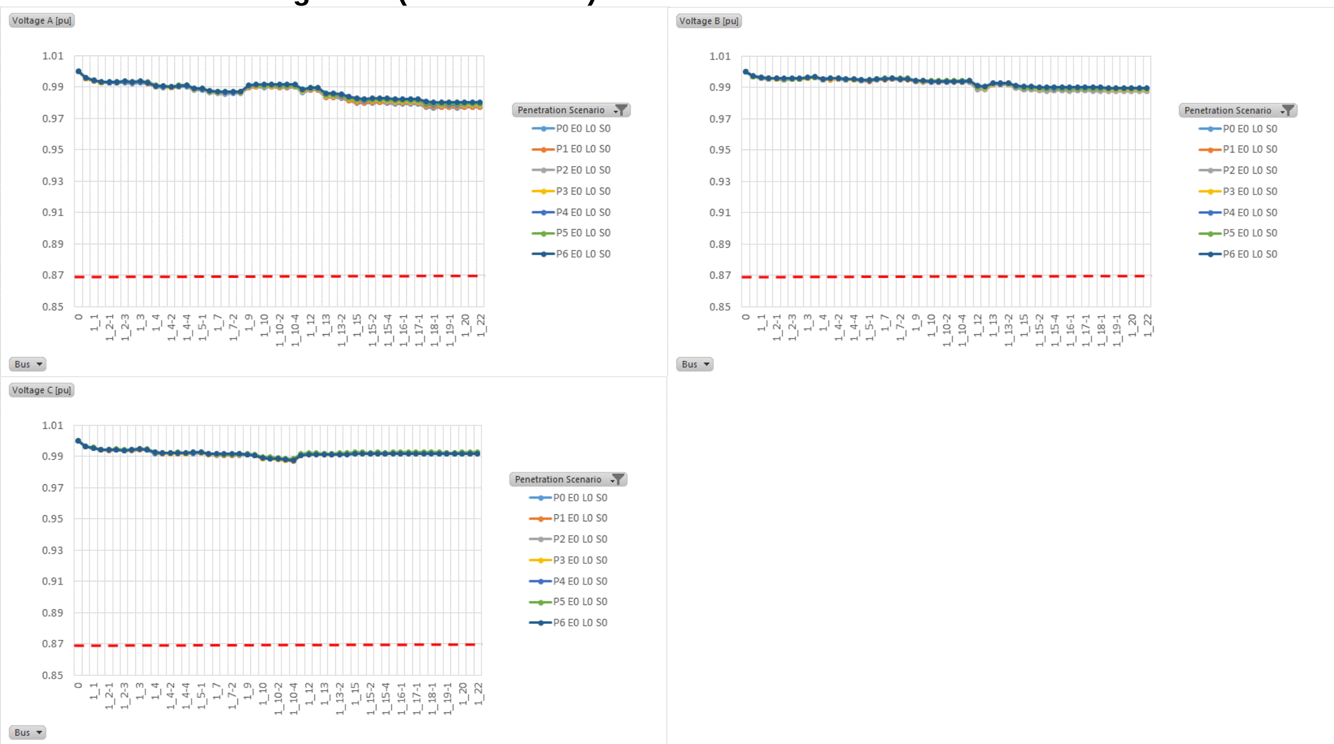


3. Undervoltage check

- To check the worst undervoltage – consider the max. consumer load with the lowest PV utilisation factor of 20%.
- The PV only DERs penetration scenarios were considered; and a more onerous scenario with only the power sinking DERs was tested.
- No undervoltages (<0.87pu) were observed in this feeder under all the scenarios considered.

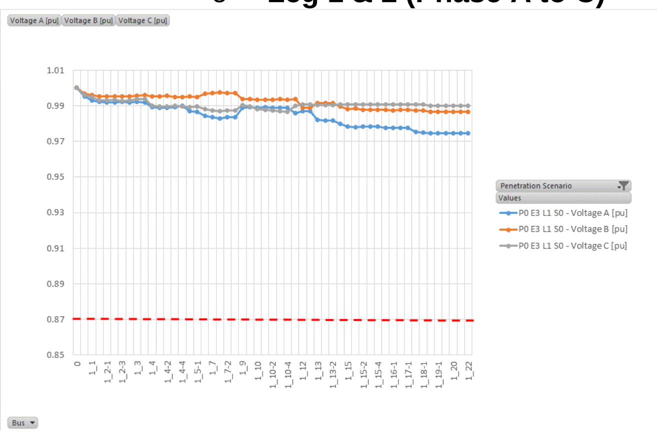
c) Max. consumer load with 20% PV utilisation factor

- **Leg 1 & 2 (Phase A to C)**



d) Max. consumer load with power sinking DERs

- **Leg 1 & 2 (Phase A to C)**

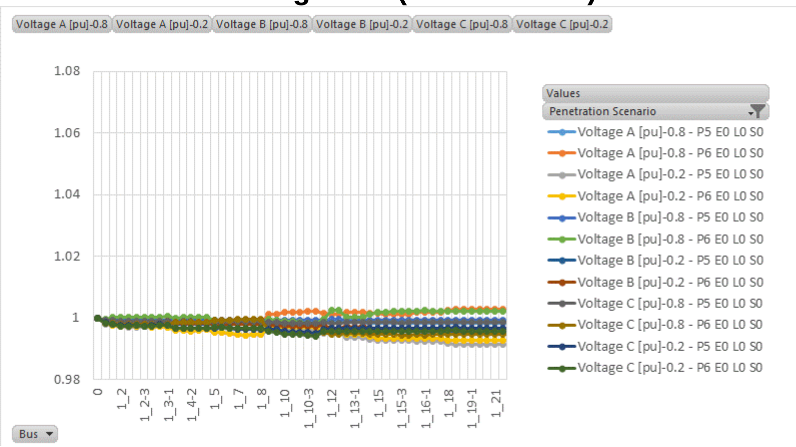


4. Voltage fluctuations

- The potential voltage fluctuation range is predicted by checking the voltages at the distribution legs from low PV utilisation factor (0.2) to high PV utilisation factor (0.8).
- The onerous fluctuation would occur should the cloud cover vary the PV utilisation factor from 0.2 to 0.8, or vice-versa, under the highest PV penetration scenario. Cloud cover reducing the PV output to zero is not considered here. Based on the solar profile provided by SAPN the periods with high solar intensity coincides with the low load periods of the day (12-2PM).
- From the voltage plots the voltage fluctuation range for any particular point in this feeder is well within the criteria in IEC/TR 61000-3-7:2008 of 3-5%.

e) Potential voltage fluctuations

- o **Leg 1 & 2 (Phase A to C)**



5. Voltage unbalance

- For max. consumer load - the highest voltage unbalance factor of 0.42% is observed under penetration scenario P0E1L1S1.
- For min. consumer load - the highest voltage unbalance factor of 0.36% is observed under penetration scenario P0E3L1S1.
- The continuous voltage unbalance factor limit is 2% hence, the unbalance factor for this feeder is within the limit.

	Max. Vneg/Vpos (%) observed		Max. Vneg/Vpos (%) observed (No DERs)	
	Peak demand case	Minimum demand case	Peak demand case	Minimum demand case
AP529E 30156	0.42%	0.36%	0.34%	0.16%

FEEDER HH496C - 26079 (NEW UNDERGROUND)

1. Details

- Golden Grove – Wynn Vale South 11 kV feeder
- 11000/433 V 150 kVA transformer
- Comprised of the following underground cable:
  - XLPE AL 150 mm^2 (888 m / 44.8%)
  - XLPE AL 35 mm^2 (1093 m / 55.2%)
- Has four meter points with four distribution legs (with two legs forming a loop):
  - Leg 1 – North of TF 26079 (159 m)
  - Leg 2 & 4 – Sunrise Crt and Summerhill Crt (514 m)
  - Leg 3 – Sunset Crt (223 m)
- 45 customers
- Feeder phase balance (as per load data)
  - Leg 1: Phase A = 24.7% Phase B = 49.8% Phase C = 25.5%
  - Leg 2&4: Phase A = 30% Phase B = 20.2% Phase C = 49.8%
  - Leg 3: Phase A = 14.4% Phase B = 71.6% Phase C = 14%
- Distribution of customers across feeder:

	Leg 1	**Leg 2 & 4**	**Leg 3**
Customers in %	37.8 %	35.6 %	26.7 %
Customers	17	16	12
3-Phase Customers	5	5	4
1-Phase Customers	12	11	8
1-Phase A	3	3	1
1-Phase B	6	3	6
1-Phase C	3	5	1

- Max. consumer load assumed = 83.7 kVA (obtained from actual data)

	Leg 1 [kVA / customer]	**Leg 2 & 4 [kVA / customer]**	**Leg 3 [kVA / customer]**
3-Phase Customers	0.90	2.85	1.91
1-Phase A	0.76	2.97	0.76
1-Phase B	1.01	1.48	2.30
1-Phase C	0.80	3.59	0.67

- Min. consumer load = 8.9 kVA (obtained from actual data assuming existing PV utilisation factor of 80%)

	Leg 1 [kVA / customer]	**Leg 2 & 4 [kVA / customer]**	**Leg 3 [kVA / customer]**
3-Phase Customers	0.10	0.30	0.20
1-Phase A	0.08	0.32	0.08
1-Phase B	0.11	0.16	0.25
1-Phase C	0.09	0.38	0.07

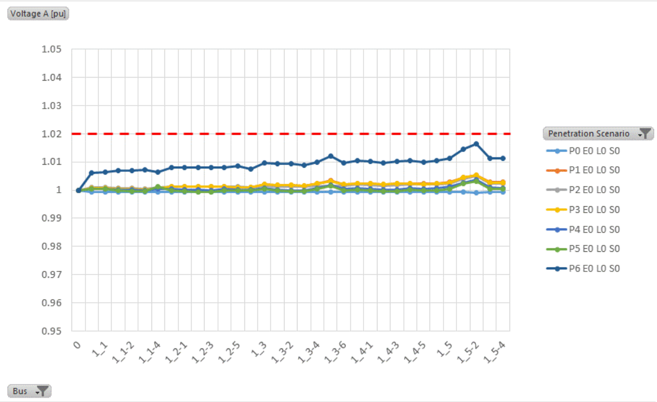
- Existing PV penetration = 36.05 % or 54.1 kW rated, i.e. 22 customers (assuming a 2.5 kW inverter size)
- Existing customers with controllable load = 5 (11 %)

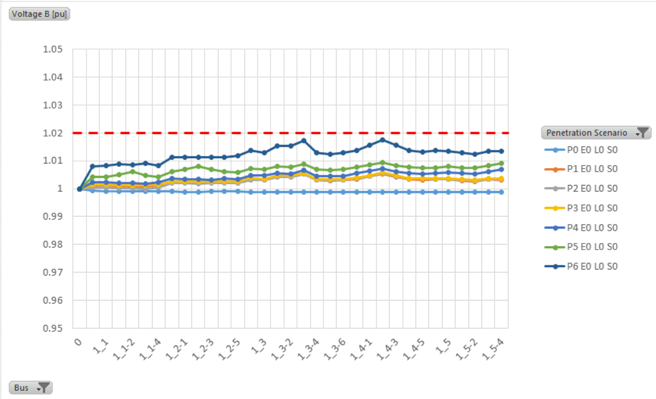
2. Overvoltage check

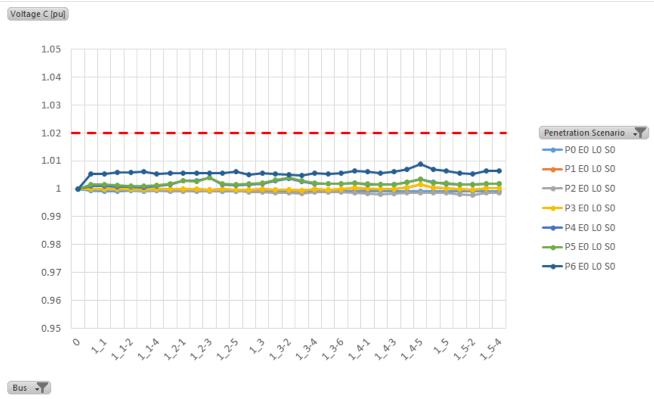
- To check the worst overvoltage – consider the min. consumer load with the highest PV utilisation factor of 80% for the PV only DERs penetration scenarios. The PV only DERs penetration scenarios are most onerous to overvoltage issues.
- No overvoltages (>1.02 pu) were observed in this feeder.
- An extreme case was tested where the consumer load is assumed to be at 10% of the max. No overvoltages were observed in this extreme case even under the most onerous penetration scenarios of *P5E0L0S0* and *P6E0L0S0*.

a) Min. consumer load with 80% PV utilisation factor

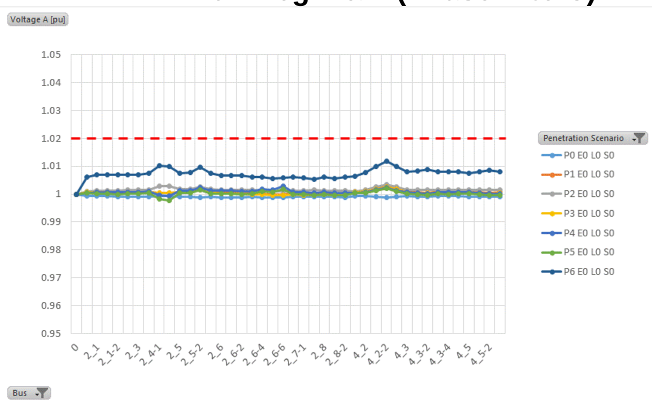
- **Leg 1 (Phase A to C)**

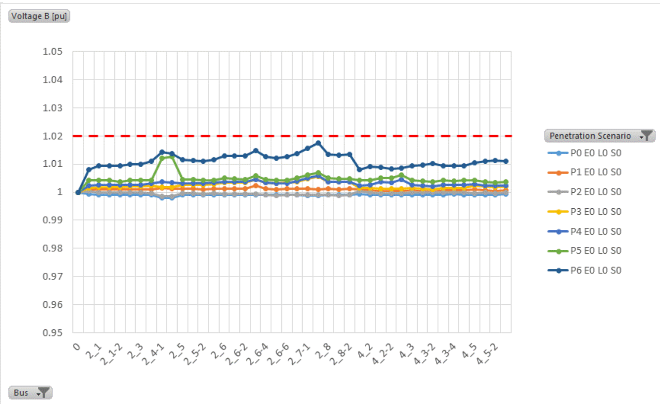


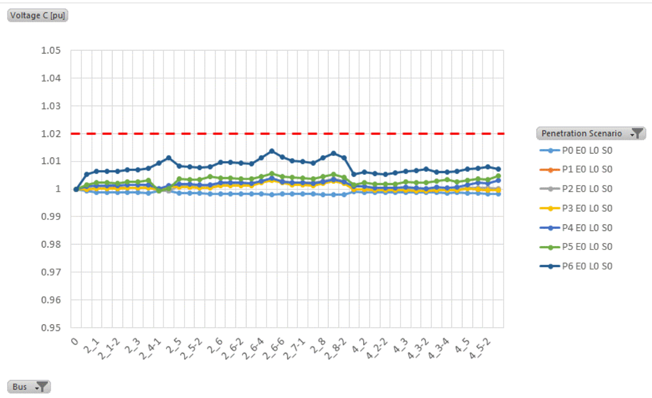




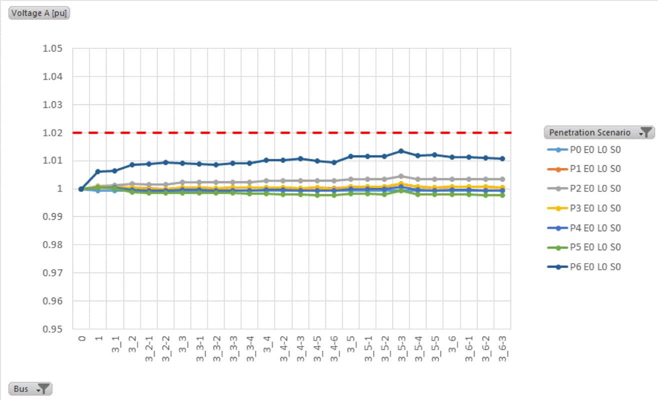
- **Leg 2 & 4 (Phase A to C)**

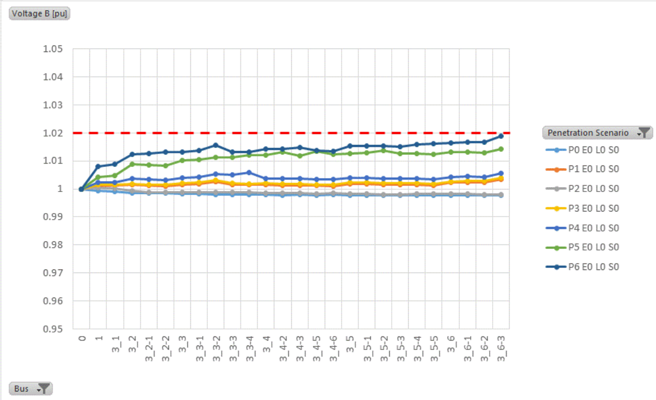


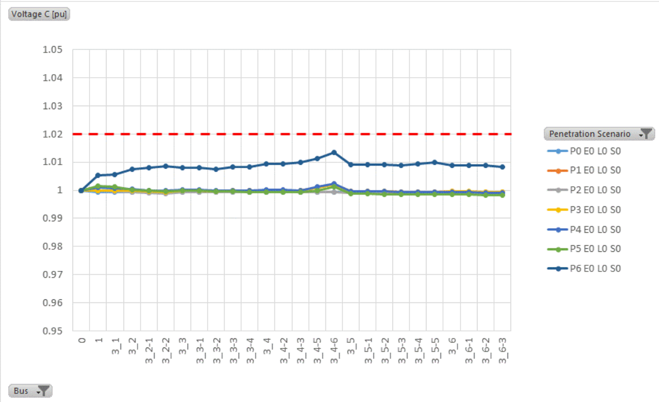




- Leg 3 (Phase A to C)

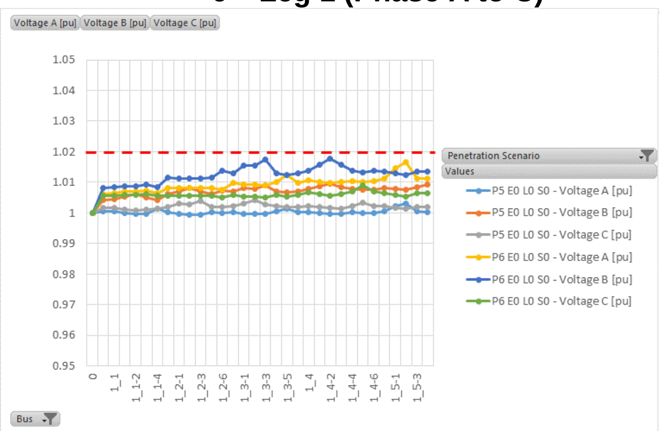




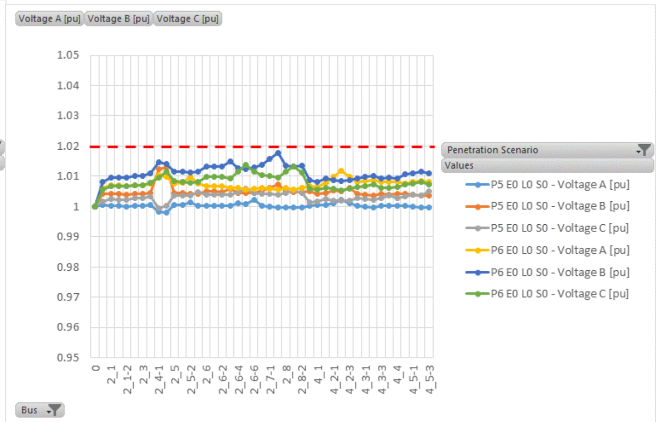


b) Extreme case with consumer load at 10% of the max.

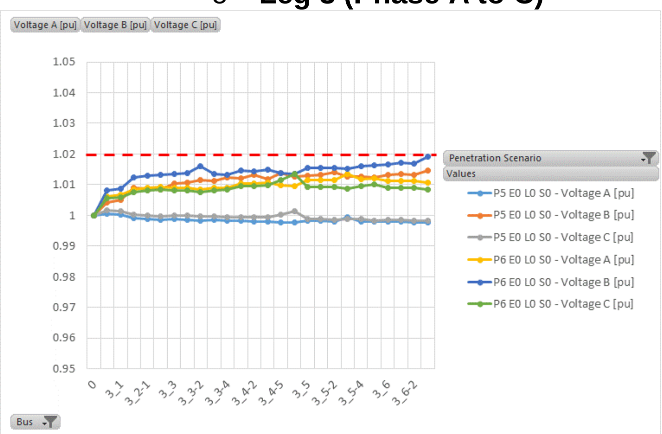
- Leg 1 (Phase A to C)



Leg 2&4 (Phase A to C)



- Leg 3 (Phase A to C)

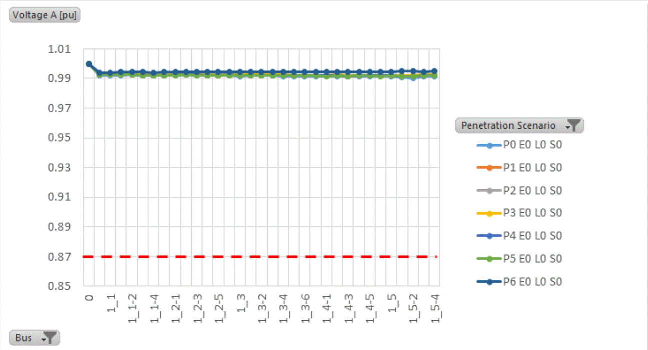


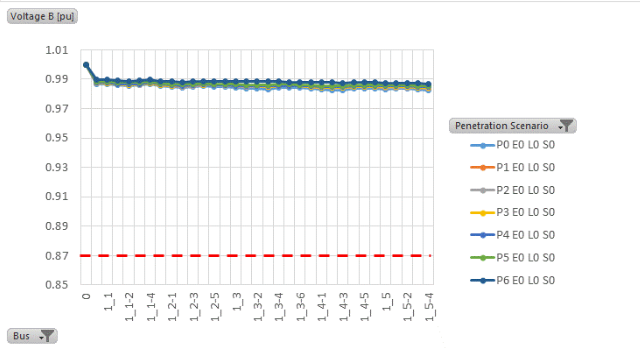
3. Undervoltage check

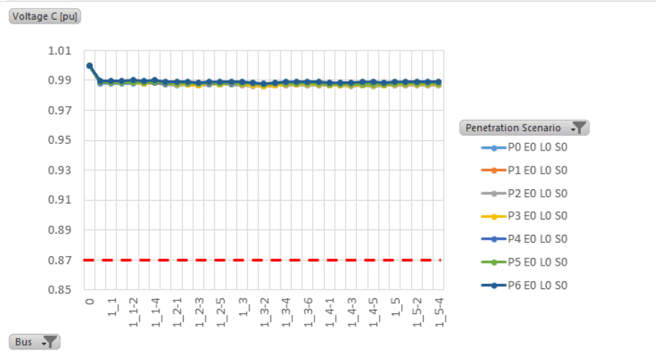
- To check the worst undervoltage – consider the max. consumer load with the lowest PV utilisation factor of 20%.
- The PV only DERs penetration scenarios were considered; and a more onerous scenario with only the power sinking DERs was tested.
- No undervoltages (<0.87pu) were observed in this feeder under all the scenarios considered.

c) Max. consumer load with 20% PV utilisation factor

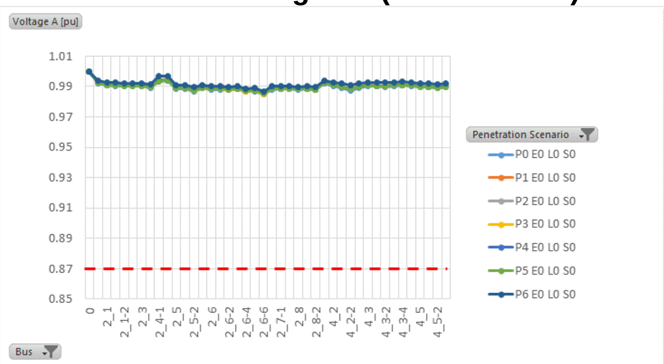
- o **Leg 1 (Phase A to C)**

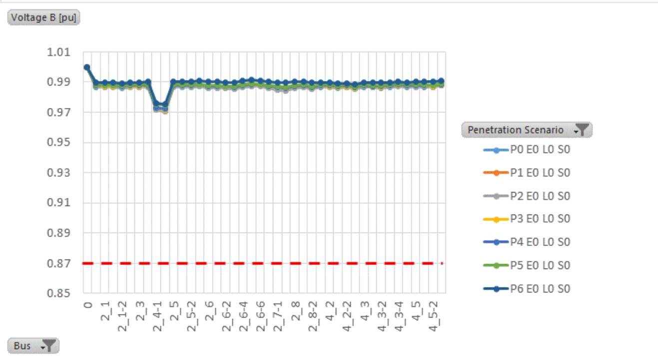


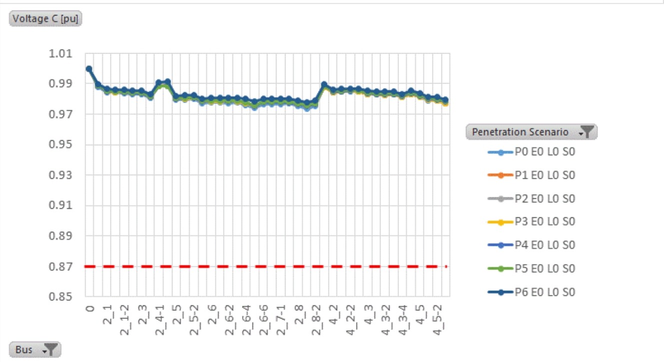




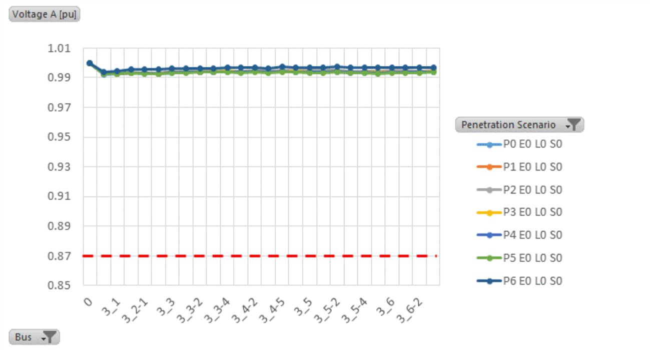
- o **Leg 2&4 (Phase A to C)**

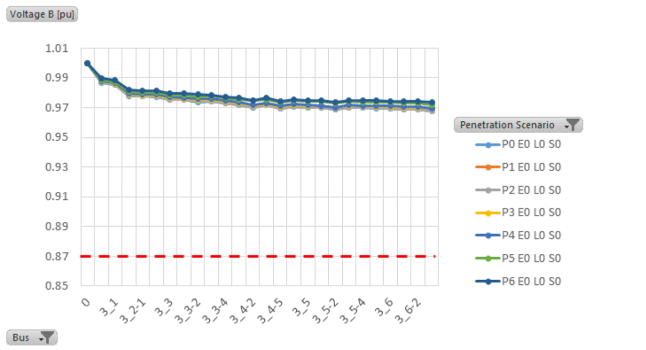


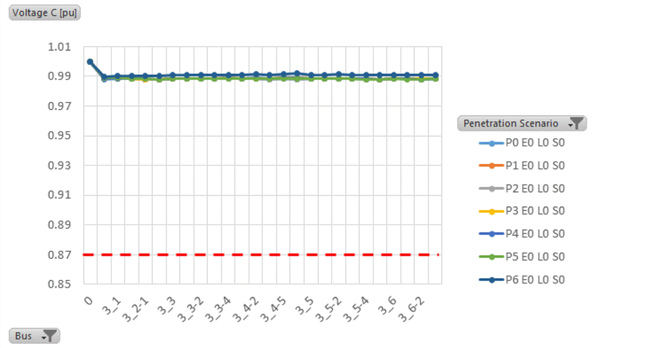




- o **Leg 3 (Phase A to C)**

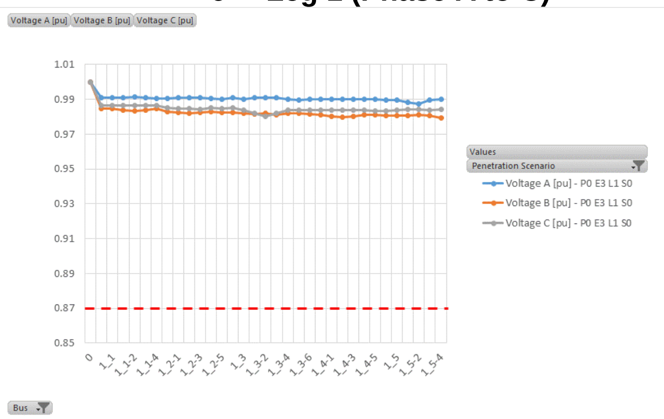


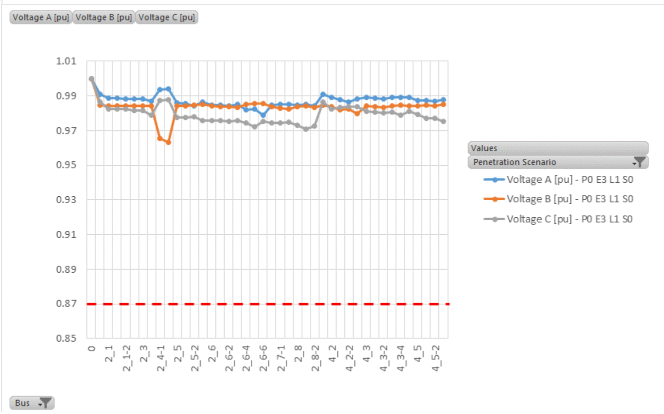




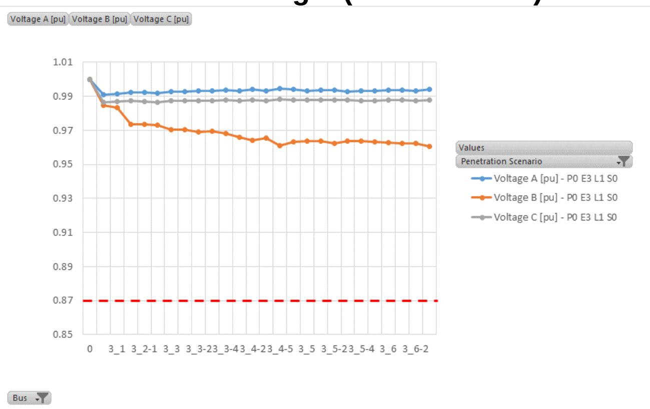
d) Max. consumer load with power sinking DERs

- o **Leg 1 (Phase A to C)** **Leg 2&4 (Phase A to C)**





- o **Leg 3 (Phase A to C)**



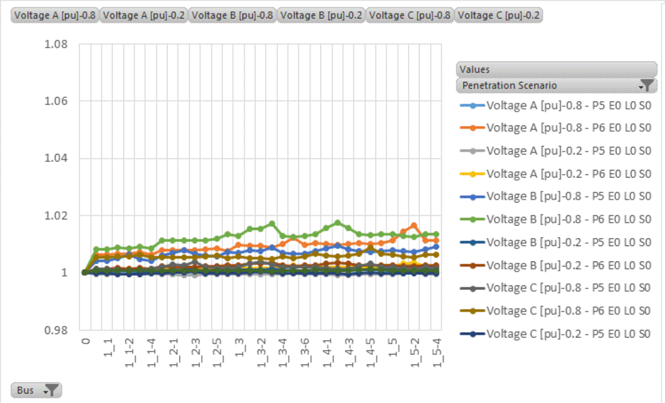
4. Voltage fluctuations

- The potential voltage fluctuation range is predicted by checking the voltages at the distribution legs from low PV utilisation factor (0.2) to high PV utilisation factor (0.8).
- The onerous fluctuation would occur should the cloud cover vary the PV utilisation factor from 0.2 to 0.8, or vice-versa, under the highest PV penetration scenario. Cloud cover reducing the PV output to zero is not considered here. Based on the solar profile provided by SAPN the periods with high solar intensity coincides with the low load periods of the day (12-2PM).

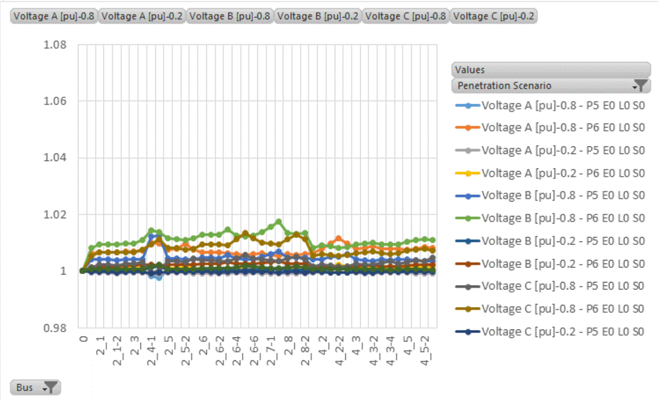
- From the voltage plots for both the distribution legs – the voltage fluctuation range for any particular point is not more than 0.05 pu (or 5%) within the criteria in IEC/TR 61000-3-7:2008 of 3-5%.

e) Potential voltage fluctuations

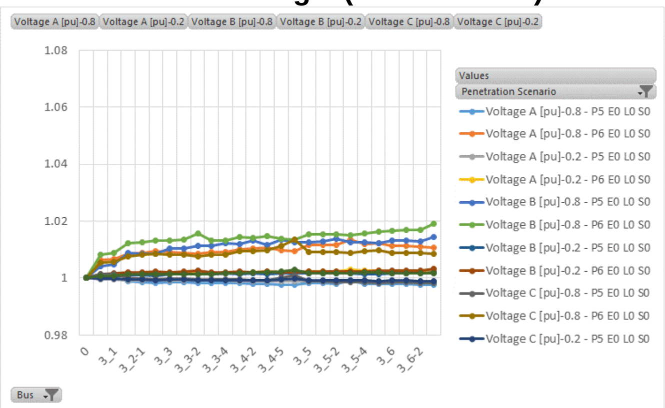
- Leg 1 (Phase A to C)



Leg 2&4 (Phase A to C)



- Leg 3 (Phase A to C)



5. Voltage unbalance

- For max. consumer load - the highest voltage unbalance factor of 0.61% is observed under penetration scenario P0E1L1S3.
- For min. consumer load - the highest voltage unbalance factor of 0.53% is observed under penetration scenario P5E0L0S2.
- The continuous voltage unbalance factor limit is 2%, hence, the unbalance factor for this feeder in within the limit.

	Max. Vneg/Vpos (%) observed		Max. Vneg/Vpos (%) observed (No DERs)	
	Peak demand case	Minimum demand case	Peak demand case	Minimum demand case
HH496C 26079	0.61%	0.53%	0.47%	0.04%

FEEDER HH121B - TC46352 (NEW UNDERGROUND)

1. Details

- Campbelltown – Felixstow 11 kV feeder
- 11000/433 V 300 kVA transformer
- Comprised of the following underground cable:
  - Cable UBC 150 mm^2
- Has four metering points with four distribution legs (with two legs forming a loop):
  - Leg 1 & 3 – Lot 502 Riverbank cct & Reserve Locheal Parkway (429 m)
  - Leg 2 – Lot 54 Riverbank cct (176 m)
  - Leg 4 – Lot 30 Locheal, Lot 61 Mundy (233 m)
- 34 customers
- Feeder phase balance (as per load data)
  - Leg 1&3 : Phase A = 29.2% Phase B = 23.6% Phase C = 47.2%
  - Leg 2: Phase A = 57.1% Phase B = 6.5% Phase C = 36.4%
  - Leg 4: Phase A = 29.7% Phase B = 60.1% Phase C = 10.2%
- Distribution of customers across feeder:

	Leg 1 & 3	**Leg 2**	**Leg 4**
Customers in %	41.2 %	26.5 %	32.4 %
Customers	14	9	11
3-Phase Customers	4	3	3
1-Phase Customers	10	6	8
1-Phase A	3	3	2
1-Phase B	2	1	5
1-Phase C	5	2	1

- Max. consumer load assumed = 59.5 kVA (obtained from actual data)

	Leg 1 & 3 [kVA / customer]	**Leg 2 [kVA / customer]**	**Leg 4 [kVA / customer]**
3-Phase Customers	2.10	2.28	0.86
1-Phase A	1.98	2.75	0.82
1-Phase B	1.76	0.00	1.01
1-Phase C	2.35	2.59	0.13

- Min. consumer load = 0 kVA (obtained from actual data assuming existing PV utilisation factor of 80%)

	All legs [kVA / customer]
3-Phase Customers	0
1-Phase A	0
1-Phase B	0
1-Phase C	0

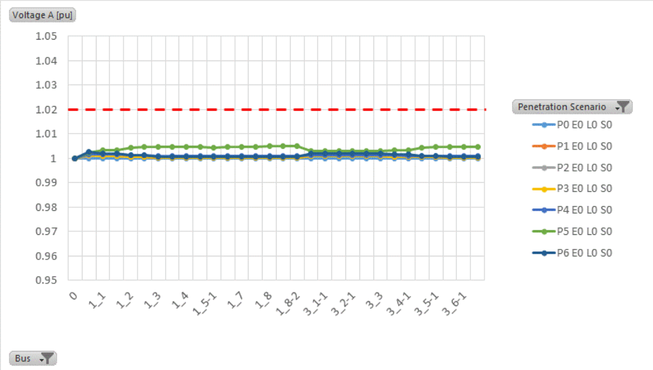
- Existing PV penetration = 23.89 % or 71.7 kW rated, i.e. 29 customers (assuming a 2.5 kW inverter size)
- Existing customers with controllable load = 2 (6 %)

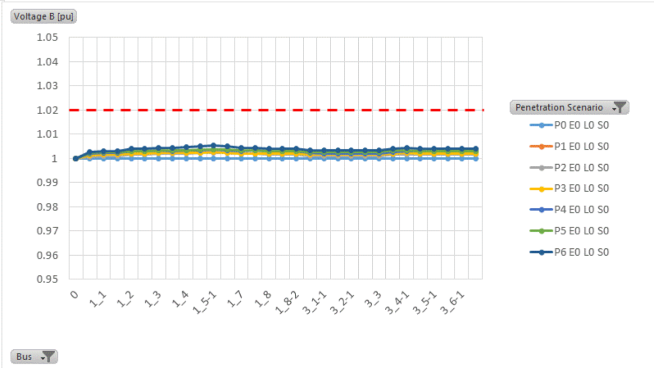
2. Overvoltage check

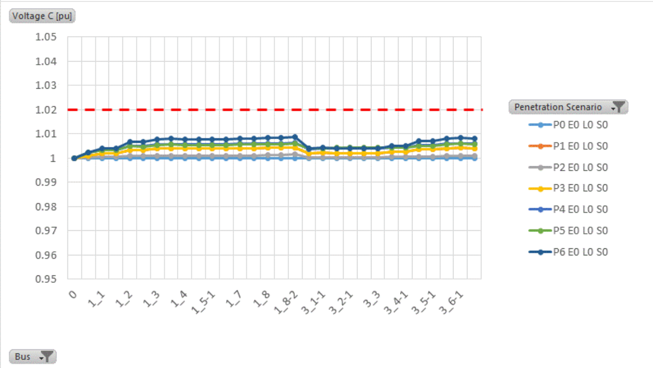
- To check the worst overvoltage – consider the min. consumer load with the highest PV utilisation factor of 80% for the PV only DERs penetration scenarios. The PV only DERs penetration scenarios are most onerous to overvoltage issues.
- No overvoltages (>1.02 pu) were observed in this feeder.

a) Min. consumer load with 80% PV utilisation factor

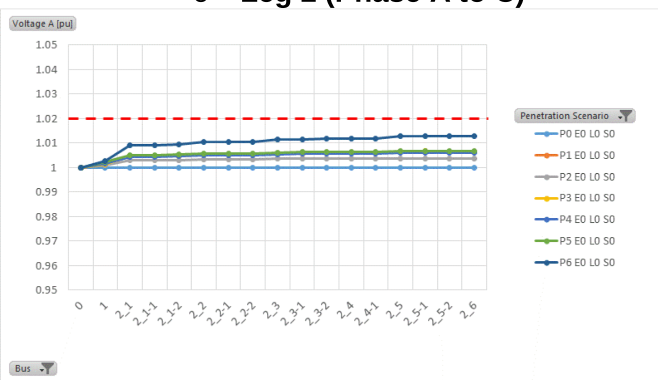
- **Leg 1&3 (Phase A to C)**

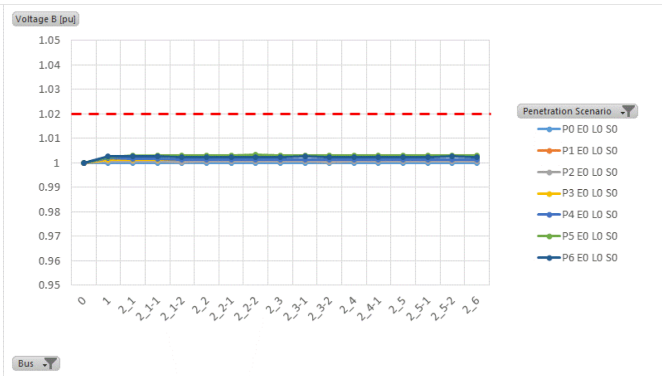


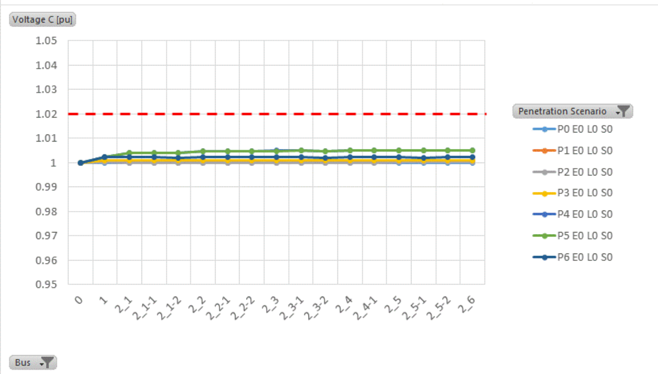




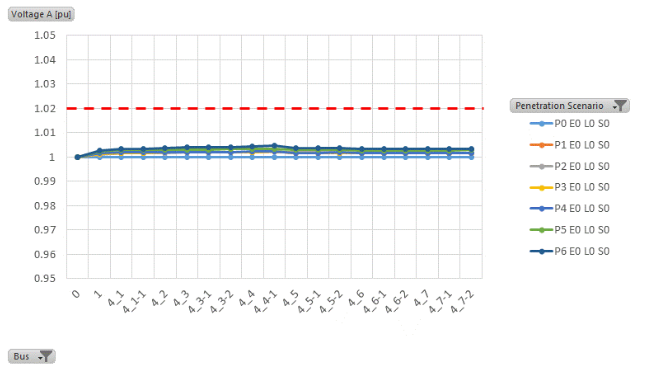
- **Leg 2 (Phase A to C)**

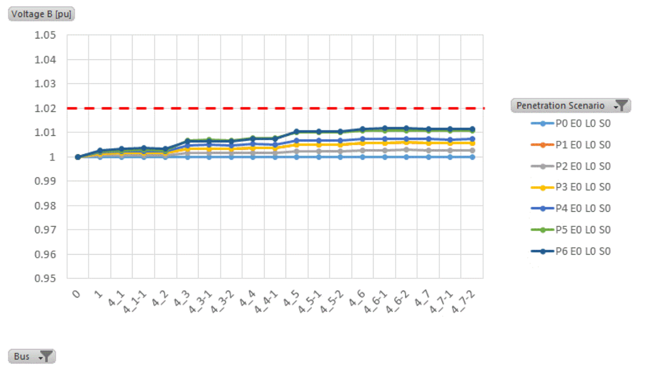


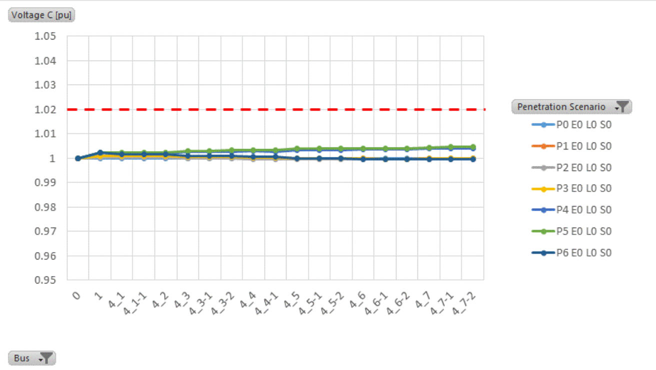




- **Leg 4 (Phase A to C)**





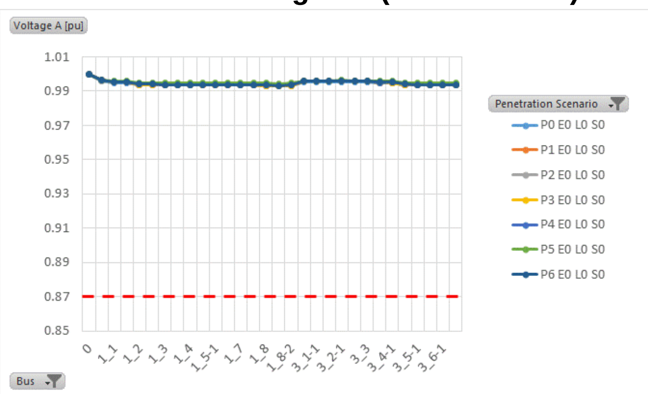


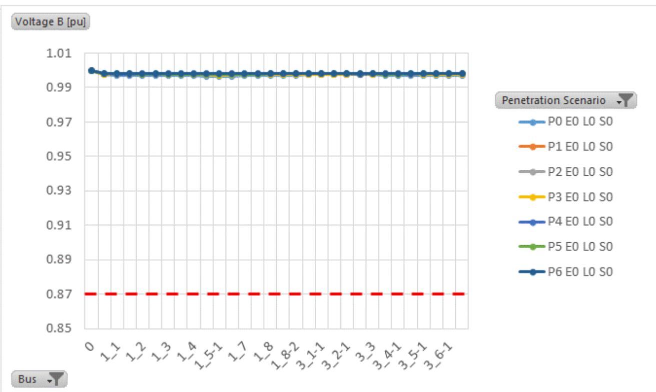
3. Undervoltage check

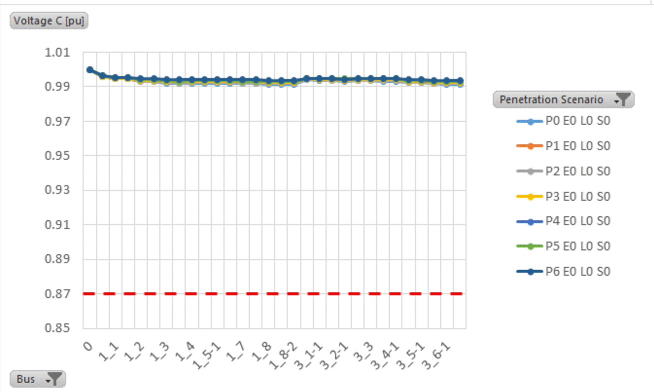
- To check the worst undervoltage – consider the max. consumer load with the lowest PV utilisation factor of 20%.
- The PV only DERs penetration scenarios were considered; and a more onerous scenario with only the power sinking DERs was tested.
- No undervoltages (<0.87pu) were observed in this feeder under all the scenarios considered.

b) Max. consumer load with 20% PV utilisation factor

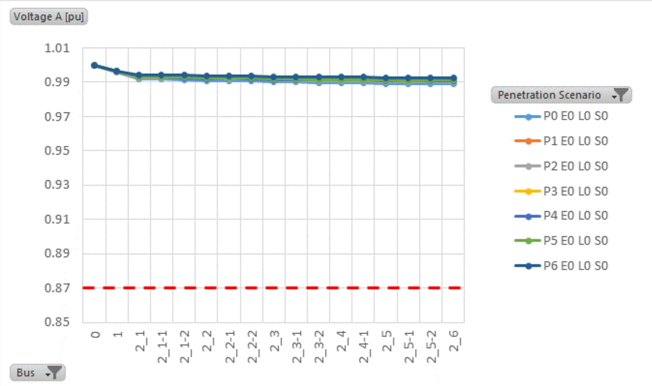
- **Leg 1&3 (Phase A to C)**

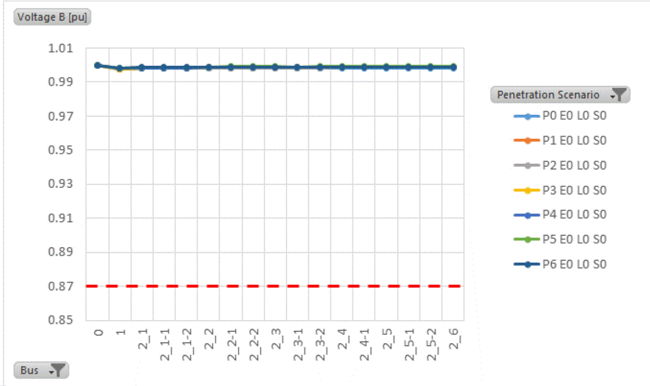


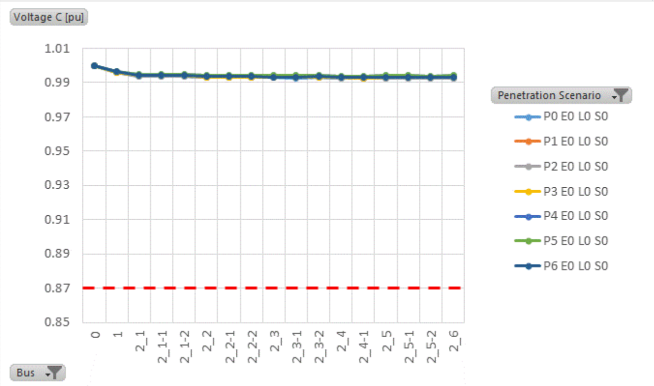




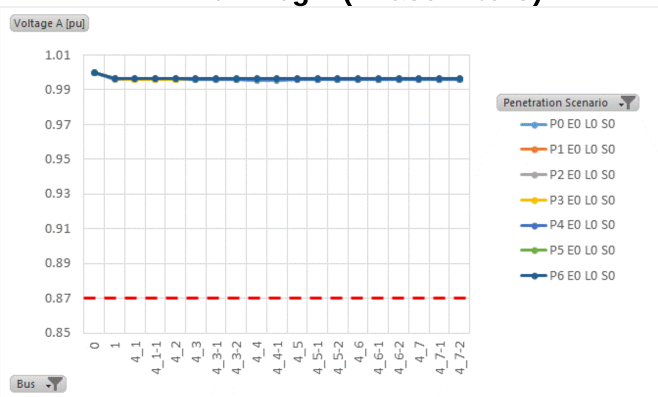
- Leg 2 (Phase A to C)

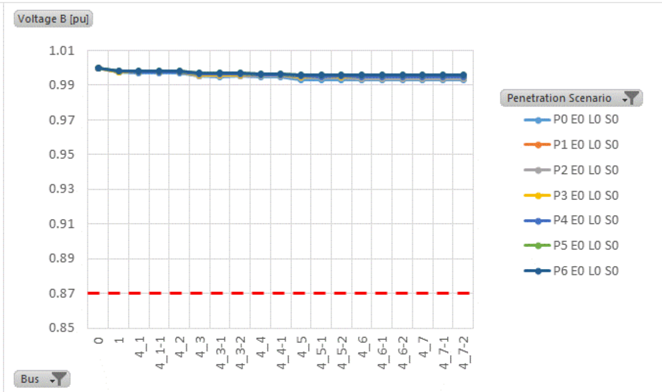


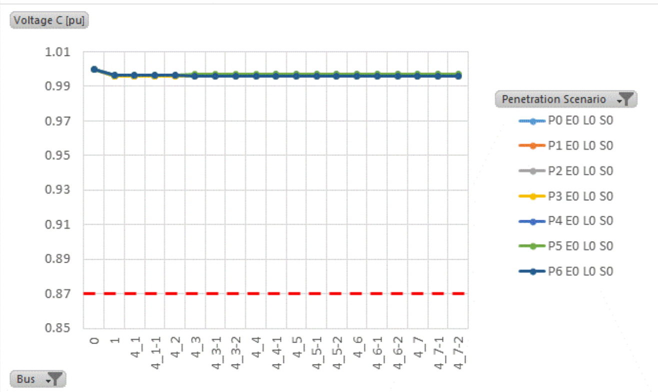




- Leg 4 (Phase A to C)

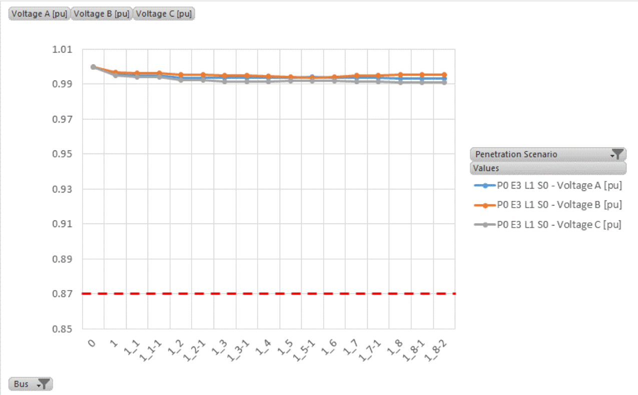


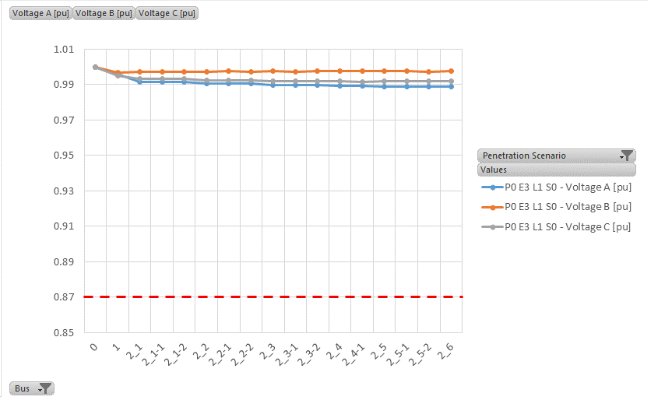




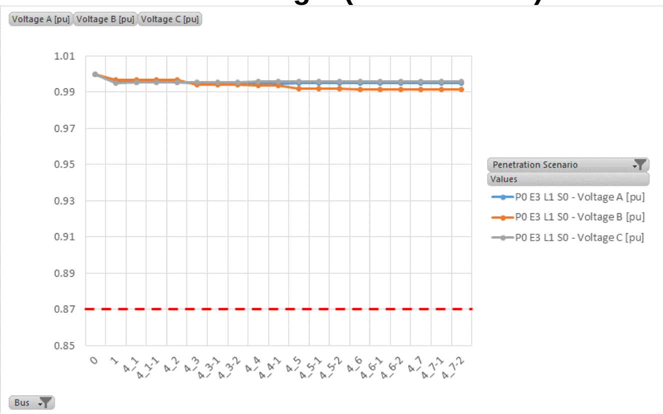
c) **Max. consumer load with power sinking DERs**

o **Leg 1&3 (Phase A to C)** **Leg 2 (Phase A to C)**





o **Leg 4 (Phase A to C)**

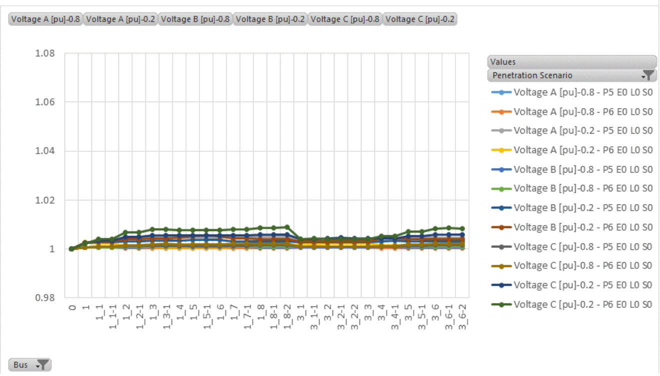


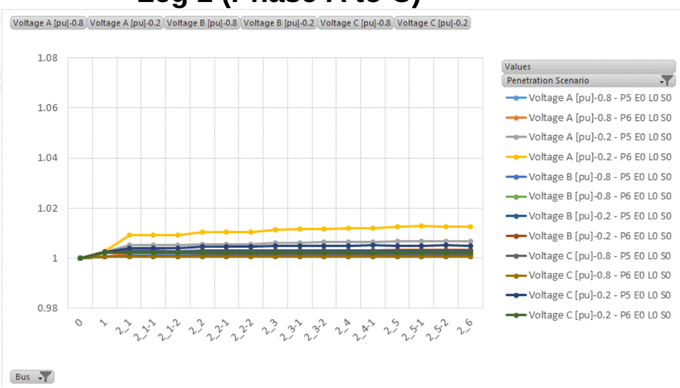
4. Voltage fluctuations

- The potential voltage fluctuation range is predicted by checking the voltages at the distribution legs from low PV utilisation factor (0.2) to high PV utilisation factor (0.8).
- The onerous fluctuation would occur should the cloud cover vary the PV utilisation factor from 0.2 to 0.8, or vice-versa, under the highest PV penetration scenario. Cloud cover reducing the PV output to zero is not considered here. Based on the solar profile provided by SAPN the periods with high solar intensity coincides with the low load periods of the day (12-2PM).
- From the voltage plots for both the distribution legs – the voltage fluctuation range for any particular point is not more than 0.05 pu (or 5%) within the criteria in IEC/TR 61000-3-7:2008 of 3-5%.

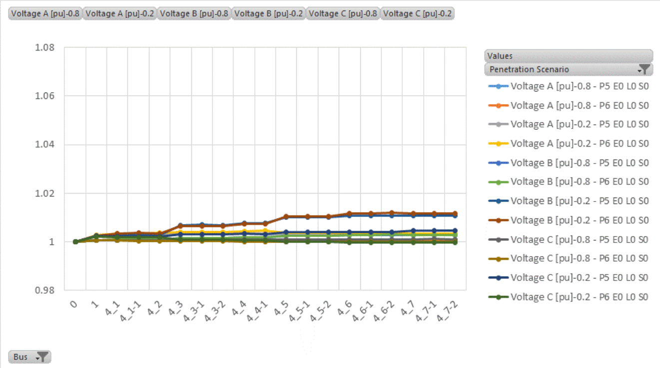
d) **Voltage fluctuations**

o **Leg 1&3 (Phase A to C)** **Leg 2 (Phase A to C)**





- **Leg 4 (Phase A to C)**



5. Voltage unbalance

- For max. consumer load - the highest voltage unbalance factor of 0.23% is observed under penetration scenario P0E2L1S3.
- For min. consumer load - the highest voltage unbalance factor of 0.31% is observed under penetration scenario P6E0L1S3.
- The continuous voltage unbalance factor limit is 2% hence, the unbalance factor for this feeder is within the limit.

	Max. Vneg/Vpos (%) observed		Max. Vneg/Vpos (%) observed (No DERs)	
	Peak demand case	Minimum demand case	Peak demand case	Minimum demand case
HH121B TC46352	0.23%	0.31%	0.22%	0.00%

FEEDER HH409F - 29068 (NEW UNDERGROUND)

1. Details

- Woodforde – Morialta 11 kV feeder
- 11000/433 V 300 kVA transformer
- Comprised of the following underground cable:
  - XLPE AL 150 mm^2 – 982 m (70.5 %)
  - XLPE AL 35 mm^2– 410 m (29.5 %)
- Has three meter points to three distribution legs:
  - Leg 1 – Lot 36 Gleeson Crs (West) (247 m)
  - Leg 2 – Lot 39 Gleeson Crs (East) (255 m)
  - Leg 3 – Lot 40 Redden Crt (279 m)
- 43 customers
- Feeder phase balance (as per load data)
  - Leg 1: Phase A = 38.2% Phase B = 26.8% Phase C = 35.1%
  - Leg 2: Phase A = 37.4% Phase B = 36.3% Phase C = 26.3%
  - Leg 3: Phase A = 35.7% Phase B = 29.3% Phase C = 34.9%
- Distribution of customers across feeder:

	Leg 1	**Leg 2**	**Leg 3**
Customers in %	41.9 %	11.6 %	46.5 %
Customers	18	5	20
3-Phase Customers	5	2	6
1-Phase Customers	13	3	14
1-Phase A	5	1	5
1-Phase B	3	1	4
1-Phase C	5	1	5

- Max. consumer load assumed = 217.7 kVA (obtained from actual data)

	Leg 1 [kVA / customer]	**Leg 2 [kVA / customer]**	**Leg 3 [kVA / customer]**
3-Phase Customers	5.35	3.06	5.31
1-Phase A	5.56	3.68	5.45
1-Phase B	5.62	3.52	5.13
1-Phase C	4.97	1.98	5.30

- Min. consumer load = 10.8 kVA (obtained from actual data assuming existing PV utilisation factor of 80%)

	Leg 1 [kVA / customer]	**Leg 2 [kVA / customer]**	**Leg 3 [kVA / customer]**
3-Phase Customers	0.27	0.15	0.26
1-Phase A	0.28	0.18	0.27
1-Phase B	0.28	0.17	0.25
1-Phase C	0.25	0.08	0.26

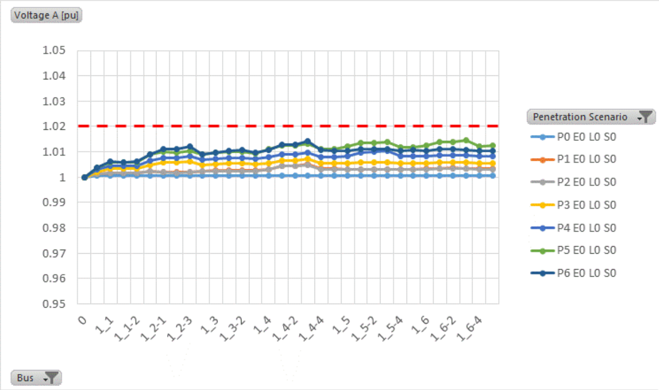
- Existing PV penetration = 10.75 % or 32.3 kW rated, i.e. 13 customers (assuming a 2.5 kW inverter size)
- Existing customers with controllable load = 4 (9 %)

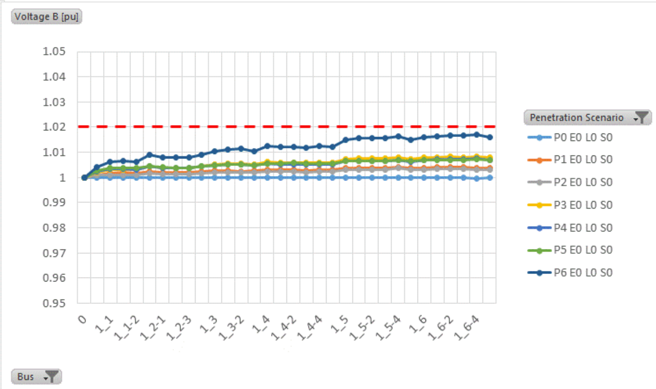
2. Overvoltage check

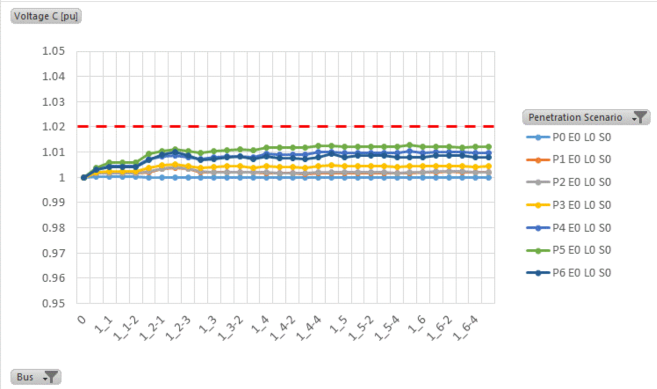
- To check the worst overvoltage – consider the min. consumer load with the highest PV utilisation factor of 80% for the PV only DERs penetration scenarios. The PV only DERs penetration scenarios are most onerous to overvoltage issues.
- No overvoltages (>1.02 pu) were observed in this feeder.

a) Min. consumer load with 80% PV utilisation factor

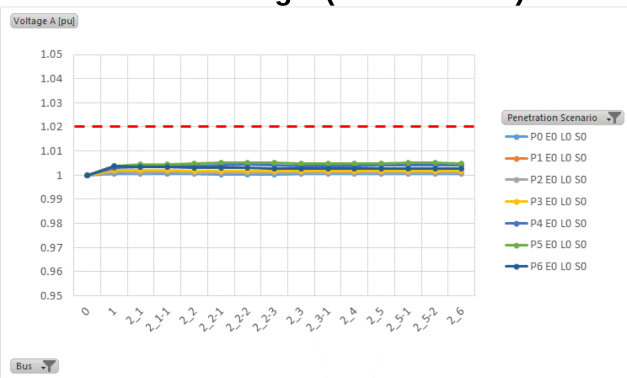
- **Leg 1 (Phase A to C)**

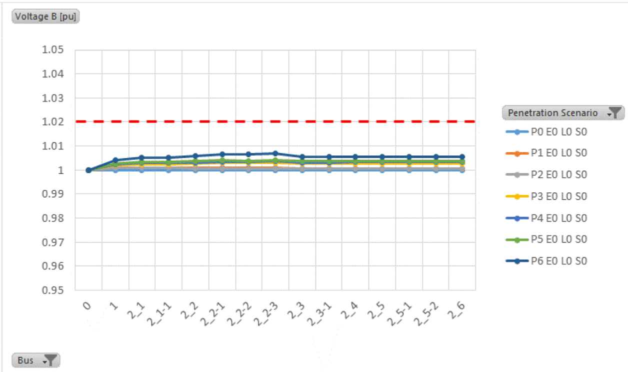


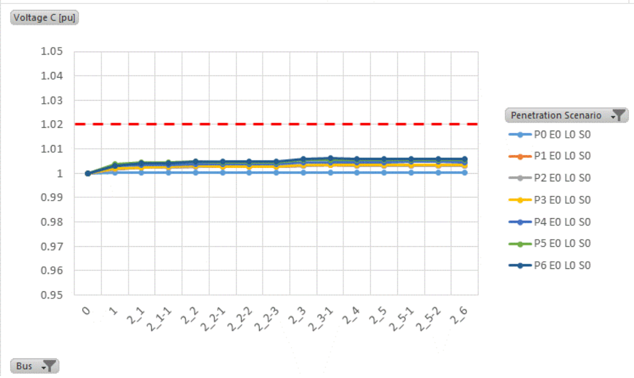




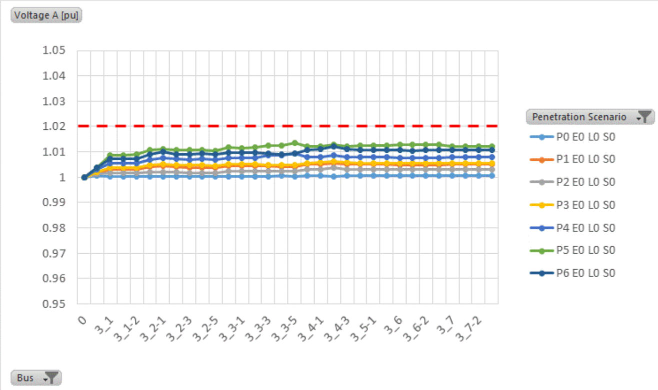
- **Leg 2 (Phase A to C)**

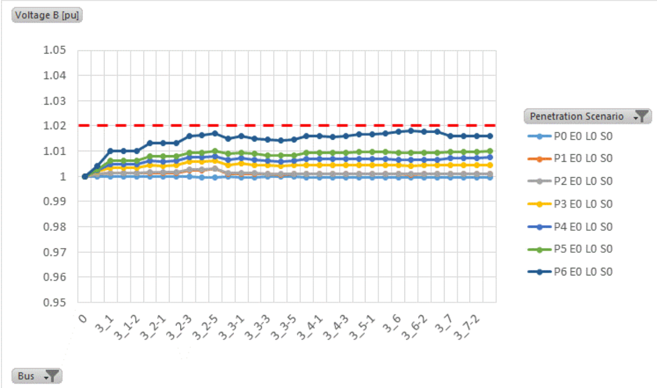


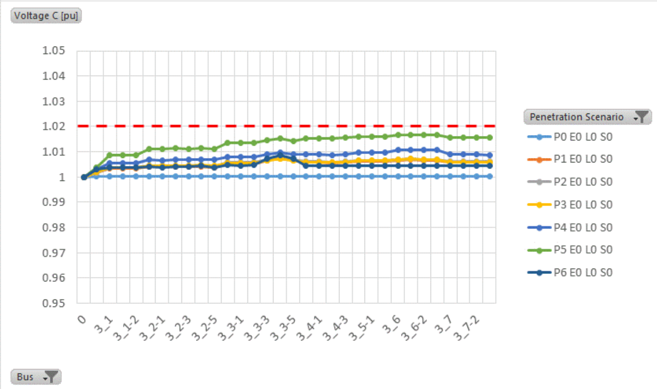




- **Leg 3 (Phase A to C)**





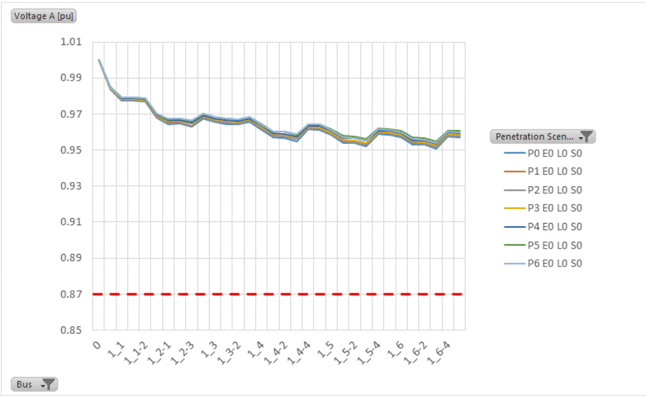


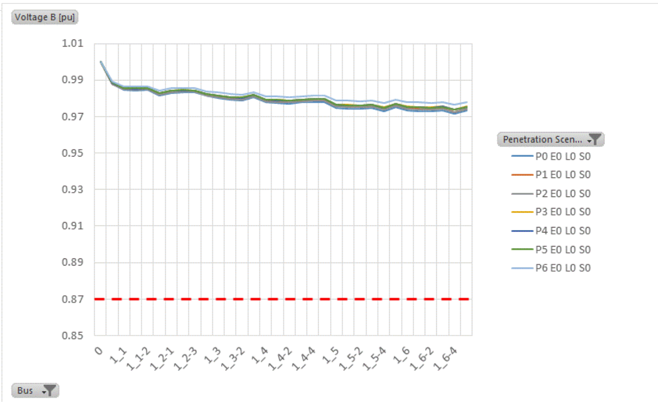
3. Undervoltage check

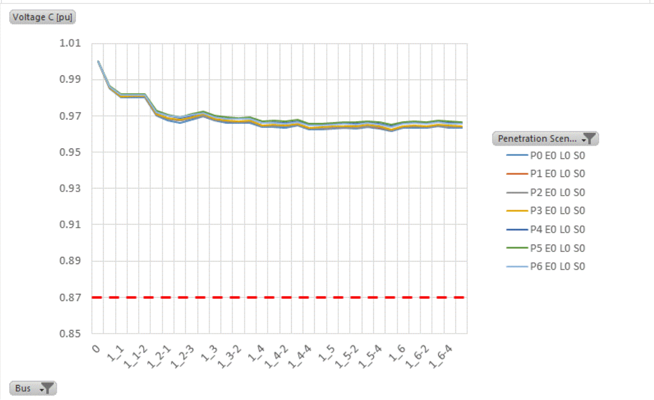
- To check the worst undervoltage – consider the max. consumer load with the lowest PV utilisation factor of 20%.
- The PV only DERs penetration scenarios were considered; and a more onerous scenario with only the power sinking DERs was tested.
- No undervoltages (<0.87pu) were observed in this feeder under all the scenarios considered.

b) Max. consumer load with 20% PV utilisation factor

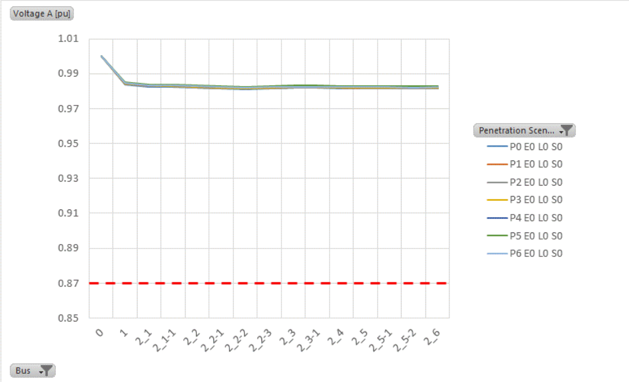
- **Leg 1 (Phase A to C)**

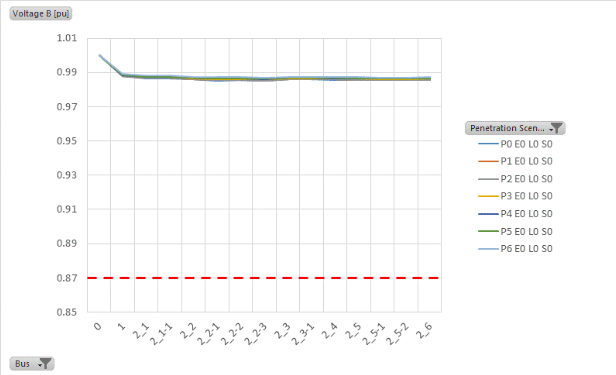


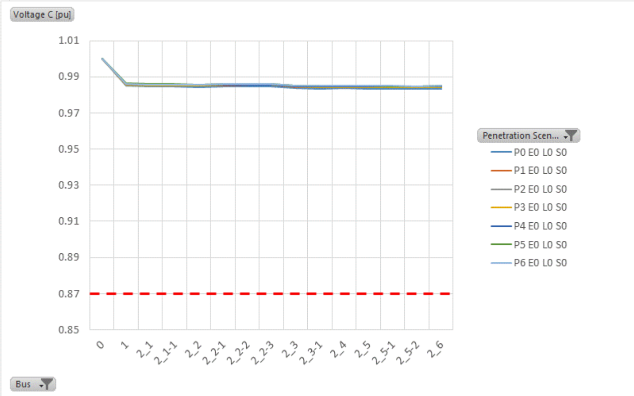




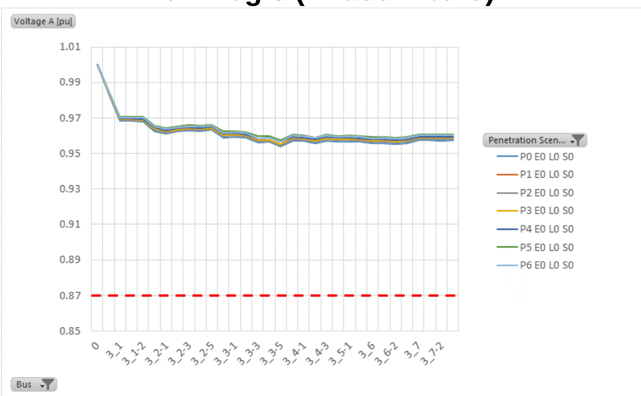
- ## Leg 2 (Phase A to C)

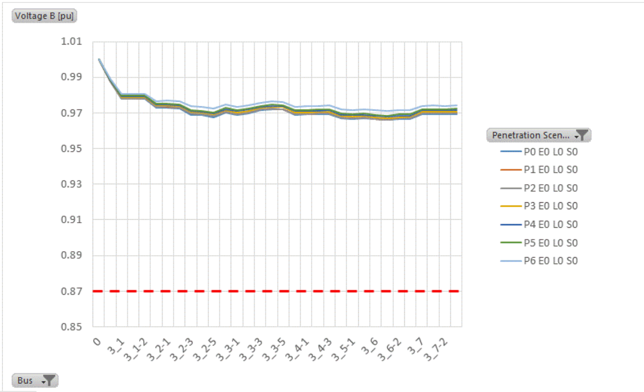


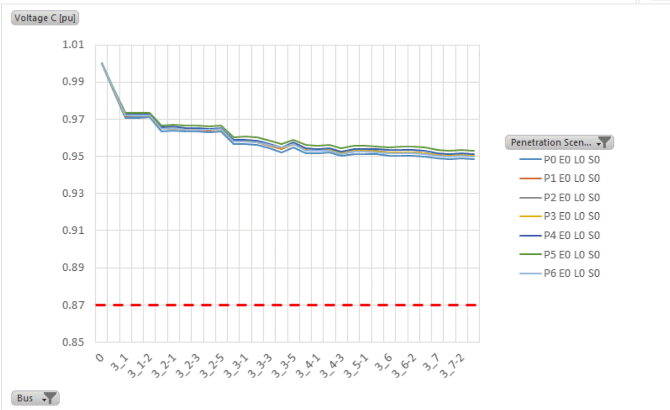




- ## Leg 3 (Phase A to C)

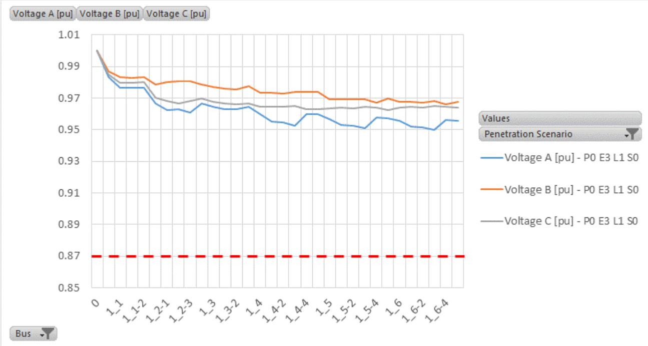




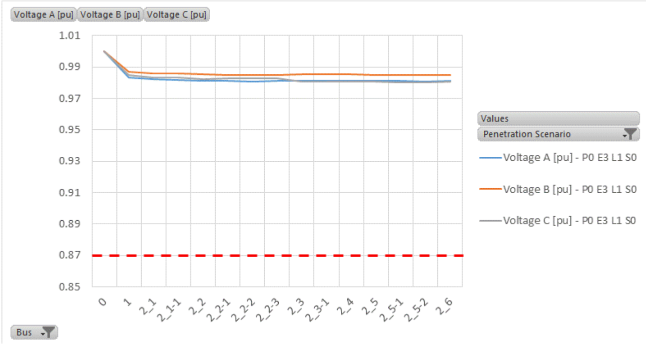


c) Max. consumer load with power sinking DERs

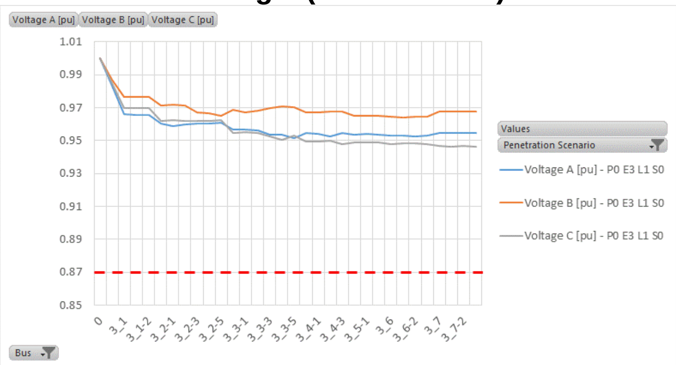
- Leg 1 (Phase A to C)



Leg 2 (Phase A to C)



- Leg 3 (Phase A to C)

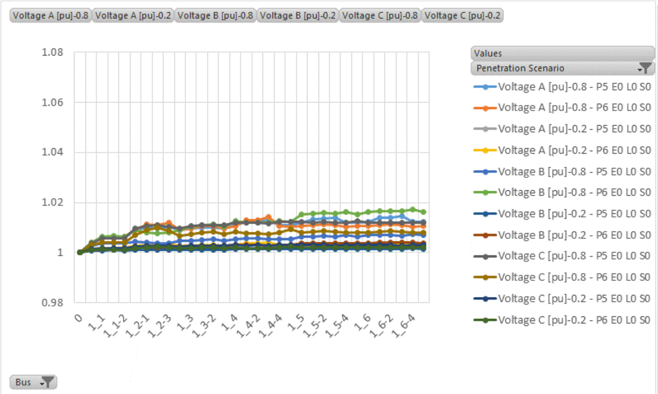


4. Voltage fluctuations

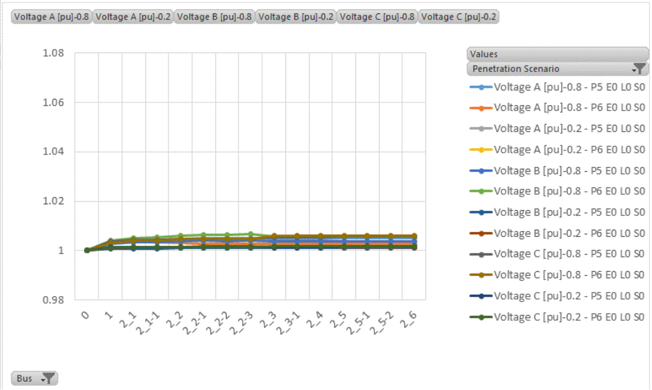
- The potential voltage fluctuation range is predicted by checking the voltages at the distribution legs from low PV utilisation factor (0.2) to high PV utilisation factor (0.8).
- The onerous fluctuation would occur should the cloud cover vary the PV utilisation factor from 0.2 to 0.8, or vice-versa, under the highest PV penetration scenario. Cloud cover reducing the PV output to zero is not considered here. Based on the solar profile provided by SAPN the periods with high solar intensity coincides with the low load periods of the day (12-2PM).
- From the voltage plots for both the distribution legs – the voltage fluctuation range for any particular point is not more than 0.05 pu (or 5%) within the criteria in IEC/TR 61000-3-7:2008 of 3-5%.

d) Potential voltage fluctuations

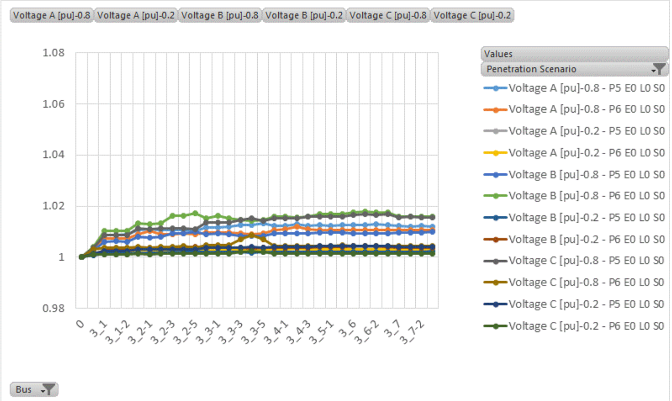
- Leg 1 (Phase A to C)



Leg 2 (Phase A to C)



- **Leg 3 (Phase A to C)**



5. Voltage unbalance

- For max. consumer load - the highest voltage unbalance factor of 0.60% is observed under penetration scenario P6E0L0S1.
- For min. consumer load - the highest voltage unbalance factor of 0.32% is observed under penetration scenario P6E0L1S4.
- The continuous voltage unbalance factor limit is 2%, hence, the unbalance factor for this feeder is within the limit.

	Max. Vneg/Vpos (%) observed		Max. Vneg/Vpos (%) observed (No DERs)	
	Peak demand case	Minimum demand case	Peak demand case	Minimum demand case
HH409F 29068	0.60%	0.32%	0.54%	0.03%

FEEDER GU-37

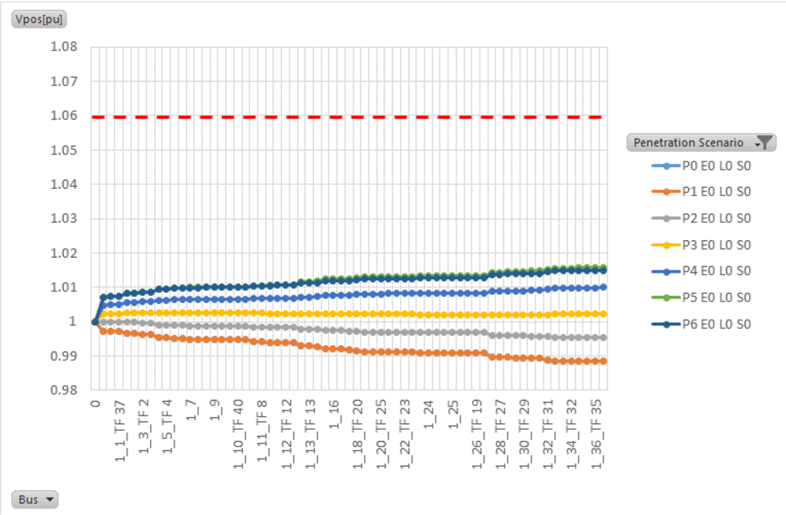
1. Details

- Cookes Hill 19 kV SWER
- 11/19 k V 150 kVA transformer
- Comprised of the following overhead conductor:
  - 3/12 SCGZ (19.5 km / 68.2%)
  - SC/AC-MET 3/2.75 (9.1 km / 31.8%)
- Total feeder backbone length – 15 km
- 58 customers
- Has one metering point to one distribution leg.
- Max. consumer load = 129 kVA (obtained from actual data)
- Min. consumer load = 42.2 kVA (obtained from actual data assuming existing PV utilisation factor of 80%).
- Existing PV penetration = 37.5 kW 15 customers (assuming a 2.5 kW inverter size)
- Existing customers with controllable load = 31 (53 %)

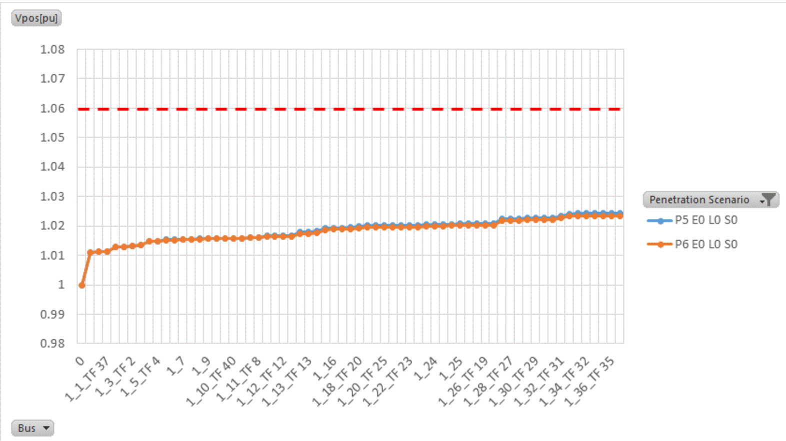
2. Overvoltage check

- To check the worst overvoltage – consider the min. consumer load with the highest PV utilisation factor of 80% for the PV only DERs penetration scenarios. The PV only DERs penetration scenarios are most onerous to overvoltage issues.
- No overvoltages (>1.06 pu) were observed in this feeder.
- An extreme case was tested where the consumer load is assumed to be at 10% of the max. Similarly, no overvoltages were observed under the most onerous penetration scenarios of *P5E0L0S0* and *P6E0L0S0*.

a) Min. consumer load with 80% PV utilisation factor



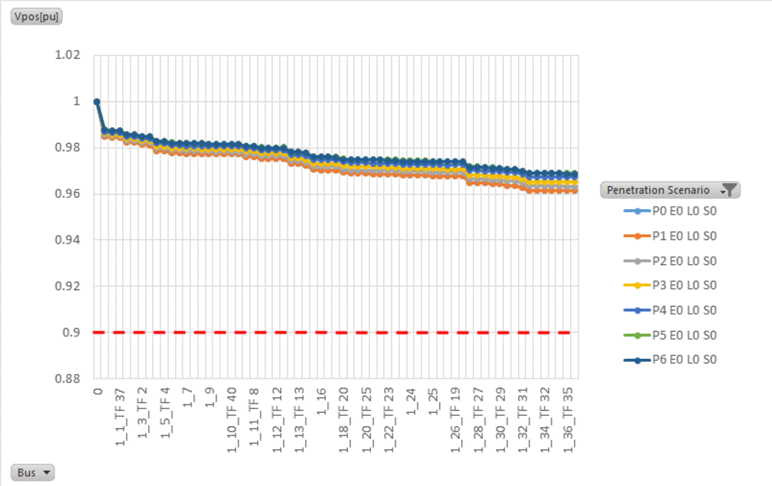
b) Extreme case with consumer load at 10% of the max.



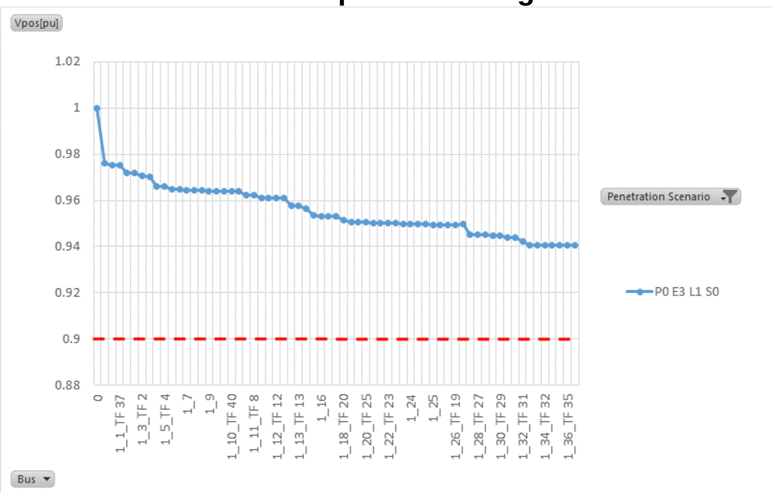
3. Undervoltage check

- To check the worst undervoltage – consider the max. consumer load with the lowest PV utilisation factor of 20%.
- The PV only DERs penetration scenarios were considered; and the most onerous for undervoltage with only the power sinking DERs.
- No undervoltages (<0.90pu) were observed in this feeder under all the scenarios considered.

c) Max. consumer load with 20% PV utilisation factor



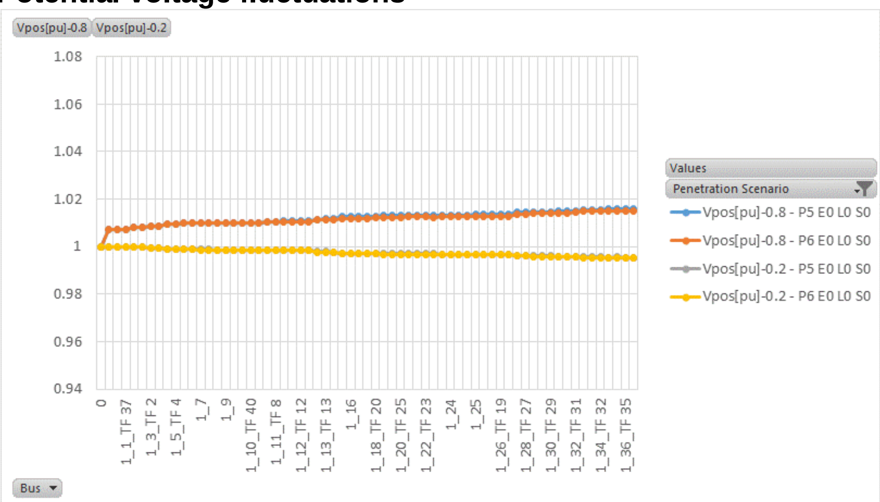
d) Max. consumer load with power sinking DERs



4. Voltage fluctuations

- The potential voltage fluctuation range is predicted by checking the step change in voltages from low PV utilisation factor (20%) to high PV utilisation factor (80%).
- The most onerous fluctuation would occur under the PV only DERs penetration scenarios. Based on the solar profile provided by SAPN the periods with high PV utilisation coincides with the min. load periods of the day (12-2PM). Hence, for this assessment a network with min. load is considered.
- From the voltage plots – the voltage fluctuation range for any particular point is not more than 0.05 pu (or 5%) within the criteria in IEC/TR 61000-3-7:2008 of 3-5%.

e) Potential voltage fluctuations



SWER MTB - 82

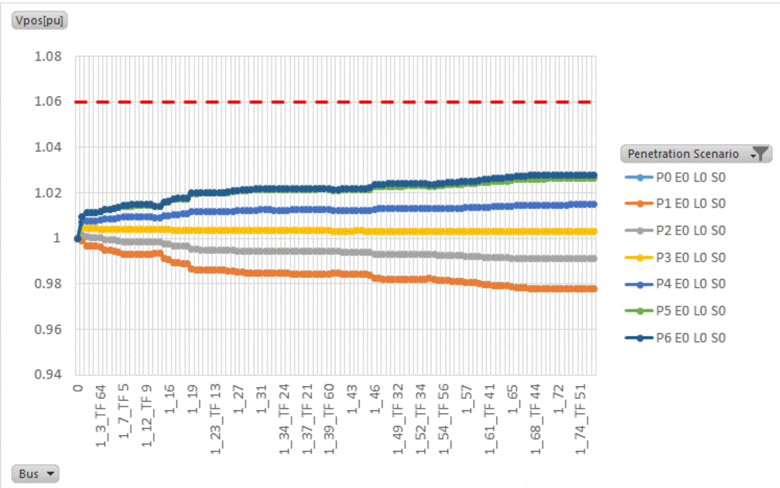
1. Details

- Bremer 19 kV SWER
- 11/19 k V 200 kVA transformer
- Comprised of the following overhead conductor:
  - 3/12 SCGZ (39.2 km / 75%)
  - SC/AC-MET 3/2.75 (11.3 km / 21.6%)
  - SC/AC-IMP 3/0.1019 3/10 (1.8 km / 3.4%)
- Total feeder length – 33 km
- 96 customers
- Has one metering point to one distribution leg.
- Max. consumer load assumed = 166 kVA (obtained from actual data)
- Min. consumer load = 69.8 kVA (obtained from actual data assuming existing PV utilisation factor of 80%)
- Existing PV penetration = 47.5 kW 19 customers (assuming a 2.5 kW inverter size)
- Existing customers with controllable load = 40 (42 %)

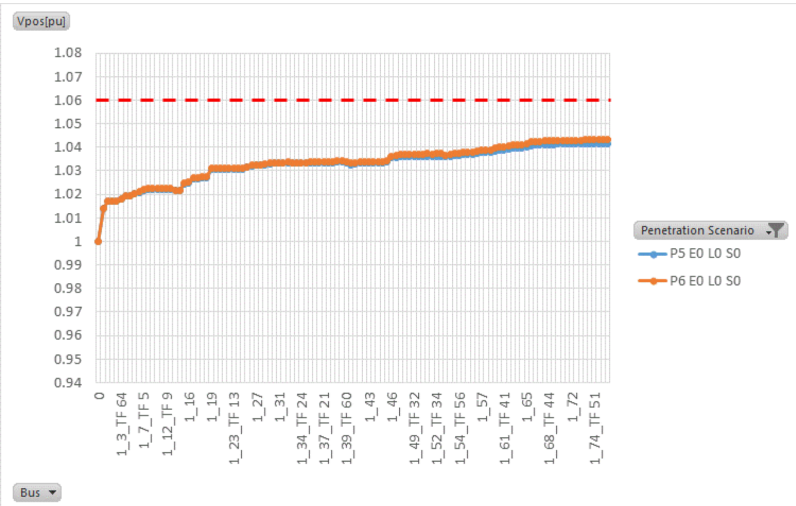
2. Overvoltage check

- To check the worst overvoltage – consider the min. consumer load with the highest PV utilisation factor of 80% for the PV only DERs penetration scenarios. The PV only DERs penetration scenarios are most onerous to overvoltage issues.
- No overvoltages (>1.06 pu) were observed in this feeder.
- An extreme case was tested where the consumer load is assumed to be at 10% of the max. No overvoltages were observed in this extreme case even under the most onerous penetration scenarios of *P5E0L0S0* and *P6E0L0S0*.

a) Min. consumer load with 80% PV utilisation factor



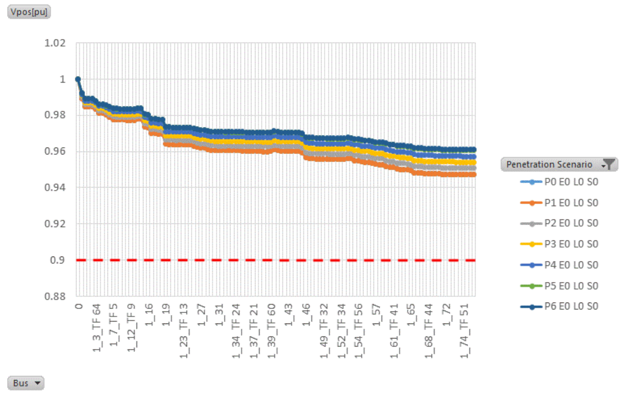
b) Extreme case with consumer load at 10% of the max.



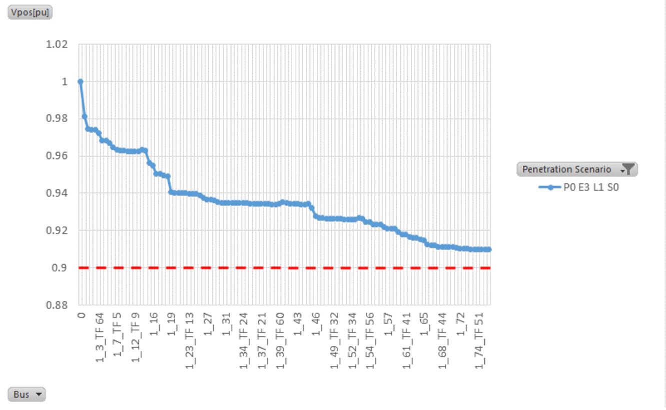
3. Undervoltage check

- To check the worst undervoltage – consider the max. consumer load with the lowest PV utilisation factor of 20%.
- The PV only DERs penetration scenarios were considered; and the most onerous for undervoltage with only the power sinking DERs.
- No undervoltages (<0.90pu) were observed in this feeder.

c) Max. consumer load with 20% PV utilisation factor



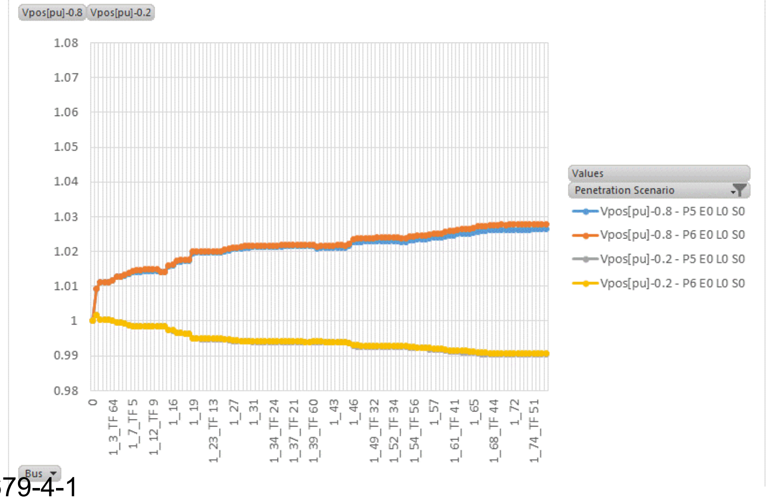
d) Max. consumer load with power sinking DERs



4. Voltage fluctuations

- The potential voltage fluctuation range is predicted by checking the step change in voltages from low PV utilisation factor (20%) to high PV utilisation factor (80%).
- The most onerous fluctuation would occur under the PV only DERs penetration scenarios. Based on the solar profile provided by SAPN the periods with high PV utilisation coincides with the min. load periods of the day (12-2PM). Hence, for this assessment a network with min. load is considered.
- From the voltage plots – the voltage fluctuation range for any particular point is not more than 0.05 pu (or 5%) within the criteria in IEC/TR 61000-3-7:2008 of 3-5%.

e) Potential voltage fluctuations



SWER M - 23

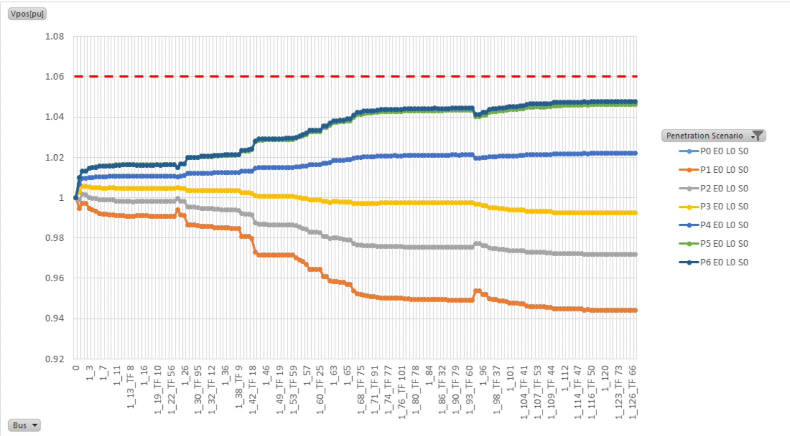
1. Details

- Rockleigh 19 kV SWER
- 11/19 k V 200 kVA transformer
- Comprised of the following overhead conductor:
  - 3/12 SCGZ
- Total feeder length – 52 km
- 132 customers
- Has one meter point to one distribution leg.
- Max. consumer load assumed = 280 kVA (obtained from actual data). Note that the max. load exceeds the rating of the transformer.
- Min. consumer load = 101.6 kVA (obtained from actual data assuming existing PV utilisation factor of 80%)
- Existing PV penetration = 77.5 kW 31 customers (assuming a 2.5 kW inverter size)
- Existing customers with controllable load = 67 (51 %)

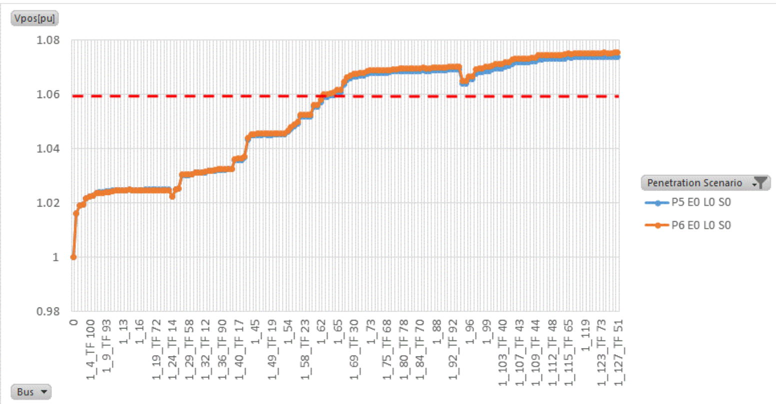
2. Overvoltage check

- To check the worst overvoltage – consider the min. consumer load with the highest PV utilisation factor of 80% for the PV only DERs penetration scenarios. The PV only DERs penetration scenarios are most onerous for overvoltage issues.
- No overvoltages (>1.06 pu) were observed in this feeder.
- An extreme case was tested where the consumer load is assumed to be at 10% of the max. Overvoltages were observed in this extreme case under the most onerous penetration scenarios of *P5E0L0S0* and *P6E0L0S0.* The controllable loads (L1) could be switched on to resolve the overvoltages issues.

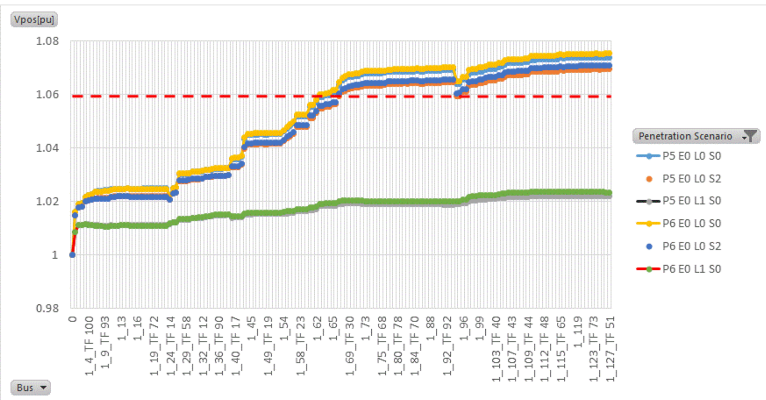
a) Min. consumer load with 80% PV utilisation factor



b) Extreme case with consumer load at 10% of the max.



- o **With CL and ST to control overvoltages**

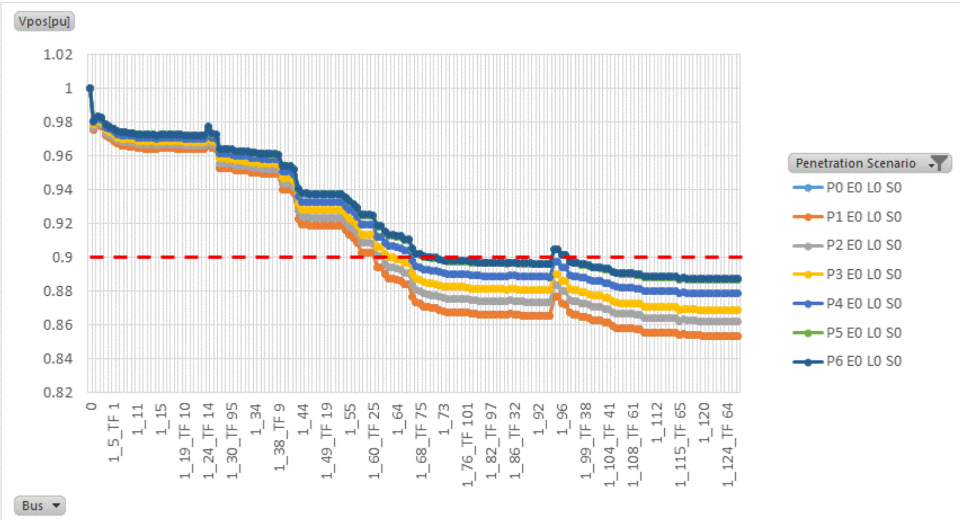


3. Undervoltage check

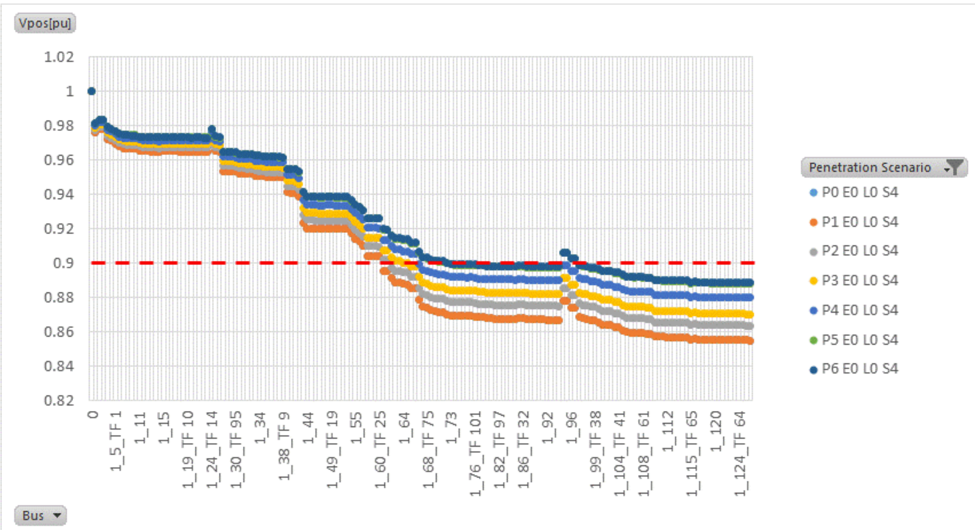
- To check the worst undervoltage – consider the max. consumer load with the lowest PV utilisation factor of 20%. PV only DERs penetration scenarios were considered.
- Undervoltages (<0.90pu) were observed due to the heavy loading on this feeder.
- This indicate that the feeder will not be able to support more power sinking DERs during the max. load period.
- Possible mitigation to be investigated:
    - Option A - Tap transformer to increase LV-side voltage of the feeder
    - Option B – Use storage as generation (insufficient)
    - Option C – reduce the loading of the feeder by shifting of load to other feeder(s)

c) Max. consumer load with 20% PV utilisation factor

- **Peak demand scenario**



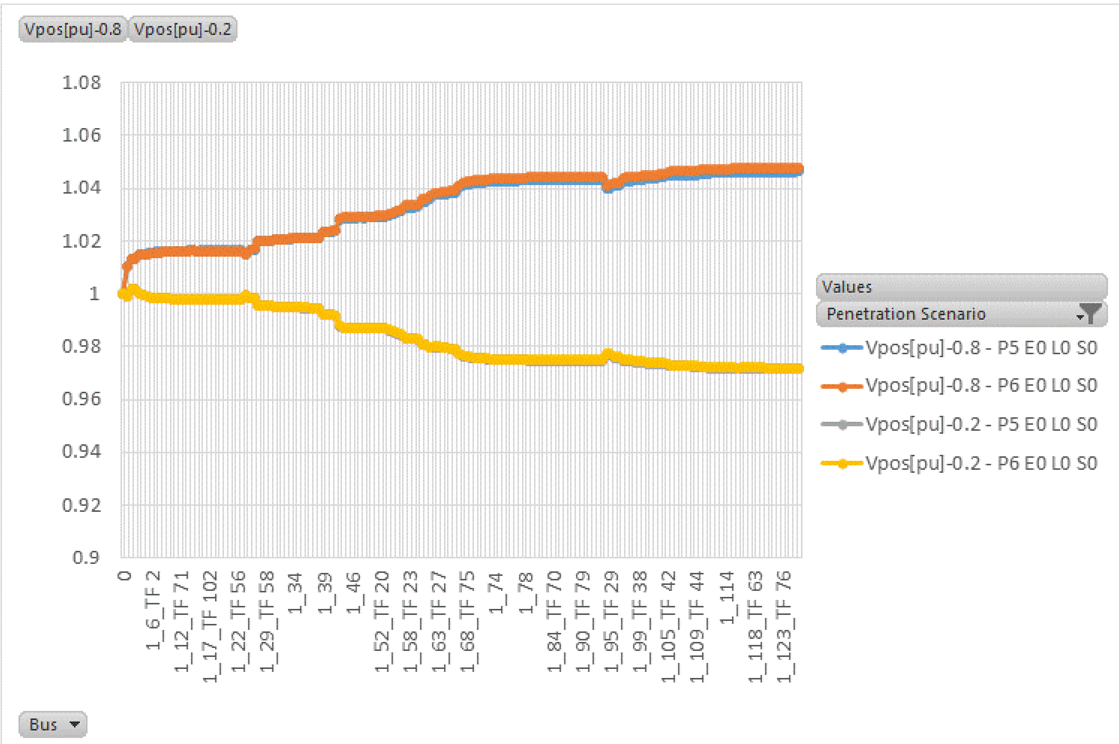
- **Impact of storage discharging during peak demand**



4. Voltage fluctuations

- The potential voltage fluctuation range is predicted by checking the step change in voltages from low PV utilisation factor (20%) to high PV utilisation factor (80%).
- The most onerous fluctuation would occur under the PV only DERs penetration scenarios. Based on the solar profile provided by SAPN the periods with high PV utilisation coincides with the min. load periods of the day (12-2PM). Hence, for this assessment a network with min. load is considered.
- From the voltage plots – the voltage fluctuation range for points at the end of the feeder is 4.5%, which is within the required criteria of IEC/TR 61000-3-7:2008 of 3-5%.

d) Potential voltage fluctuations



Appendix C. Feeder Mitigation Result Summaries

FEEDER HH341A - 81 (OLD OVERHEAD) – MITIGATION ANALYSIS

Details

- Norwood – Kensington 11 kV feeder
- 11000/433 V 315 kVA transformer
- Comprised of the following underground cable:
  - 7 / 4.75 AAC (81 m / 2.8%)
  - 7 / 3.75 AAC (473 m / 16.5%)
  - 7 / 16 Cu (44 m / 1.5%)
  - 7/14 Cu (680 m / 23.7%)
  - 4 x 95 ABC (913 m / 31.8%)
  - 0.2 Cu (459 m / 16%)
  - 0.1 Cu (219 m / 7.6%)
- Has one meter point to four distribution legs:
  Leg 1 – 113 m
  Leg 2 – 157 m
  Leg 3 – 297 m
  Leg 4 – 933 m
- 85 customers
- Feeder phase balance (as per load data)
  - Leg 1: Phase A = 35.3% Phase B = 31.1% Phase C = 33.6%
- Distribution of customers across feeder:

	Leg 1 to 4
Customers in %	100 %
Customers	85
3-Phase Customers	25
1-Phase Customers	60
1-Phase A	21
1-Phase B	19
1-Phase C	20

- Max. consumer load assumed = 213.2 kVA (obtained from actual data)

	Leg 1 to 4 [kVA / customer]
3-Phase Customers	2.51
1-Phase A	2.59
1-Phase B	2.39
1-Phase C	2.54

- Min. consumer load = 38.7 kVA (obtained from actual data assuming existing PV utilisation factor of 80%)

	Leg 1 to 4 [kVA / customer]
3-Phase Customers	0.46
1-Phase A	0.47
1-Phase B	0.43
1-Phase C	0.46

- Existing PV penetration = 18.05% or 56.86 kW rated, i.e. 23 customers (assuming a 2.5 kW inverter size)
- Existing customers with controllable load = 32 (38 %)

Mitigation measures

1. Transformer taps

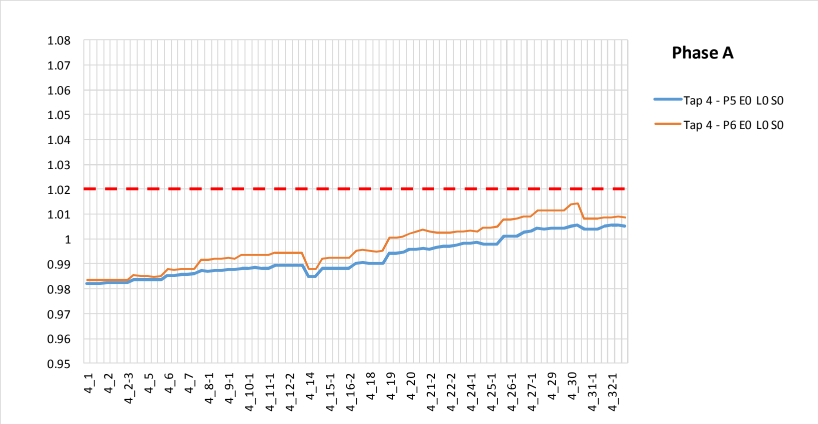
In the original analysis, with the MV/LV transformer at nominal tap (tap 3), overvoltages were observed in Leg 4 (all phases). This section assesses the impact of changing the tap position on the voltage under each the minimum and peak demand scenarios.

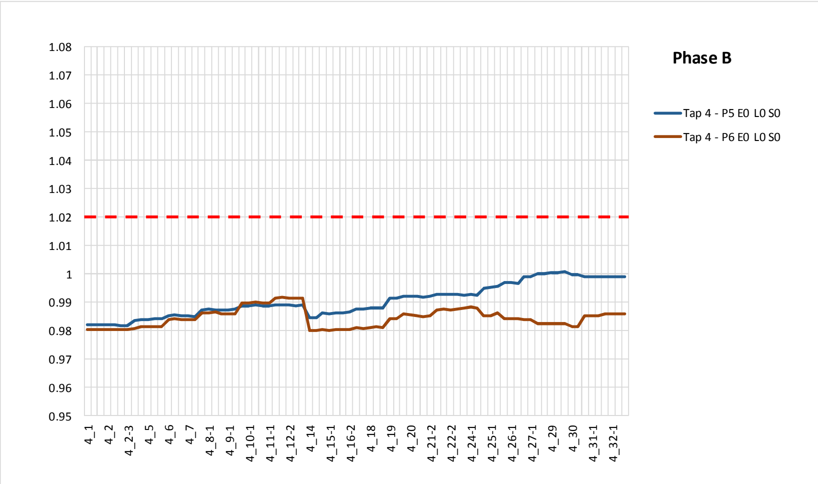
Tap 4

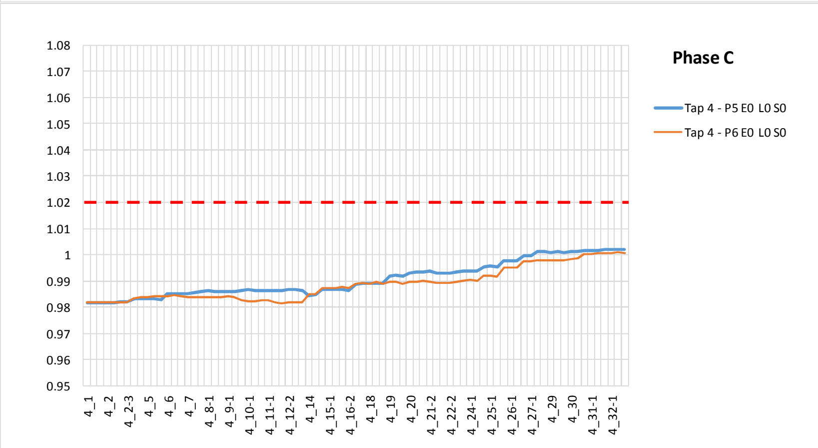
Overvoltage

- To check the worst overvoltage – consider the min. consumer load with the highest PV utilisation factor of 80% for the PV-only DER penetration scenarios. The PV-only DER penetration scenarios are most onerous to overvoltage issues.
- No overvoltages (>1.02 pu) were observed in distribution Leg 4 or any of the other Legs on this feeder.

a) Min. consumer load with 80% PV utilisation factor



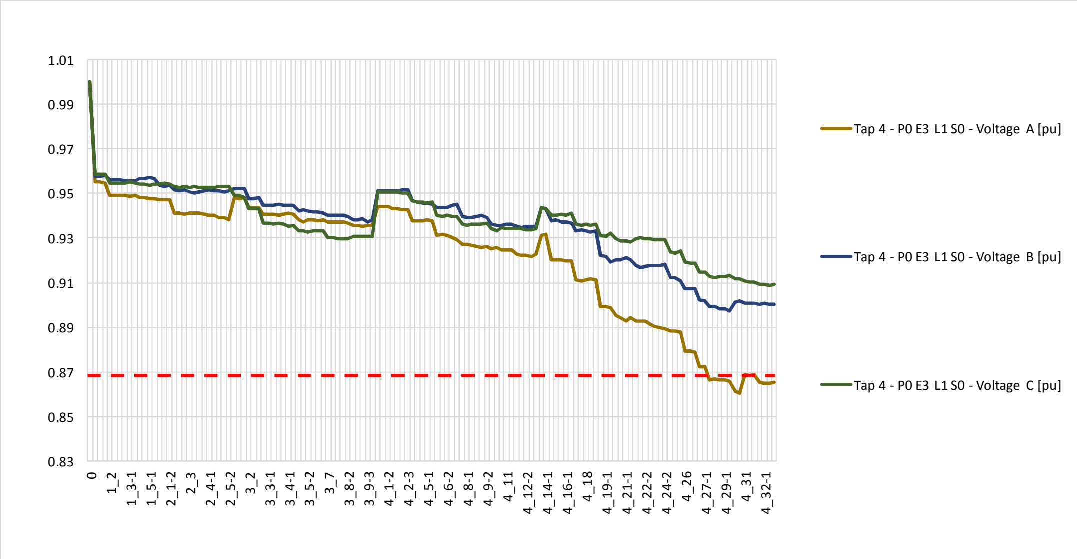




Undervoltage

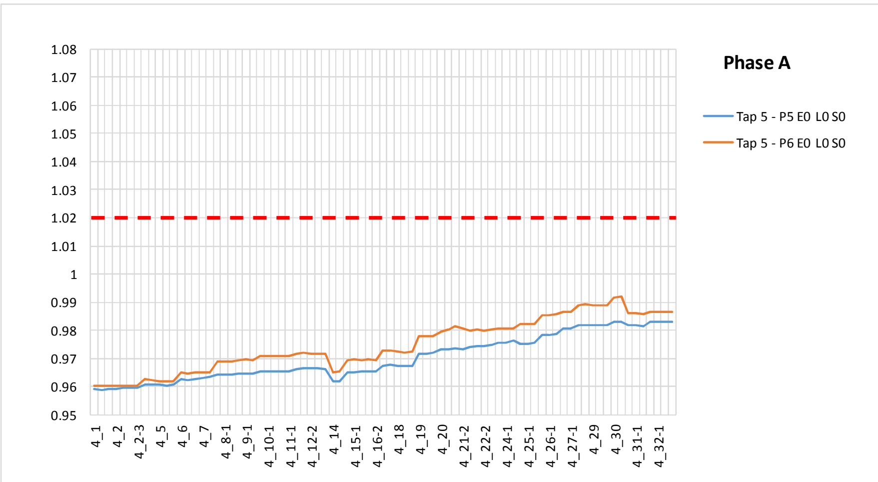
- To check the worst undervoltage – consider the max. consumer load with the lowest PV utilisation factor of 20%.
- Undervoltages (<0.87pu) were observed for Tap 4 Phase under P0E3L1S0.

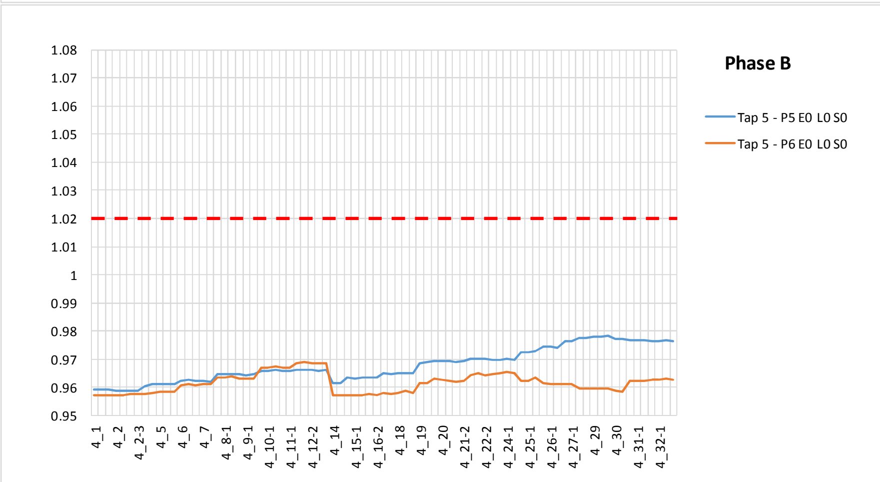
b) Max. consumer load with 20% PV utilisation factor

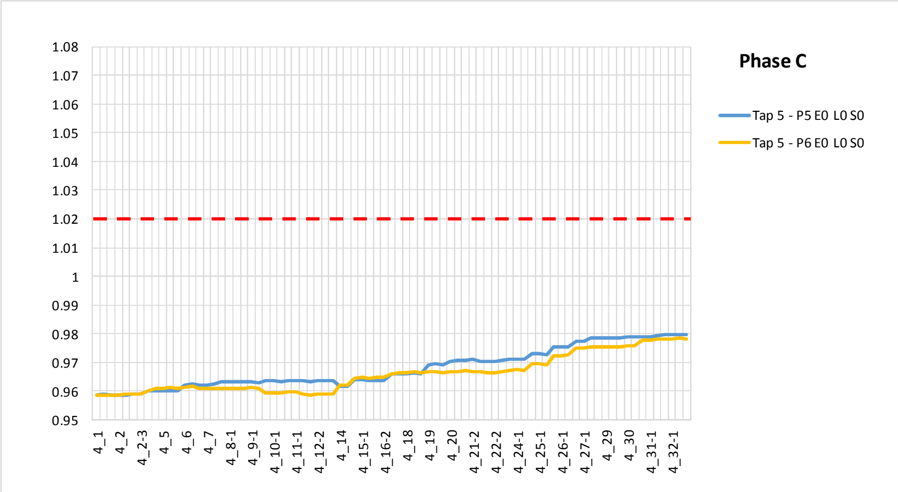


Tap 5
Overvoltage

- No overvoltages (>1.02 pu) were observed in distribution Leg 4 or any of the other Legs on this feeder.

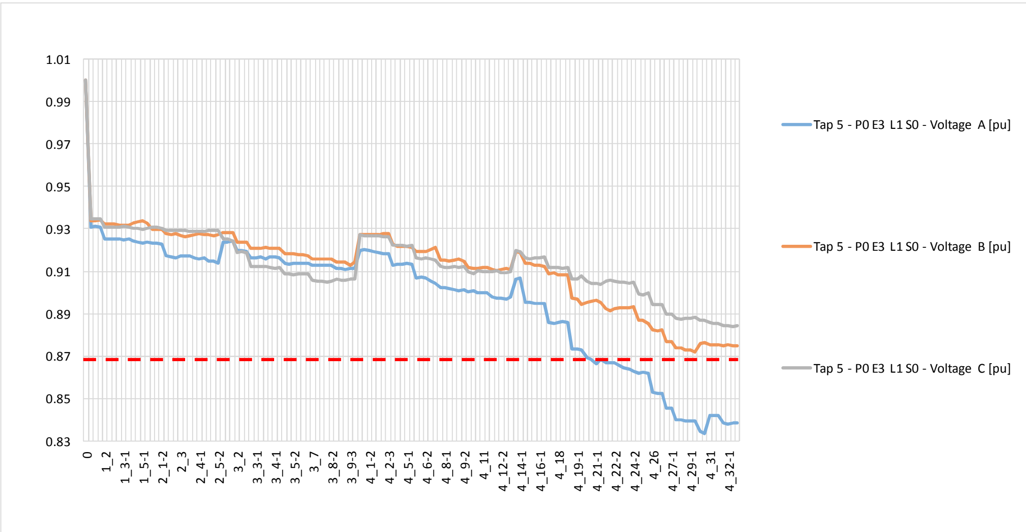






Undervoltage

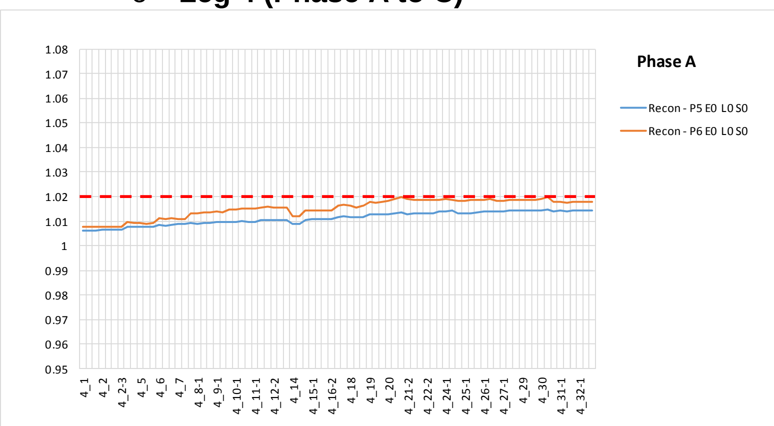
- Undervoltages (<0.87pu) were observed under Tap 5 Phase A under P0E3L1S0.

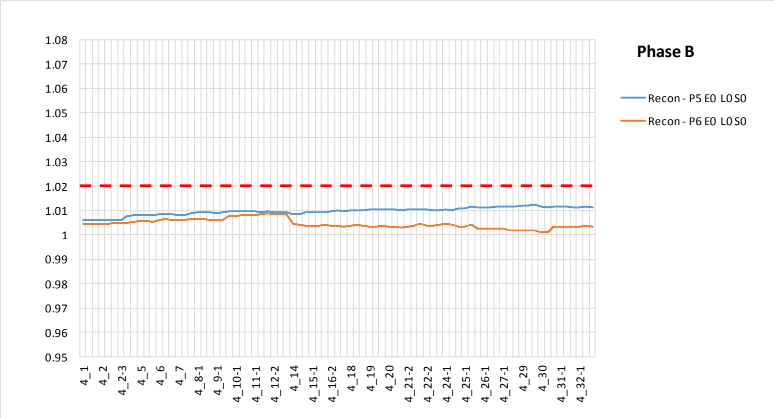


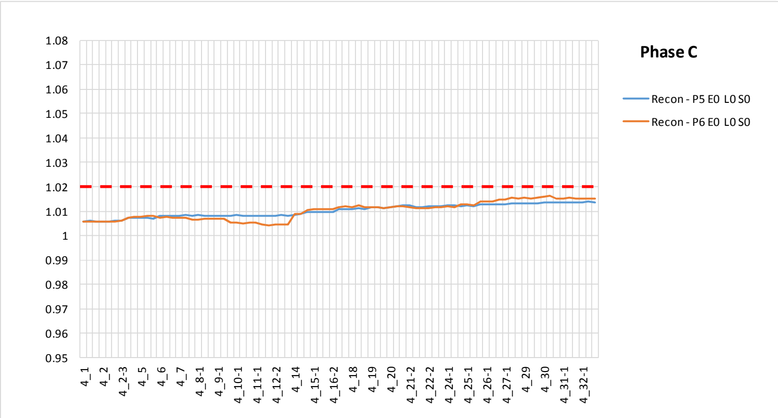
2. Reconductor feeder backbone

This section assesses the impact of changing the feeder backbone conductor type on the voltage under minimum and peak demand scenarios. The conductor type on the feeder backbone has been changed to 0.2 Cu.

- No overvoltages (>1.02 pu) were observed in distribution Leg 4 or any of the other Legs on this feeder.
    - **Leg 4 (Phase A to C)**

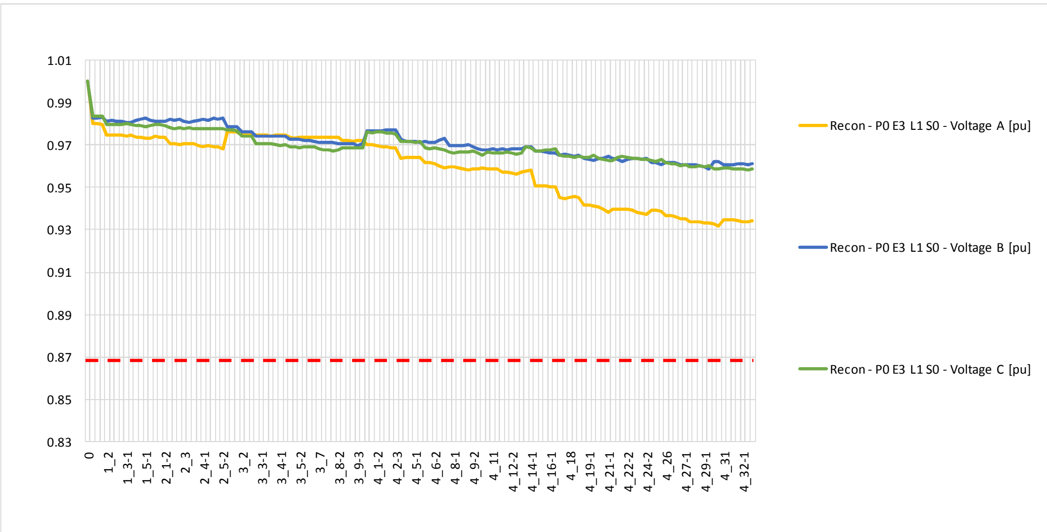






Undervoltage

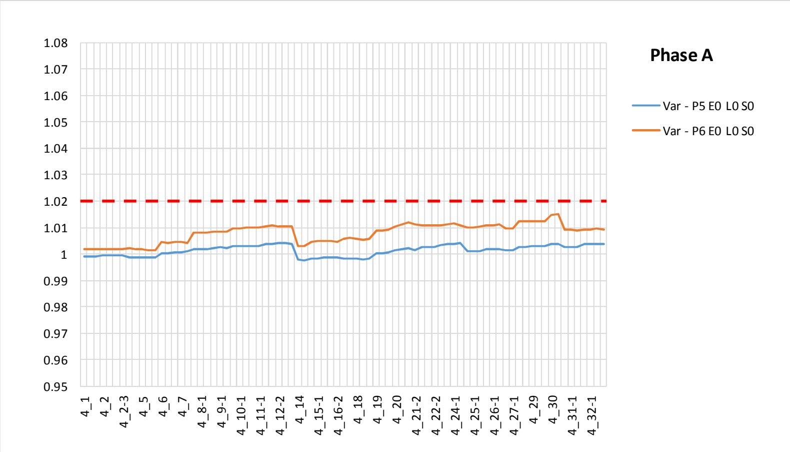
- No undervoltages (<0.87pu) were observed under reconductoring.

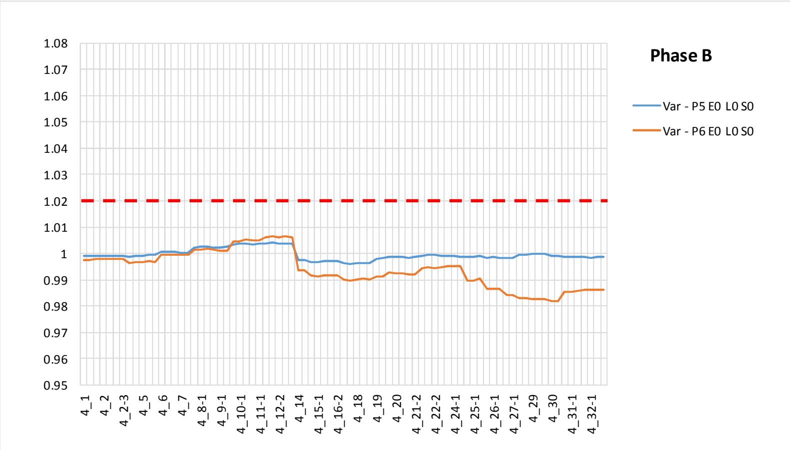


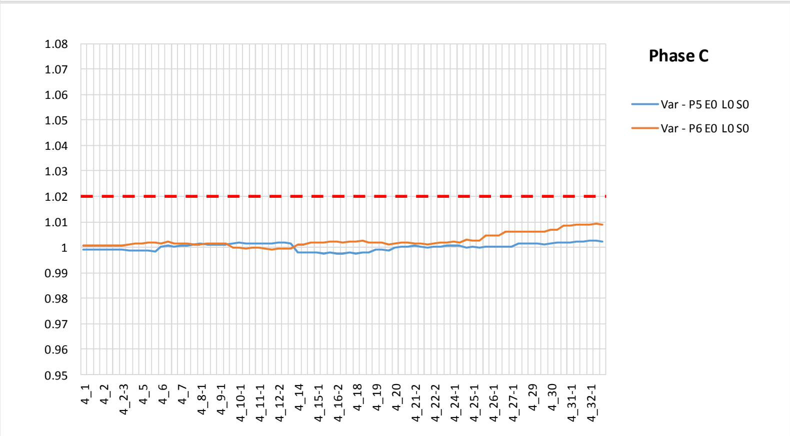
3. Dynamic VAr Support

This section assesses the impact of dynamic VAr support on the voltage under a minimum demand scenario. The amount of var support required to reduce the overvoltages on distribution Leg 4 as well as the resulting voltage profiles are given below:

- Leg 4 – 24 kVAr





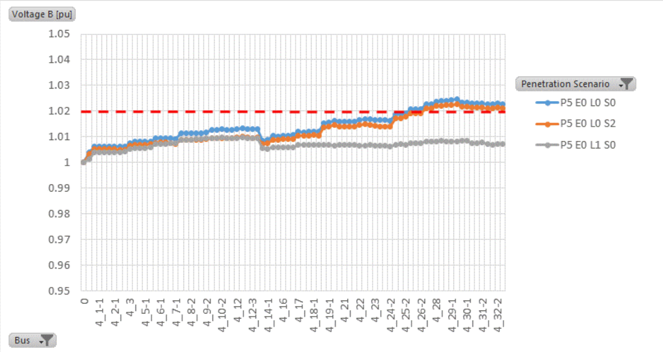


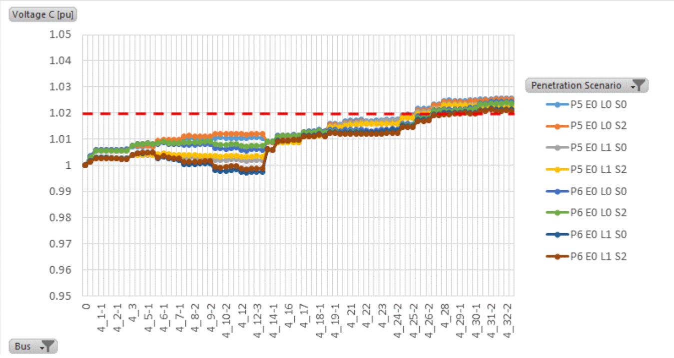
4. Controllable load and storage

Since there is an overvoltage issue on this feeder, the controllable load measures that may assist in mitigation are controlled hot water load and battery storage (in charging mode i.e. operating as a load rather than as a source).

- In Leg 4, the Phase A boundary penetration scenario before overvoltages occur is P3. The controllable loads (L1) could be switched on to increase PV penetration to P4, P5 or P6 while maintaining voltage within limits. Connecting the storage loads (S2) alone is insufficient to maintain the voltage within limits.
- In Leg 4, the Phase B overvoltages occur under the P5 penetration scenario. The controllable loads (L1) could be switched on to resolve the issues. Connecting the storage loads (S2) alone is insufficient to keep the voltage within limit.
- In Leg 4, the Phase C boundary penetration scenario before overvoltages occur is P4. Both the controllable loads (L1) and storage (S2) are required to be switched on to increase PV penetration to P5 or P6, resulting in only marginal overvoltages. The overvoltages cannot be resolved completely in this phase.

- Leg 4 (Phase A to C) with CL and ST to control overvoltages

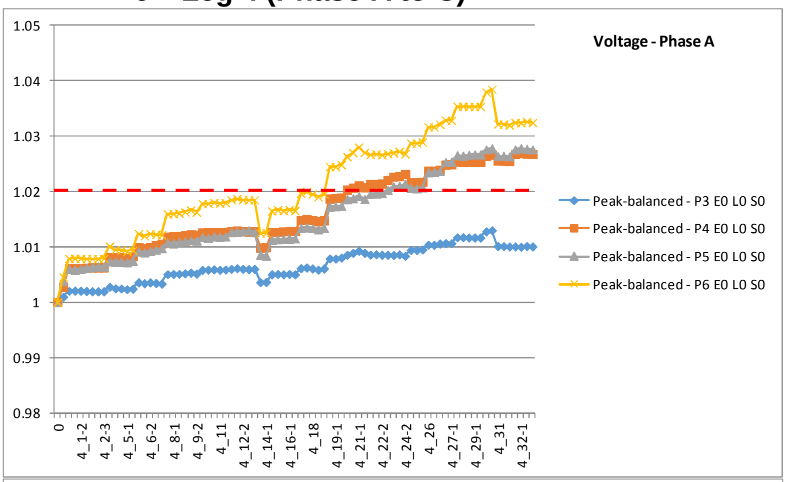


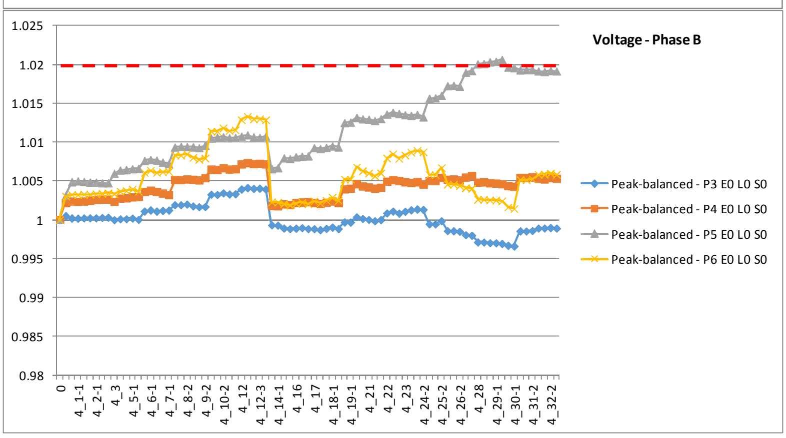


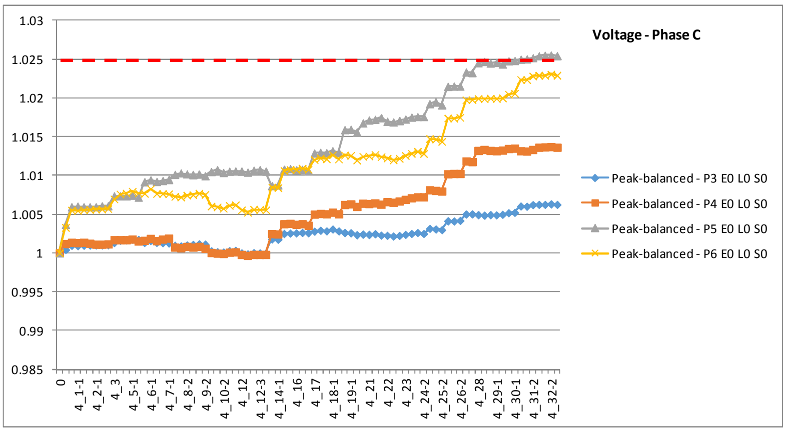
5. Feeder load balancing

This section assesses the impact of balancing the feeder load on the voltage under minimum and peak demand scenarios. The load was distributed as evenly as possible across each of the phases for each of the feeder distribution legs.

- Leg 4 (Phase A to C)



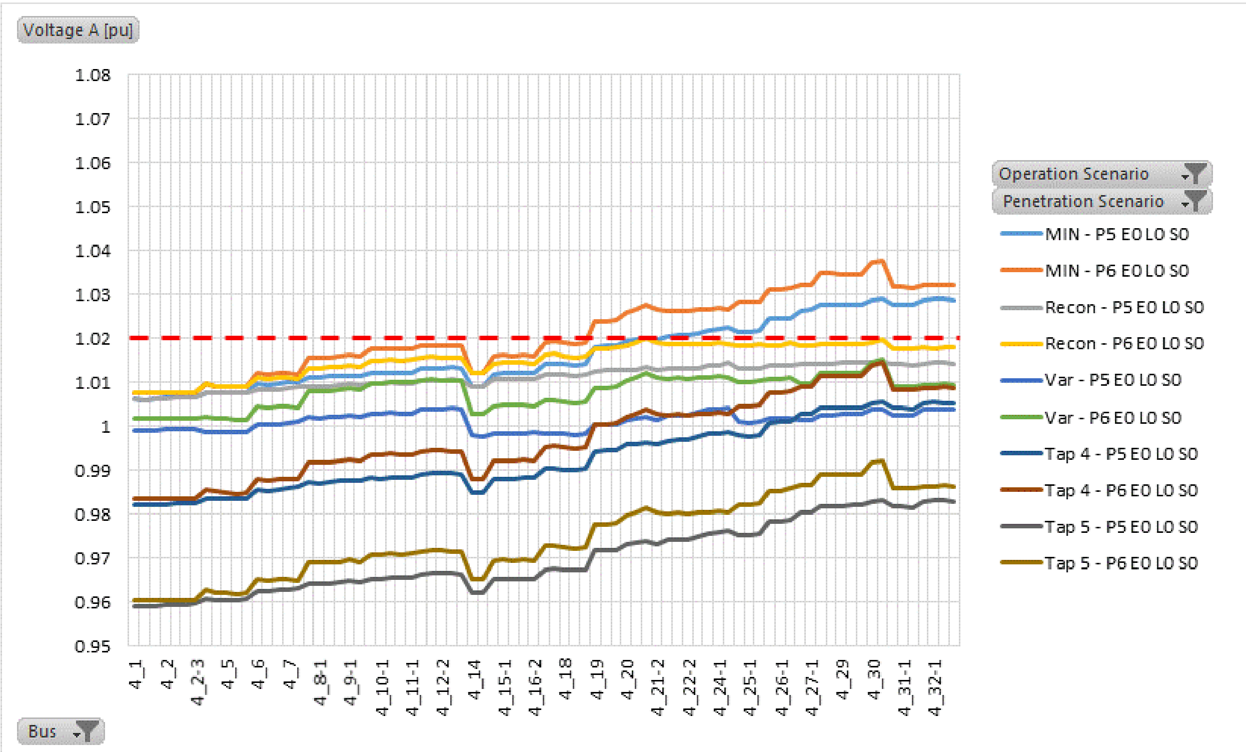




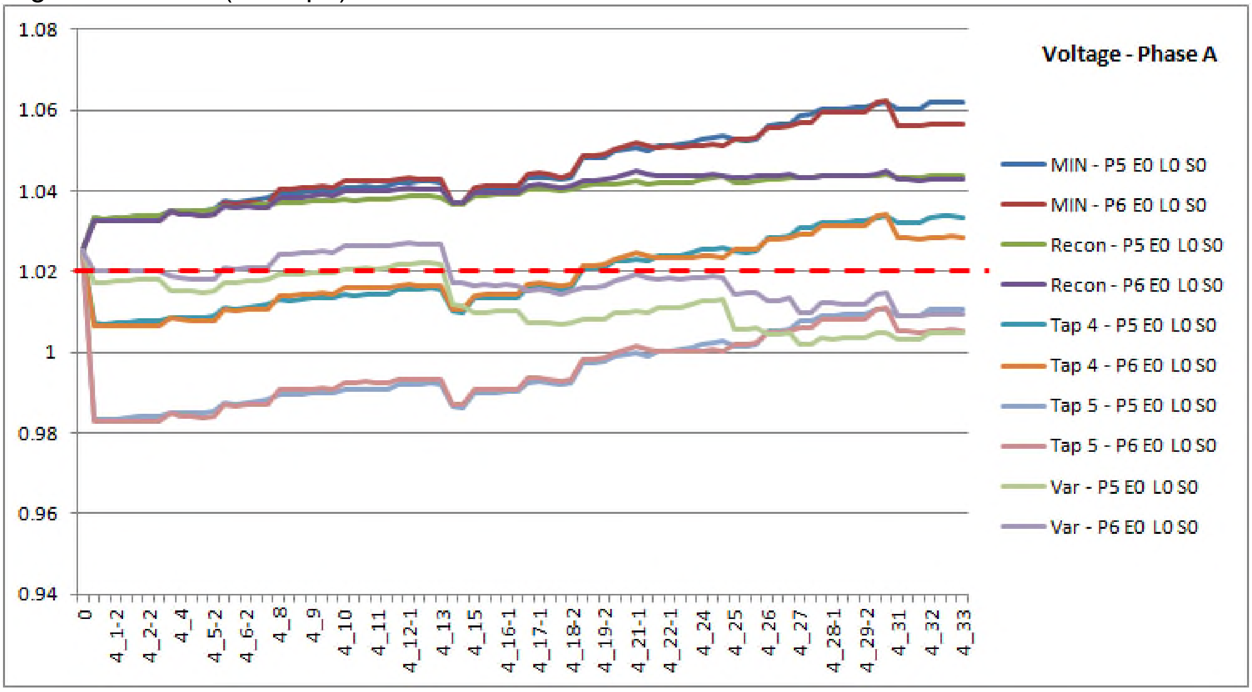
Aggregated results

The graphs below summarise all the mitigation measures investigated and the impact they have on each phase of distribution Leg 4 of the feeder under a minimum demand scenario. The results are shown for each of the assumed MV voltages of 1 pu, 1.025 pu and 0.975 pu.

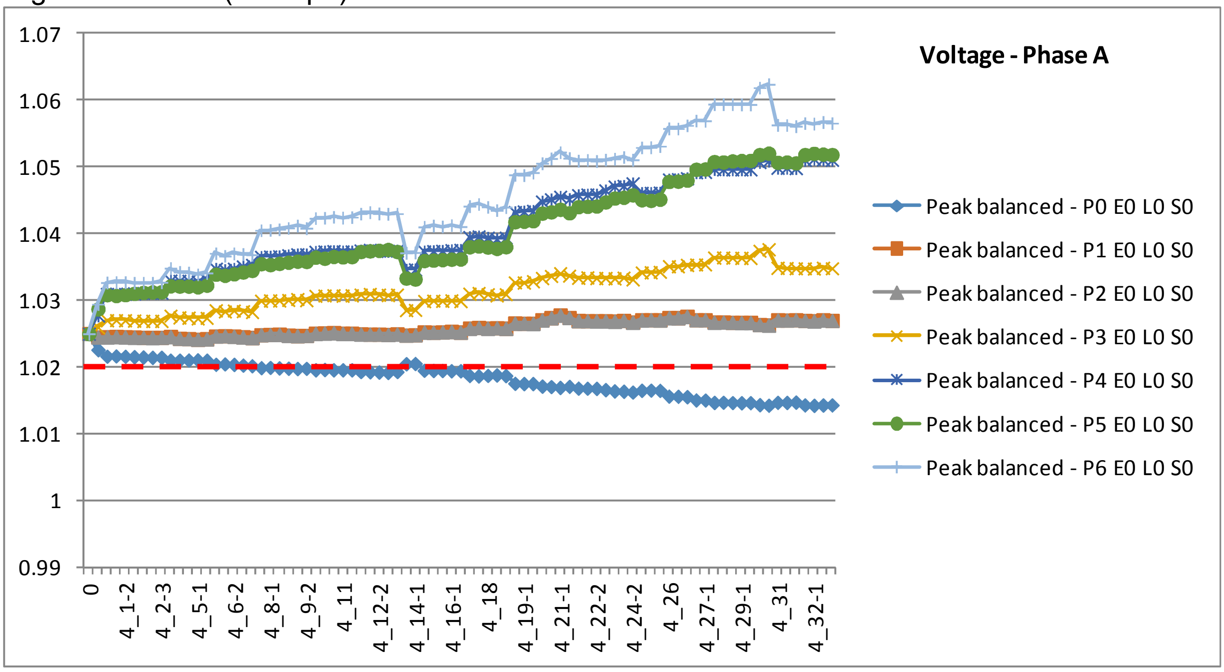
Leg 4 – Phase A



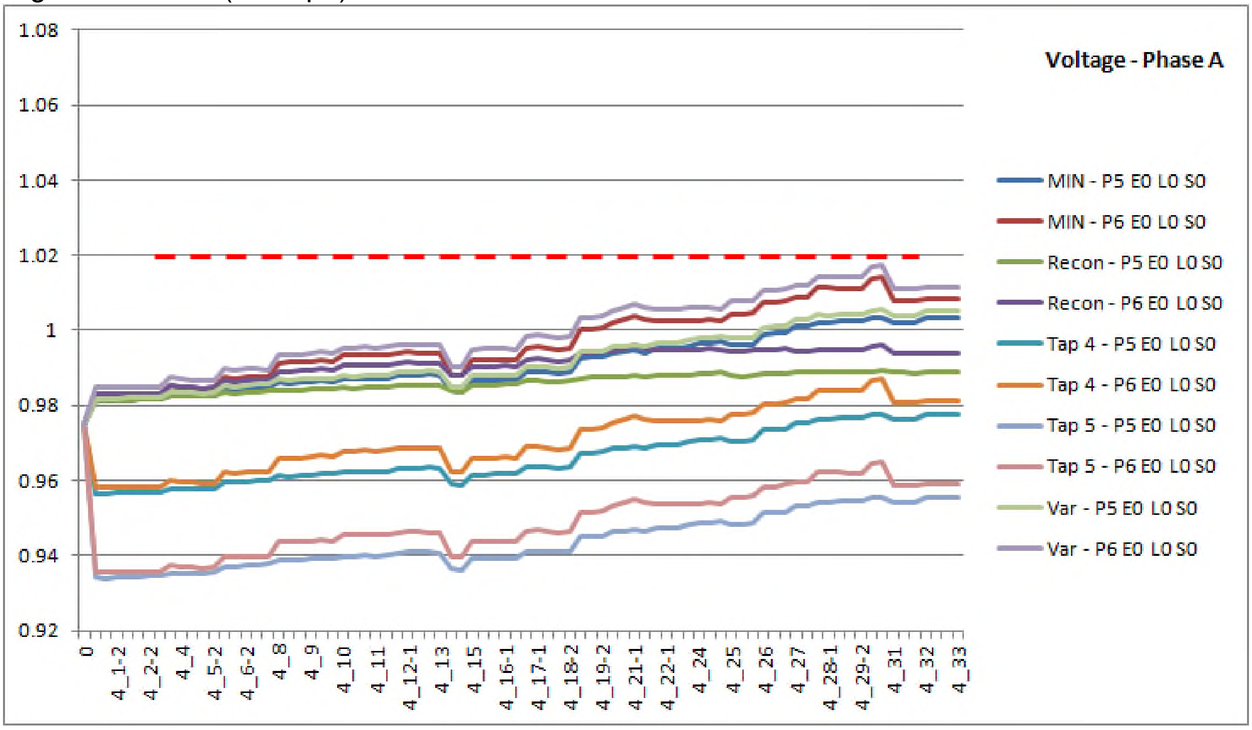
Leg 4 – Phase A (1.025pu)



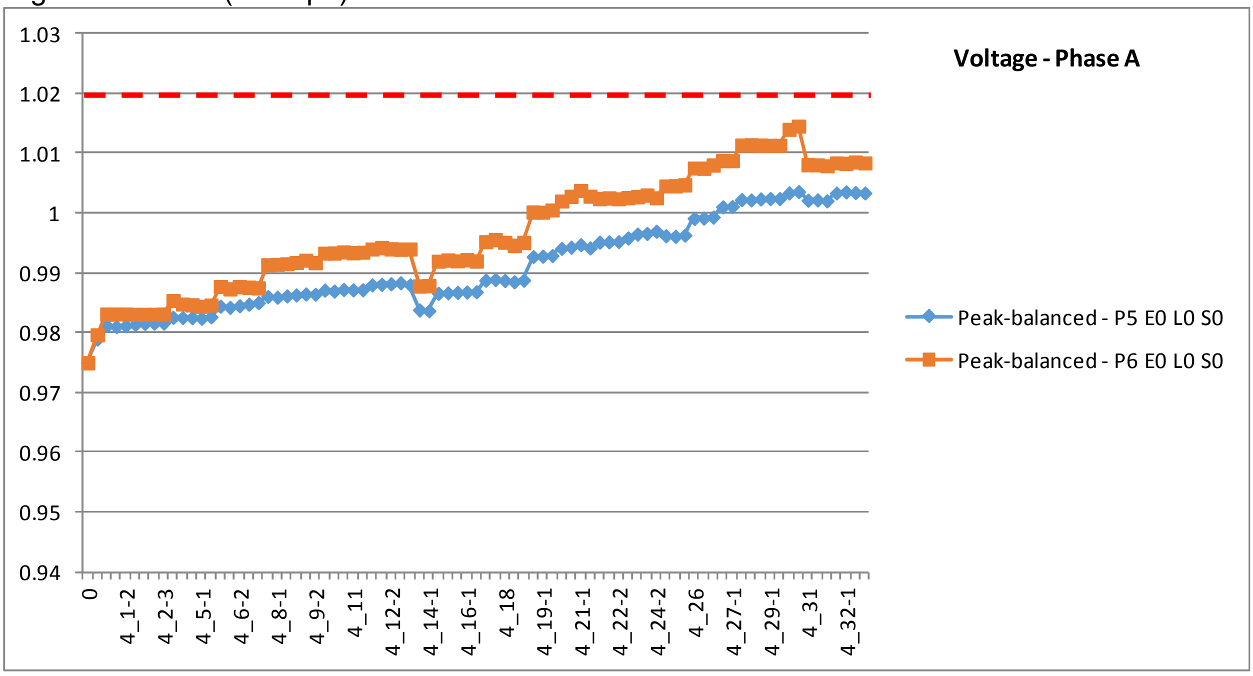
Leg 4 – Phase A (1.025pu) – feeder balanced load



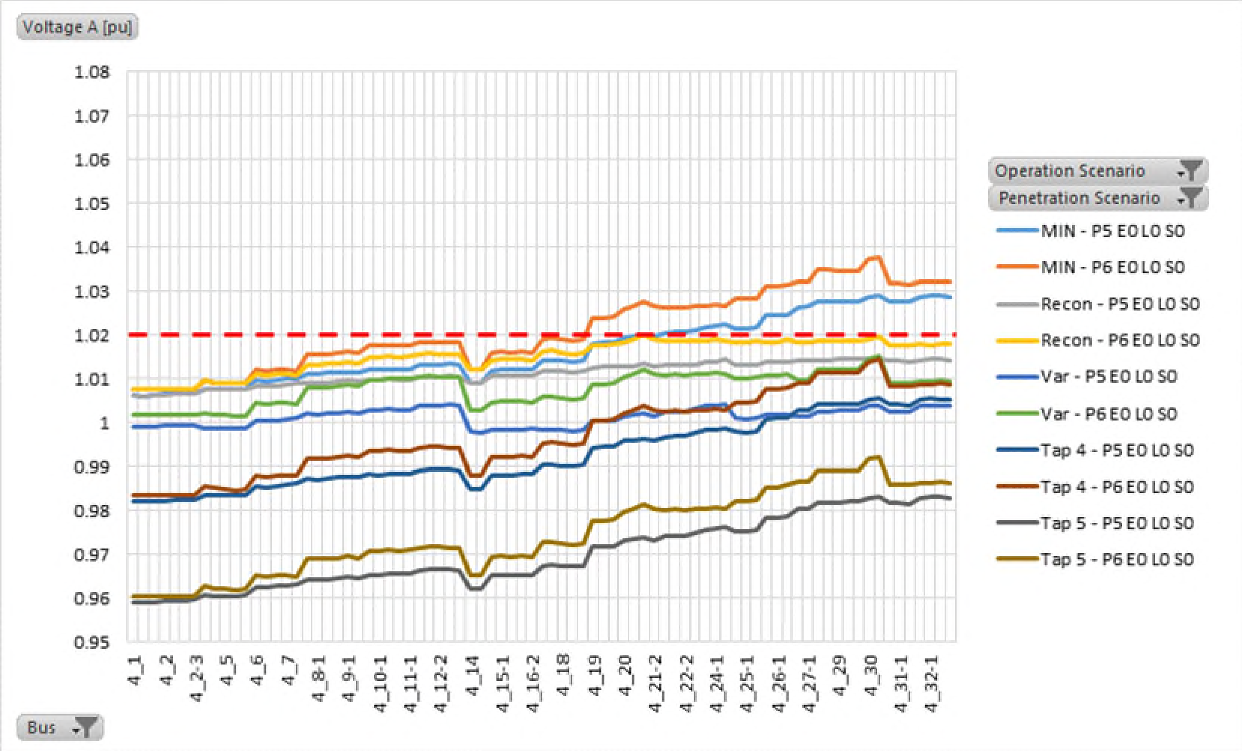
Leg 4 – Phase A (0.975pu)



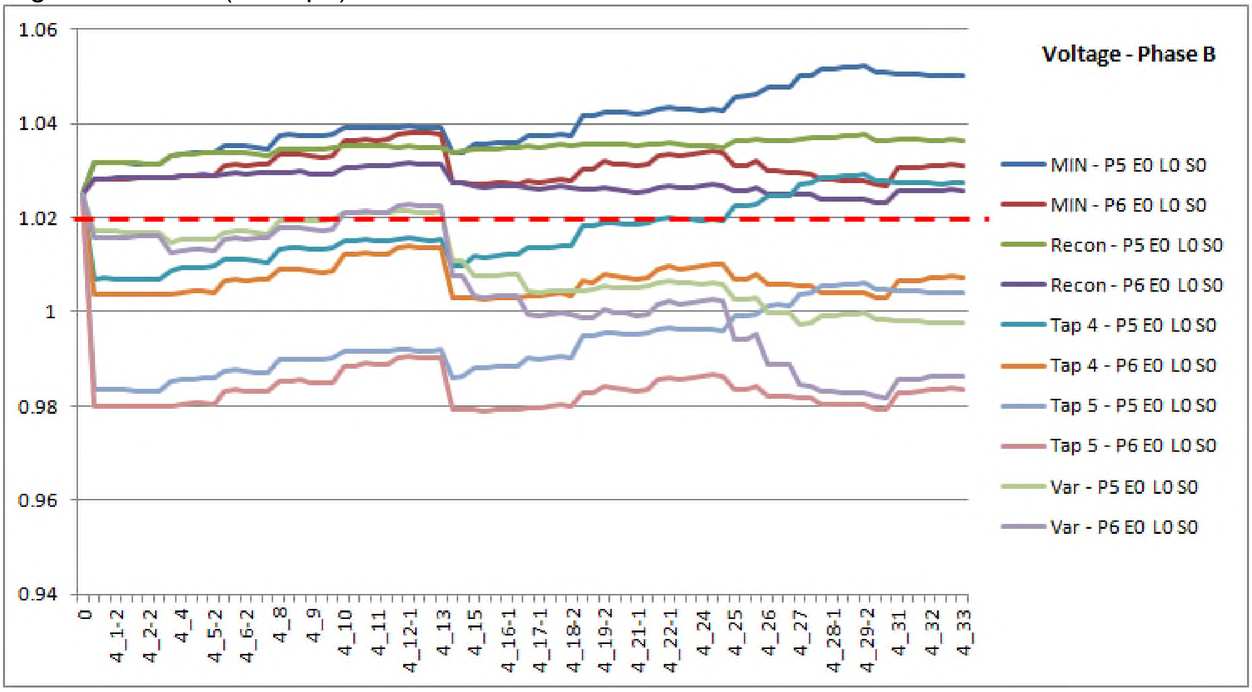
Leg 4 – Phase A (0.975pu) – feeder balanced load



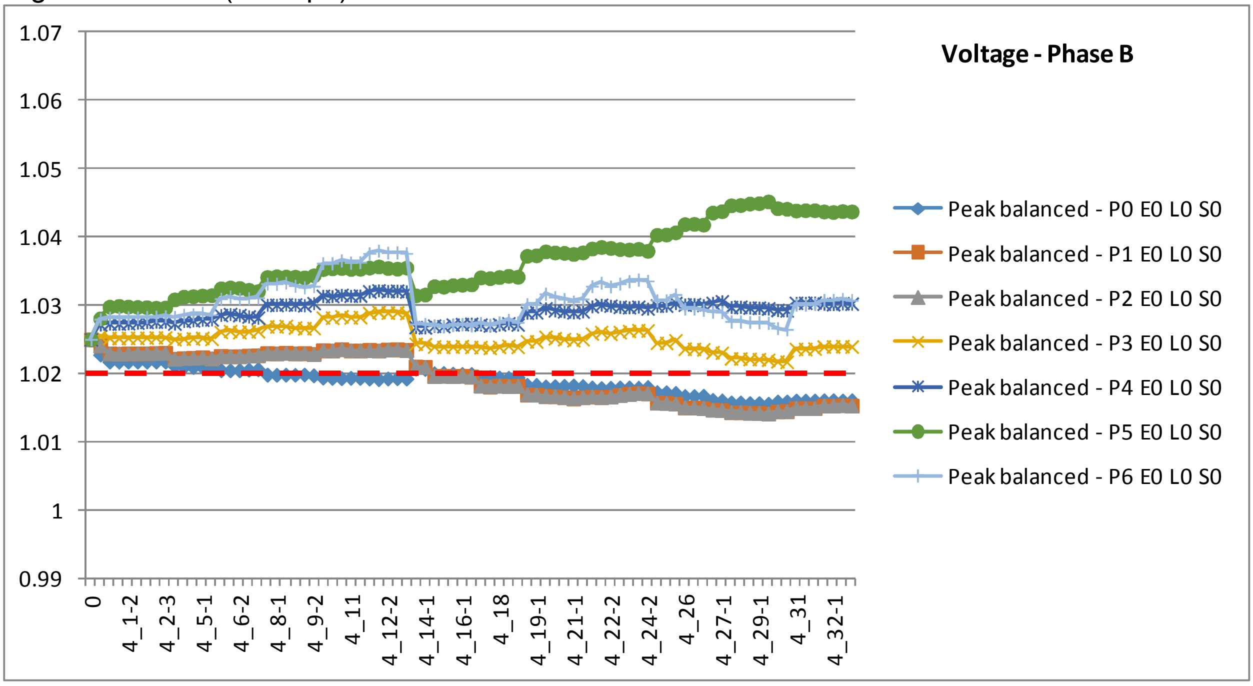
Leg 4 – Phase B



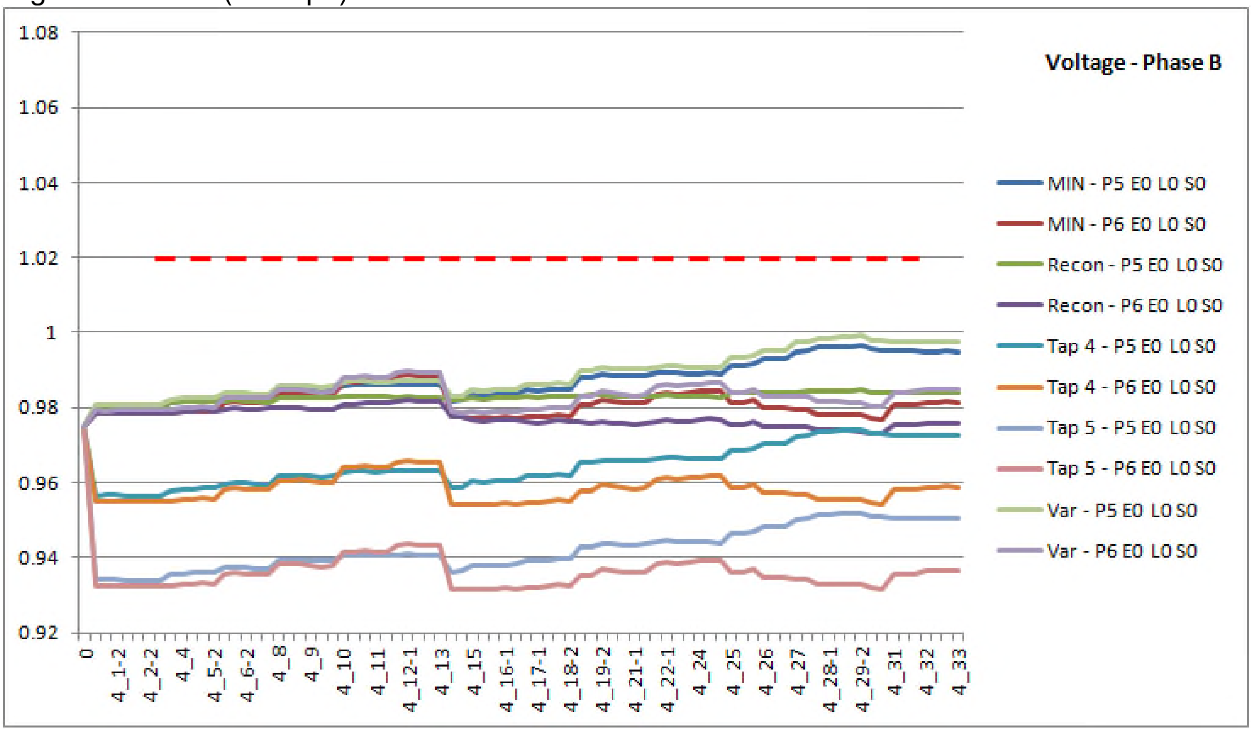
Leg 4 – Phase B (1.025pu)



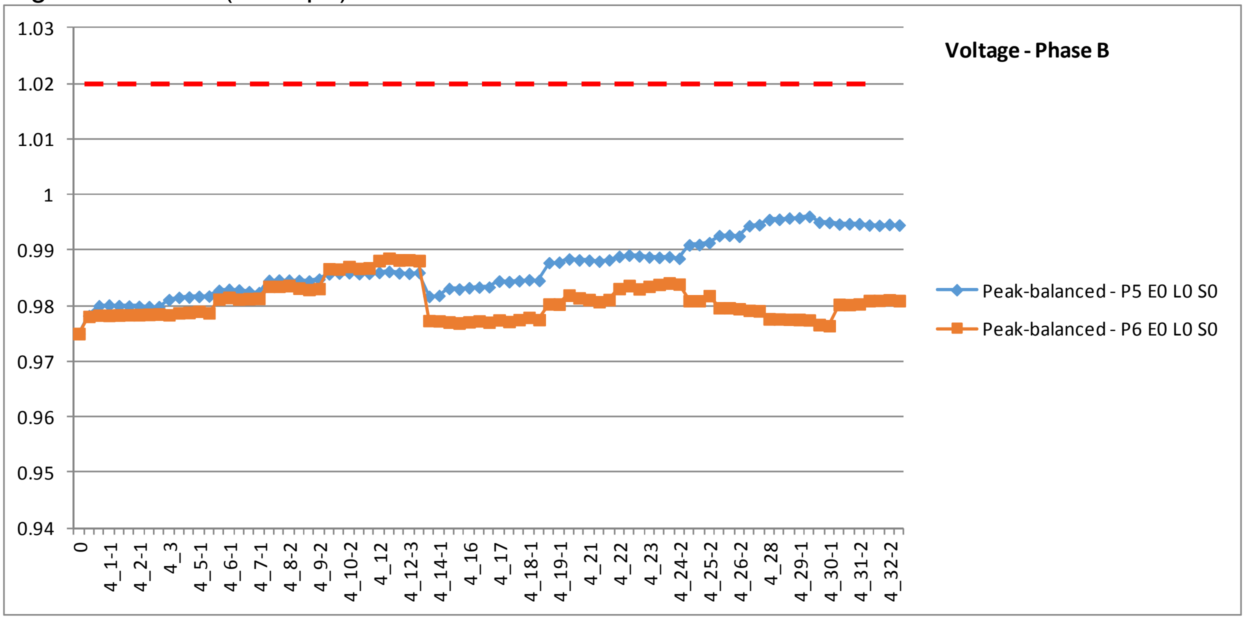
Leg 4 – Phase B (1.025pu) – feeder balanced load



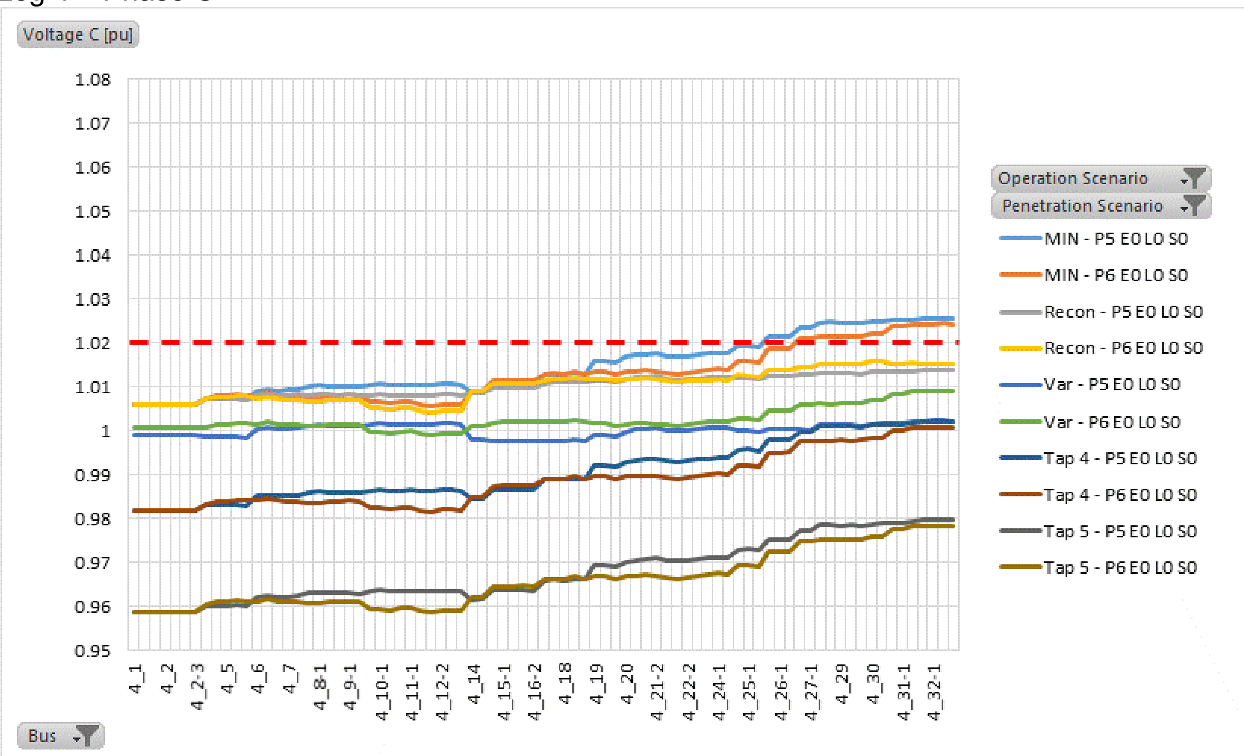
Leg 4 – Phase B (0.975pu)



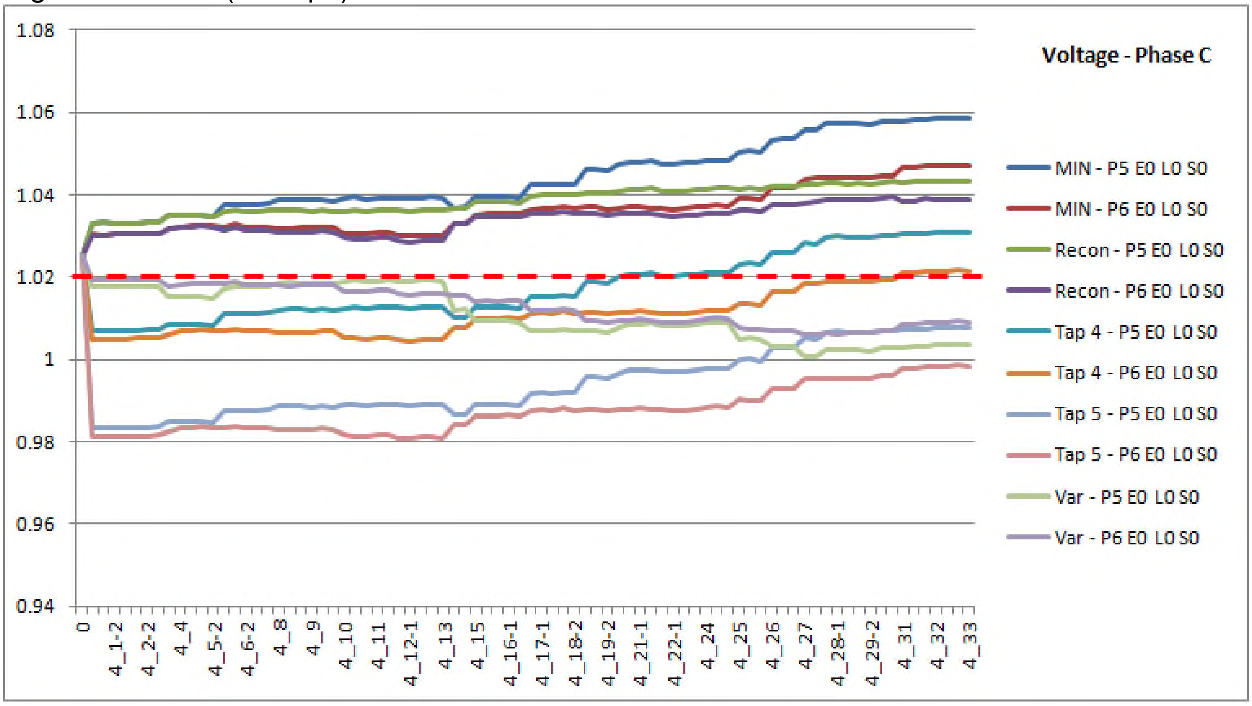
Leg 4 – Phase B (0.975pu) – feeder balanced load



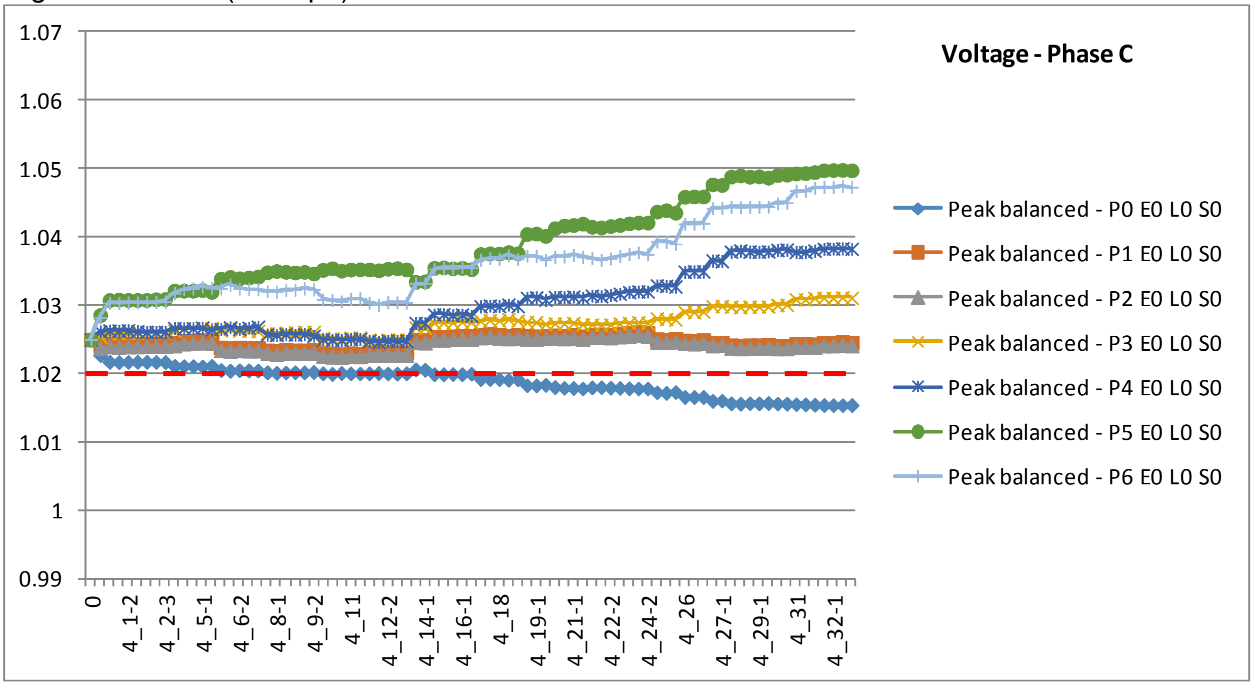
Leg 4 – Phase C



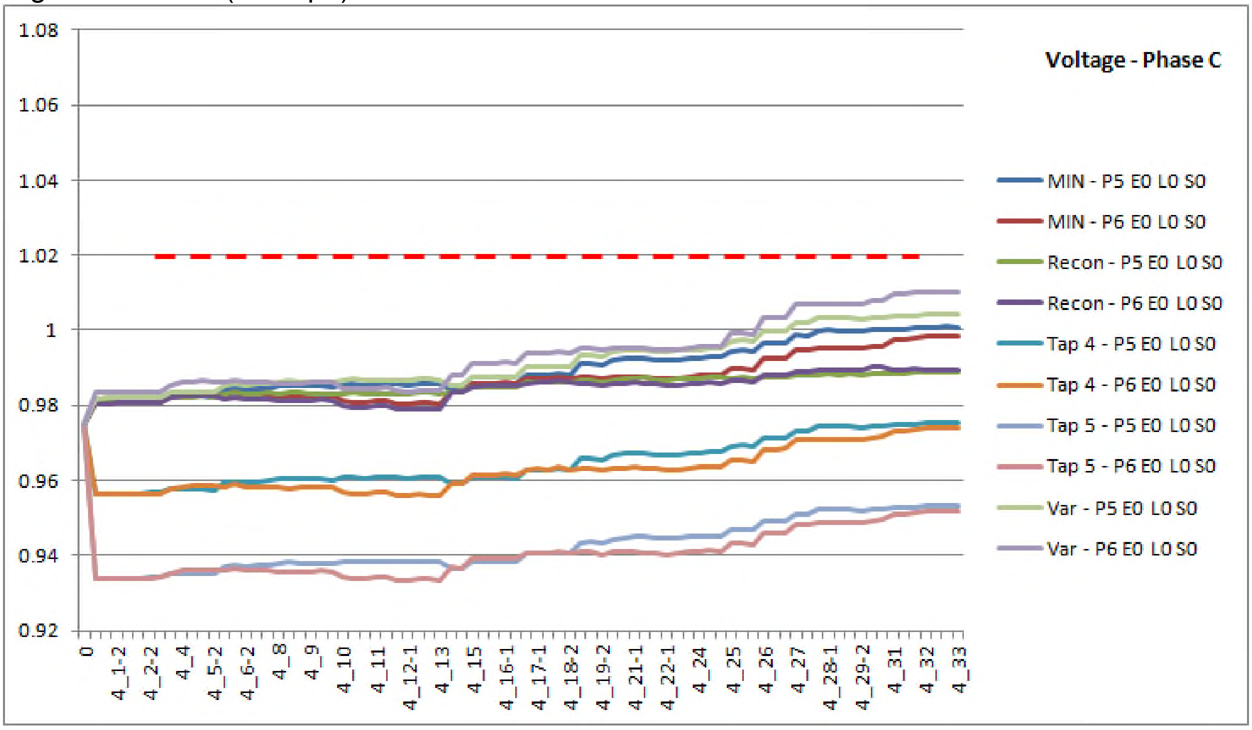
Leg 4 – Phase C (1.025pu)



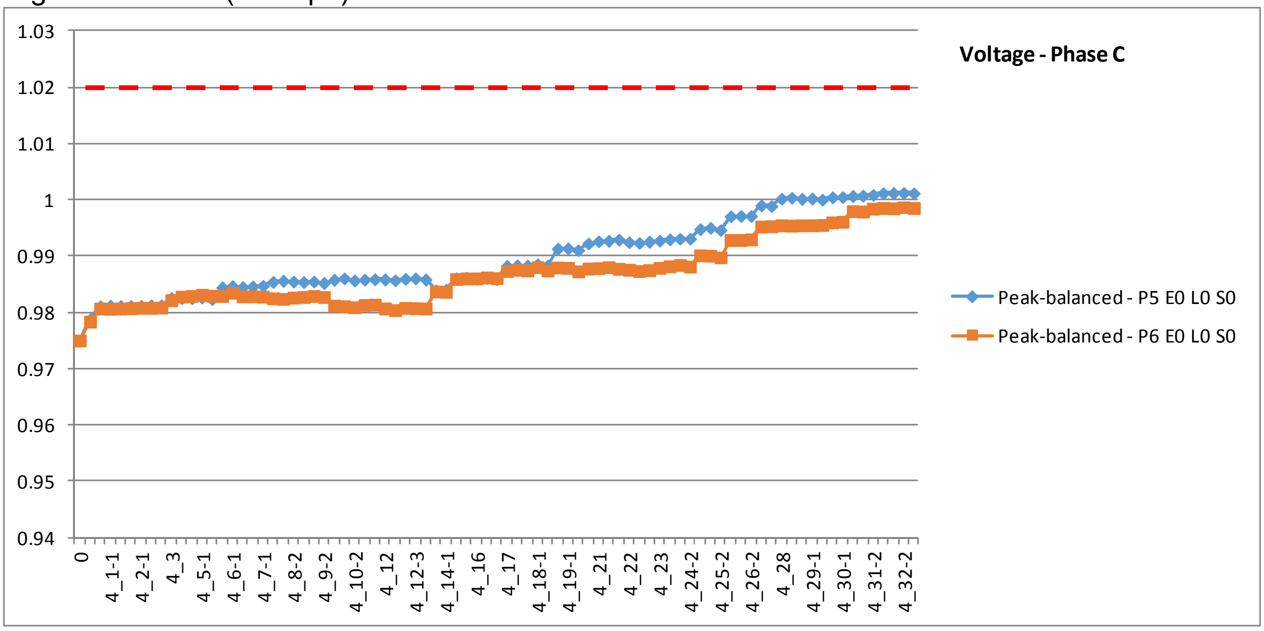
Leg 4 – Phase C (1.025pu) – feeder balanced load



Leg 4 – Phase C (0.975pu)

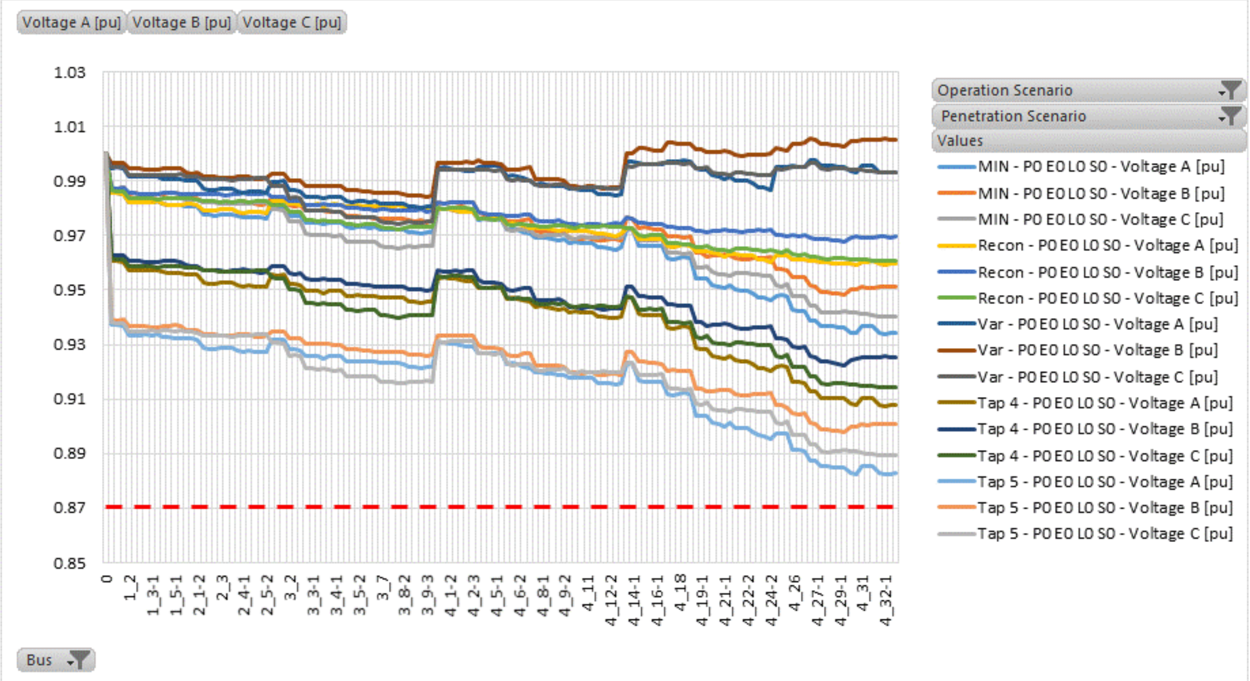


Leg 4 – Phase C (0.975pu) – feeder balanced load

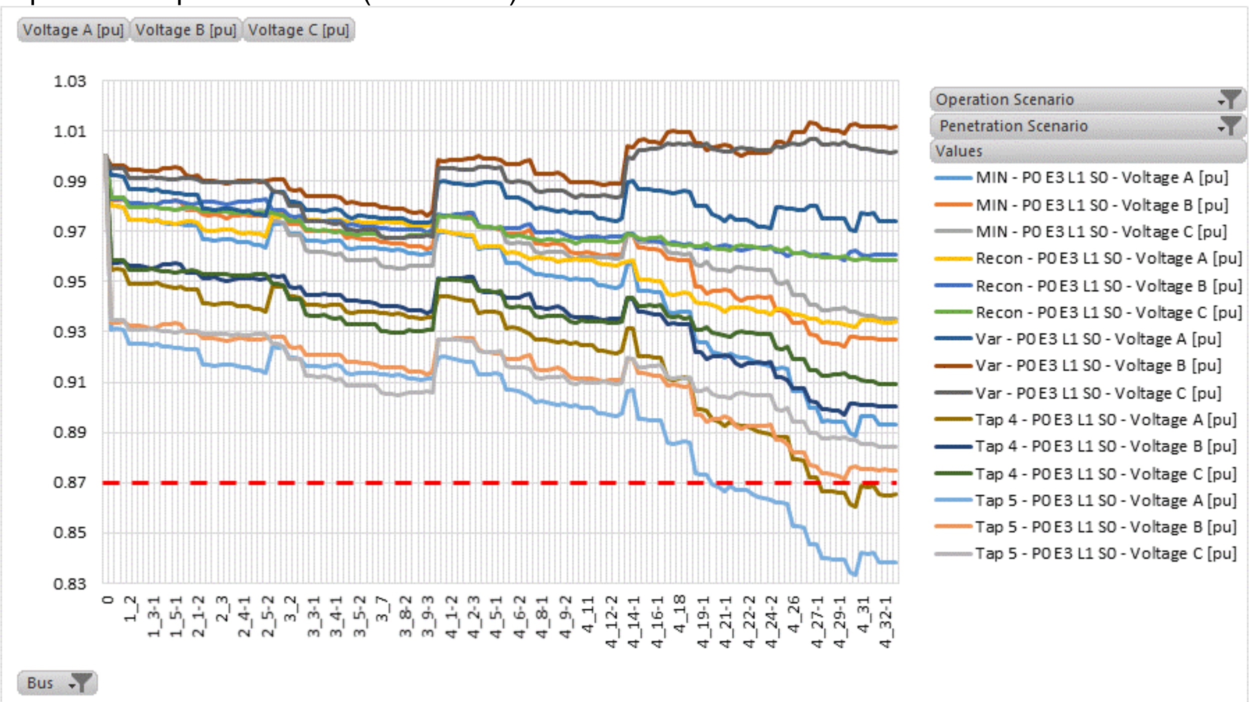


The graphs below summarise all the mitigation measures investigated and the impact they have on the worst phase of each distribution Leg on the feeder under a peak demand scenario, with and without DERs.

Impact under peak demand



Impact under peak demand (with DERs)



FEEDER EL14-TC54743 (OLD UNDERGROUND) – MITIGATION ANALYSIS

Details

- Elizabeth Downs – JK Cable Elizabeth Downs 11 kV feeder
- 11000/433 V 300 kVA transformer
- Comprised of the following underground cable:
  - XLPE AL 150 mm^2 OR 37 / 0.093 XLPE (218 m / 8.5%)
  - XLPE AL 35 mm^2 OR 19 / 0.064 XLPE (79 m / 3.1%)
  - Cable PVC Cu 0.06 sq inch (955 m / 37.5%)
  - Cable PVC Cu 0.0225 sq inch (1294 m / 83.5%)
- Has three metering points to three distribution legs:
  - Leg 1 – Pit East, Heath Court (575 m)
  - Leg 2 – No. 4 Brixton (349 m)
  - Leg 3 – No.14 Brixton (581 m)
- 48 customers
- Feeder phase balance (as per load data)
  - Leg 1: Phase A = 46.8% Phase B = 22.2% Phase C = 30.9%
  - Leg 2: Phase A = 37.6% Phase B = 33.2% Phase C = 29.3%
  - Leg 3: Phase A = 44.9% Phase B = 34% Phase C = 21.1%
- Distribution of customers across feeder:

	Leg 1	Leg 2	Leg 3
Customers in %	39.6 %	33.3 %	27.1 %
Customers	19	16	13
3-Phase Customers	6	5	4
1-Phase Customers	13	11	9
1-Phase A	6	4	4
1-Phase B	3	4	3
1-Phase C	4	3	2

- Max. consumer load assumed = 101 kVA (obtained from actual data)

	Leg 1 [kVA / customer]	Leg 2 [kVA / customer]	Leg 3 [kVA / customer]
3-Phase Customers	2.61	1.66	1.92
1-Phase A	2.99	1.80	2.17
1-Phase B	1.93	1.51	1.98
1-Phase C	2.53	1.67	1.35

- Min. consumer load = 16.9 kVA (obtained from actual data assuming existing PV utilisation factor of 80%)

	Leg 1 [kVA / customer]	Leg 2 [kVA / customer]	Leg 3 [kVA / customer]
3-Phase Customers	0.44	0.28	0.32
1-Phase A	0.50	0.30	0.36
1-Phase B	0.32	0.25	0.33
1-Phase C	0.42	0.28	0.23

- Existing PV penetration = 4.23 % or 12.7 kW rated, i.e 5 customers (assuming a 2.5 kW inverter size)
- Existing customers with controllable load = 48 (100 %)

Mitigation measures

1. Transformer taps

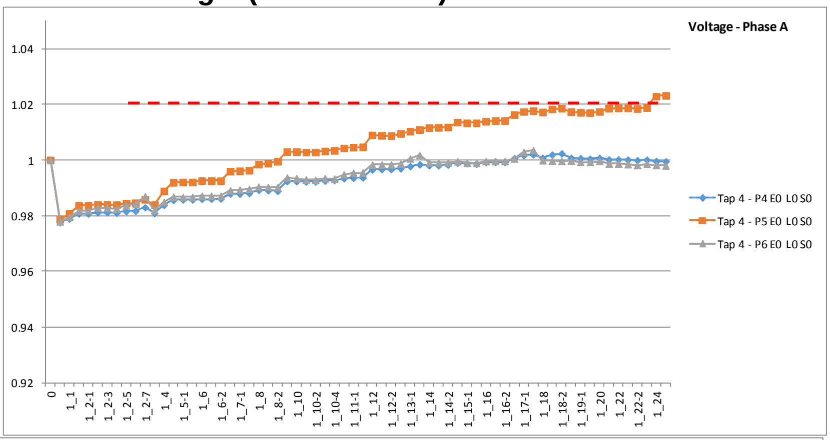
In the original analysis, with the MV/LV transformer at nominal tap (tap 3), overvoltages were observed in Leg 1 (phases A and C), Leg 2 (phase B) and Leg 3 (all phases). This section assesses the impact of changing the tap position on the voltage under minimum and peak demand scenarios.

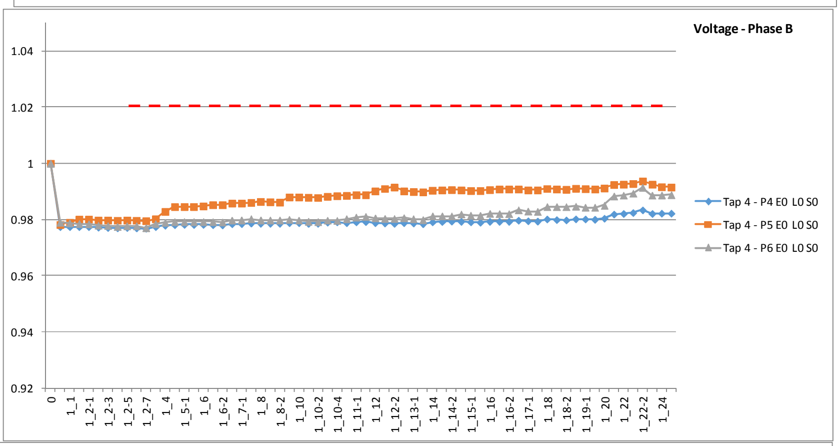
Tap 4

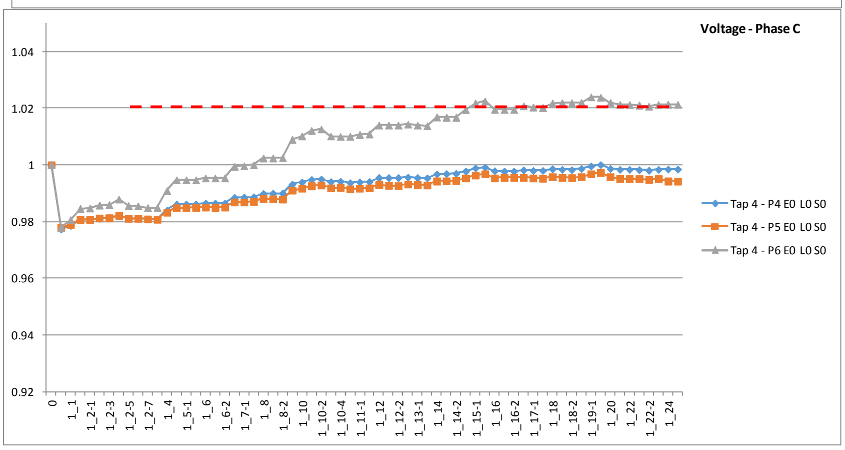
Overvoltage

- To check the worst overvoltage – consider the min. consumer load with the highest PV utilisation factor of 80% for the PV-only DER penetration scenarios. The PV-only DER penetration scenarios are most onerous for overvoltage issues.
- Overvoltages (>1.02 pu) were observed in Phase C of distribution Leg 1, Phase B of distribution Leg 2 and Phase B of distribution Leg 3.
- Highest overvoltages observed:
  Leg 1 – Phase C: 1.025 pu (P6E0L0S0)
  Leg 2 – Phase B: 1.047 pu (P6E0L0S0)
  Leg 3 – Phase B: 1.03 pu (P6E0L0S0)

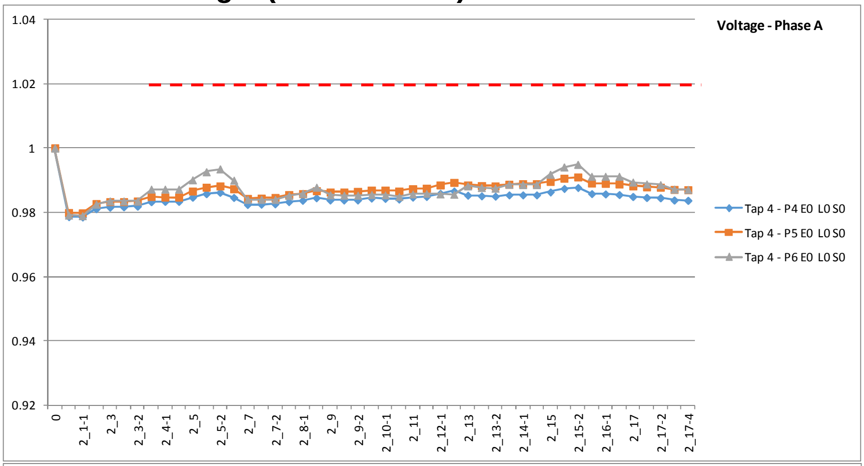
  - **Leg 1 (Phase A to C)**

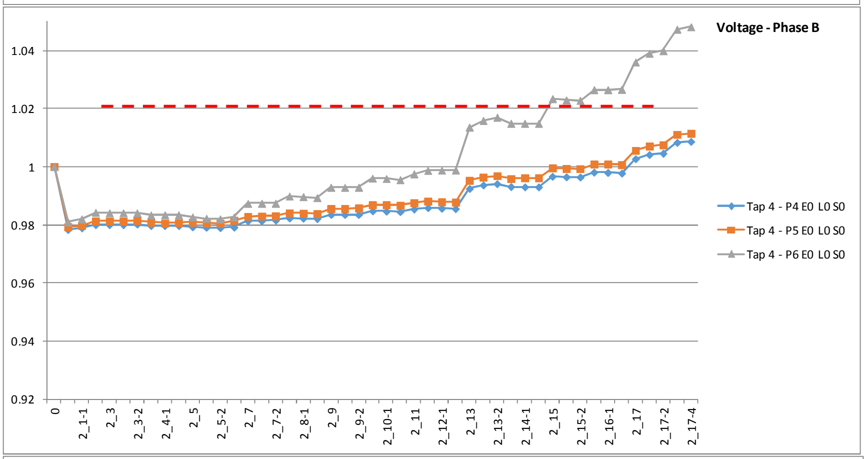


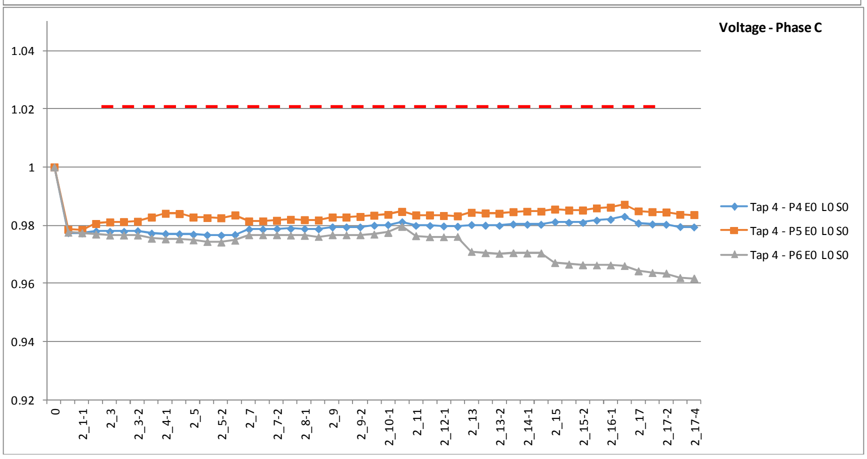




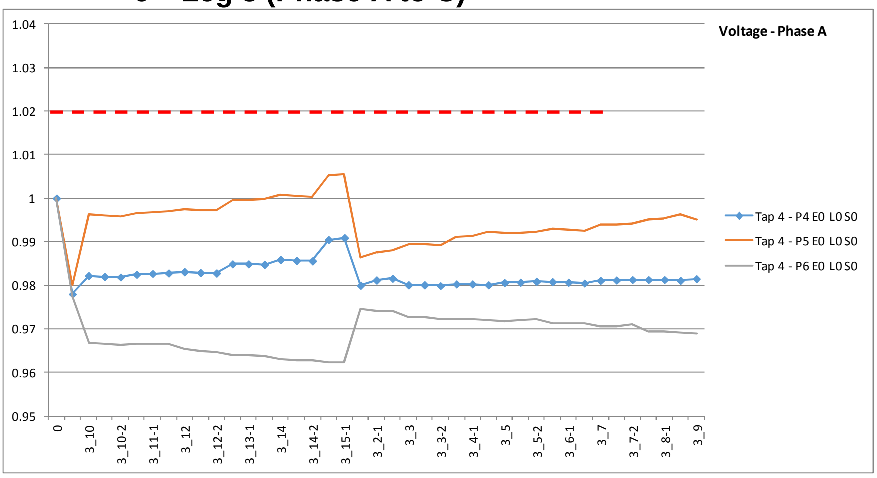
- o **Leg 2 (Phase A to C)**

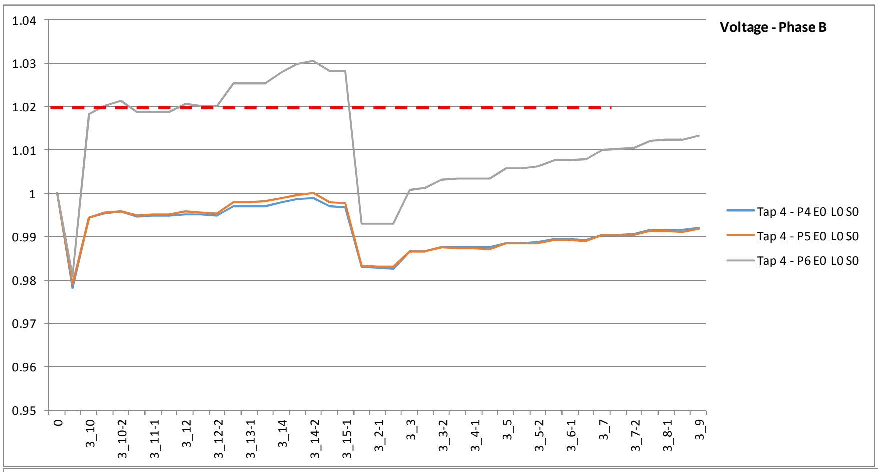


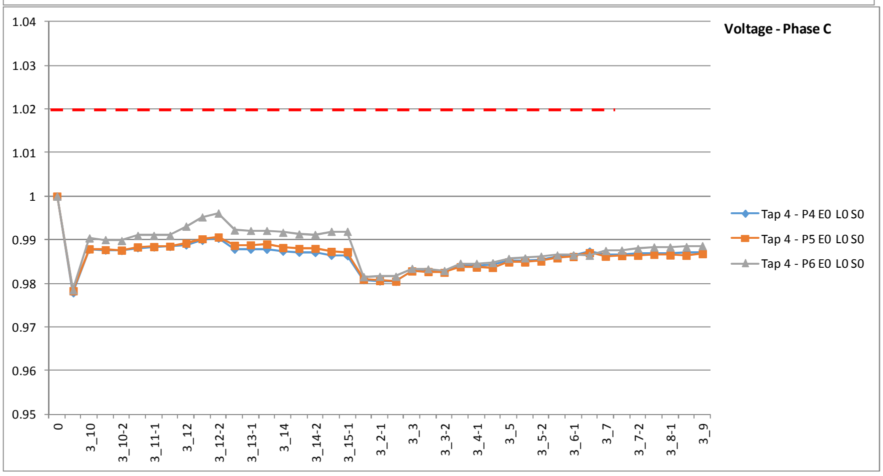




- o **Leg 3 (Phase A to C)**







Undervoltage

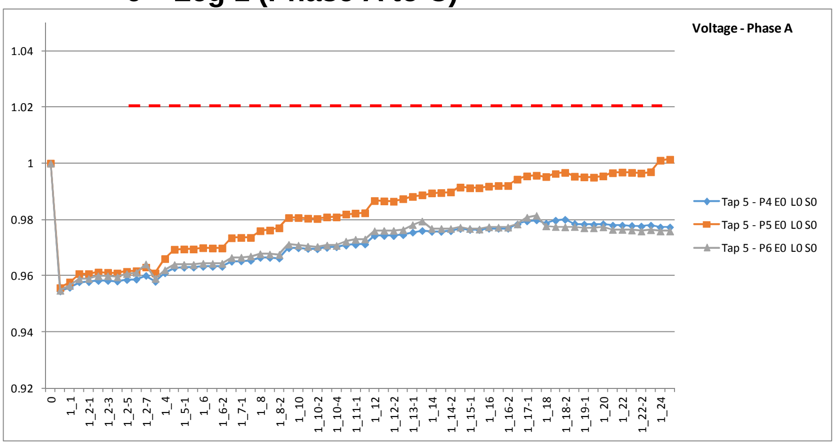
- To check the worst undervoltage – consider the max. consumer load with the lowest PV utilisation factor of 20%.
- No undervoltages (<0.87pu) were observed in Phase A of distribution Leg 1.

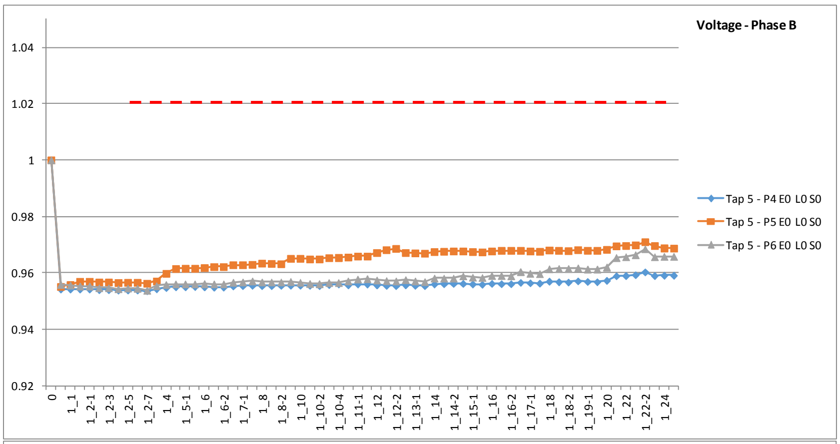
Tap 5

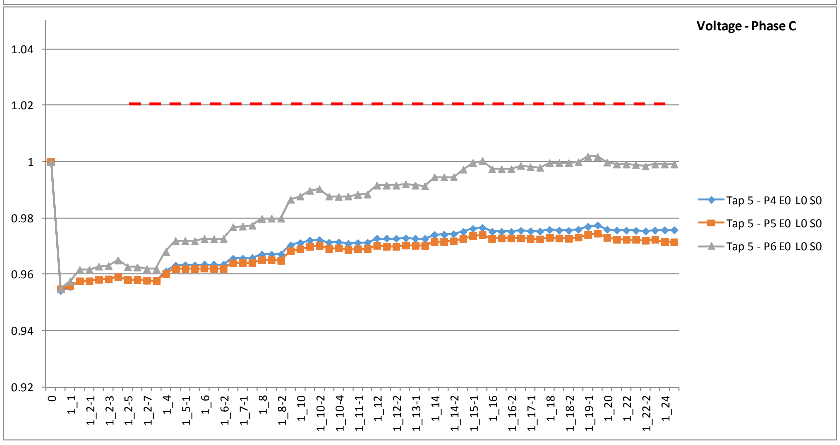
Overvoltage

- Overvoltages (>1.02 pu) were observed in Phase C of distribution Leg 1, Phase B of distribution Leg 2 and Phase B of distribution Leg 3.
- Highest overvoltages observed:
  Leg 1 – Phase C: 1.025 pu (P6E0L0S0)
  Leg 2 – Phase B: 1.047 pu (P6E0L0S0)
  Leg 3 – Phase B: 1.03 pu (P6E0L0S0)

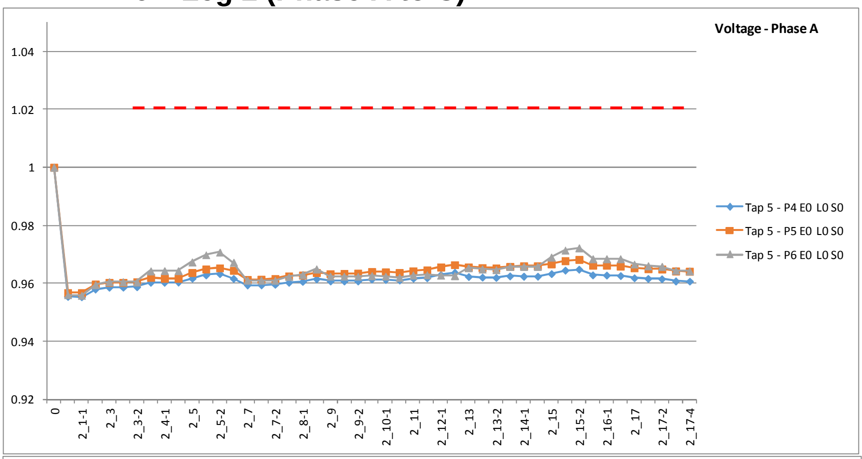
  - **Leg 1 (Phase A to C)**

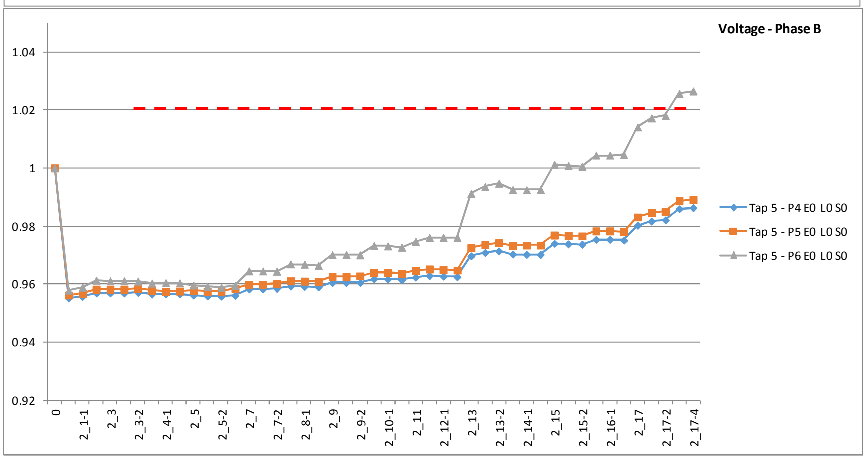


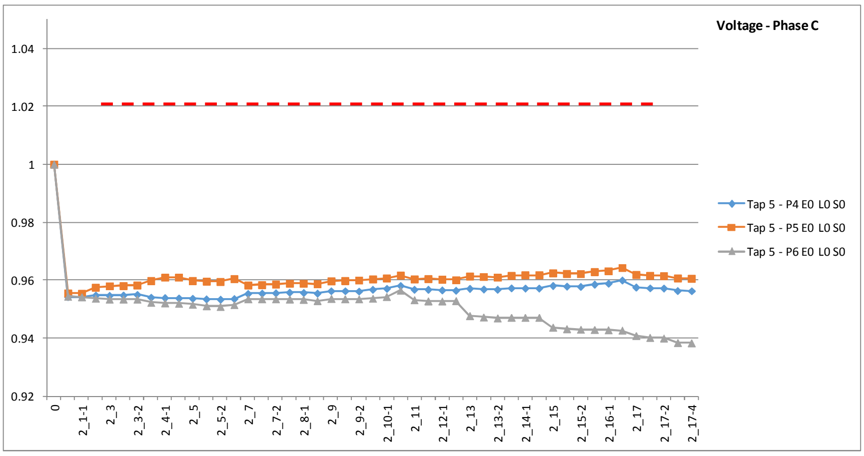




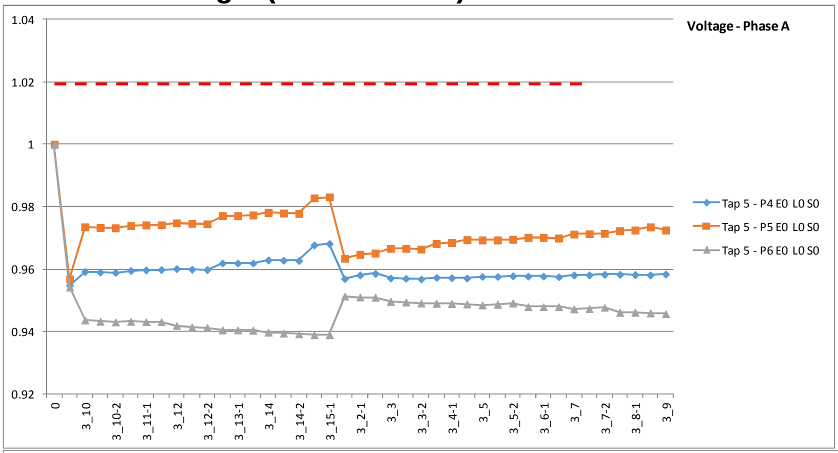
- **Leg 2 (Phase A to C)**

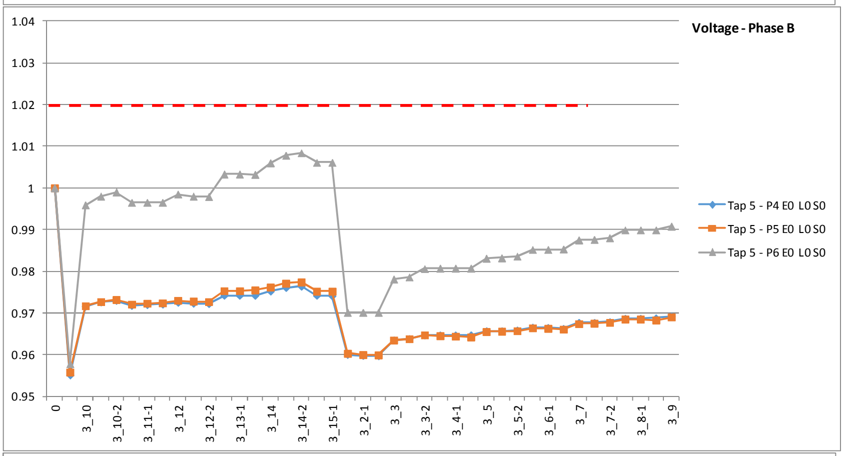


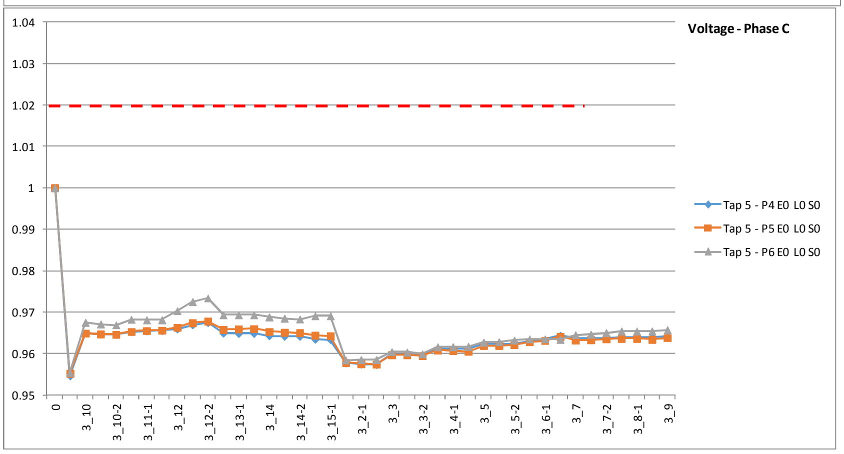




o **Leg 3 (Phase A to C)**



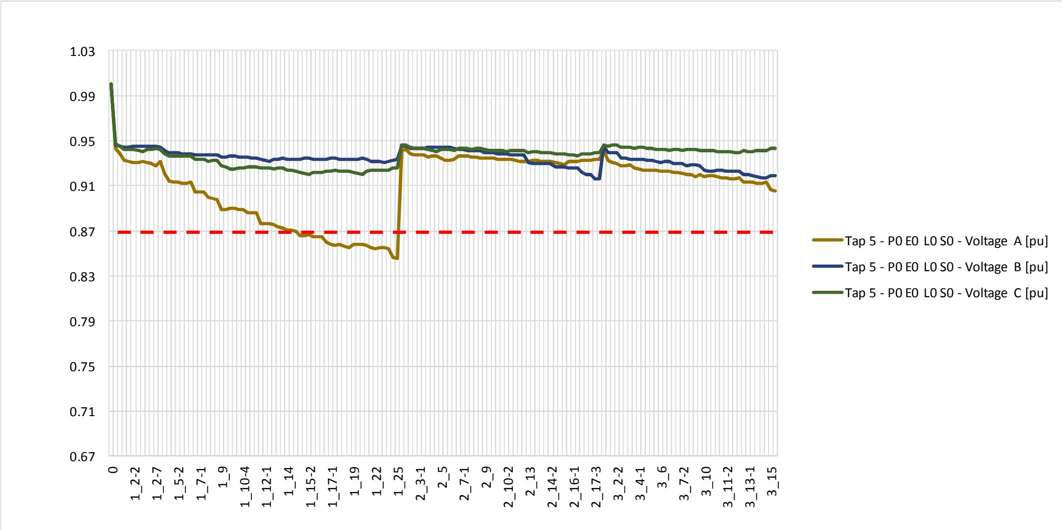




Undervoltage

- **Leg 1, 2 & 3 (Phase A to C)**

- Undervoltage (<0.87pu) observed in Phase A of distribution Leg 1.

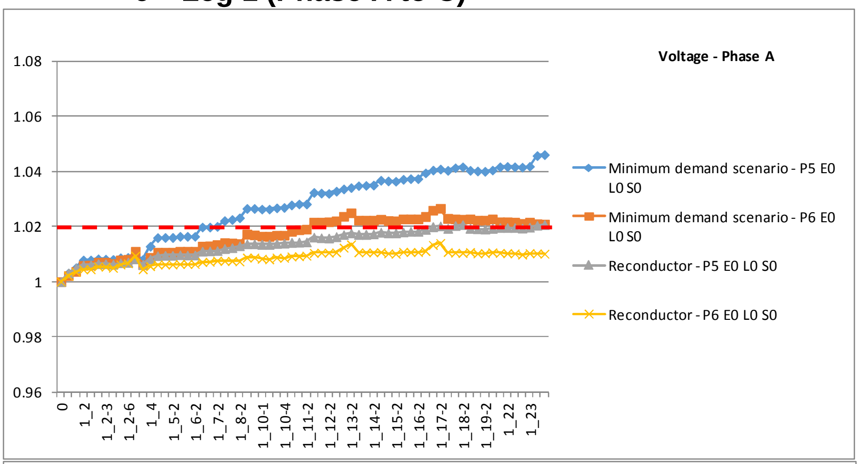


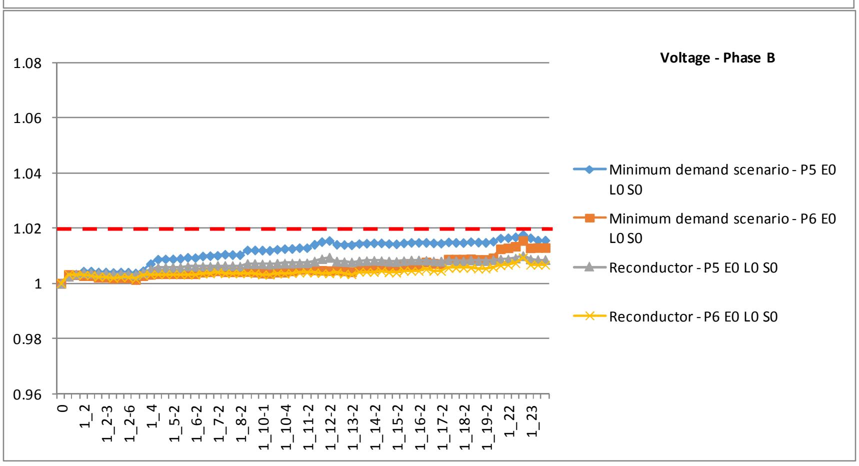
2. Reconductor feeder backbone

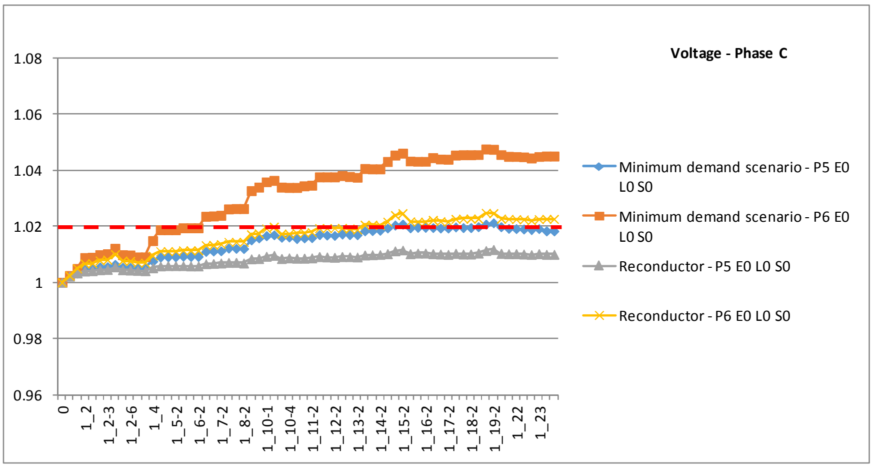
This section assesses the impact of changing the feeder backbone conductor type on the voltage under minimum and peak demand scenarios. The conductor type on the feeder backbone has been changed to 150 mm^2 AL XLPE cable. Results are as follows:

- Leg 1 – No overvoltages observed under P5 or P6 for Phases A and B
- Leg 2 – Overvoltage observed on Phase B under P6
- Leg 3 – Overvoltage observed on Phase B under P6

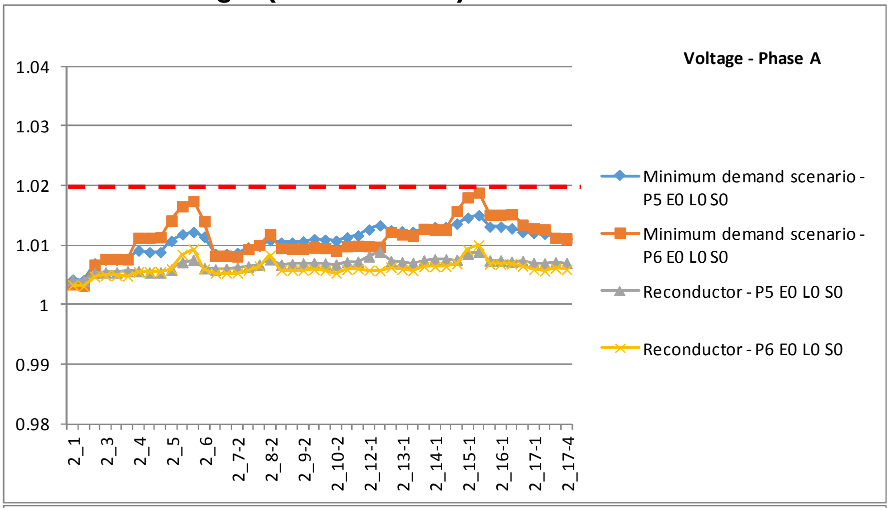
- **Leg 1 (Phase A to C)**

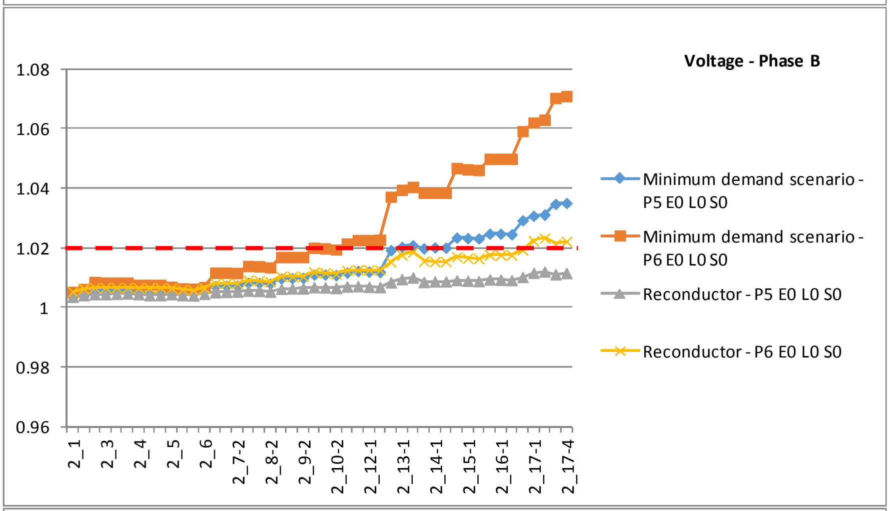


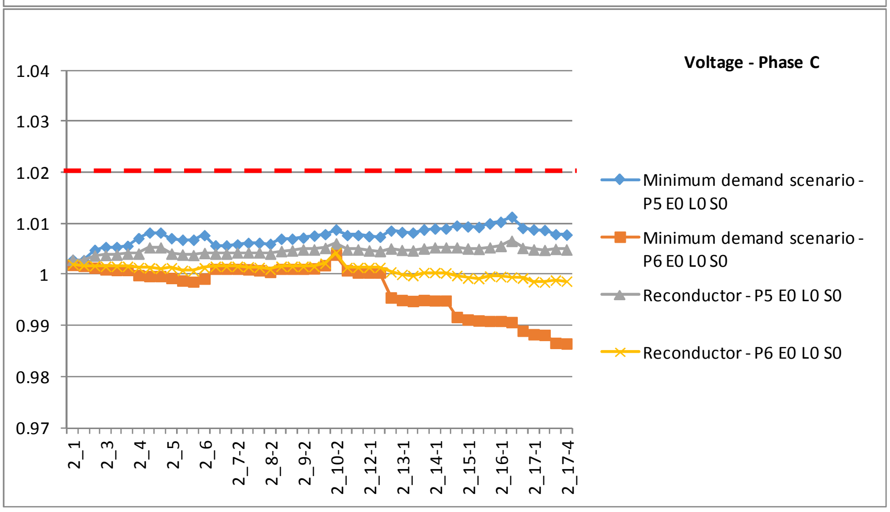




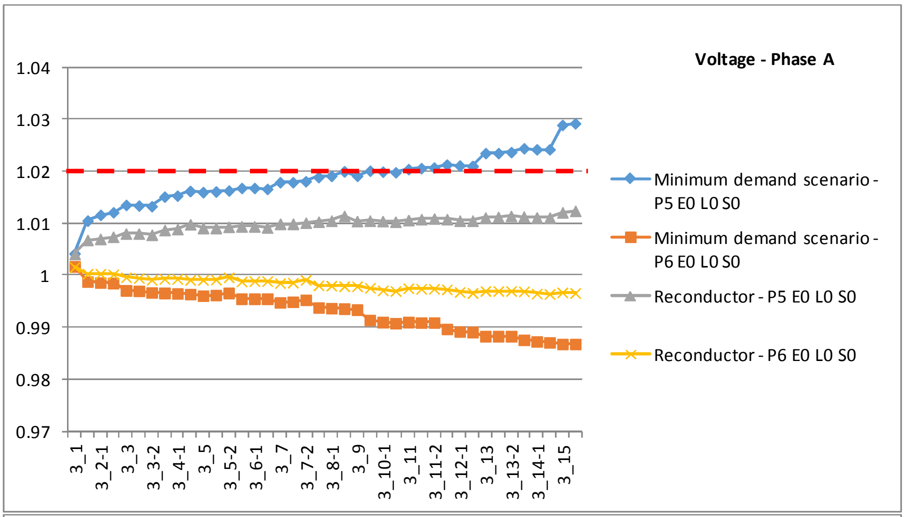
- o **Leg 2 (Phase A to C)**

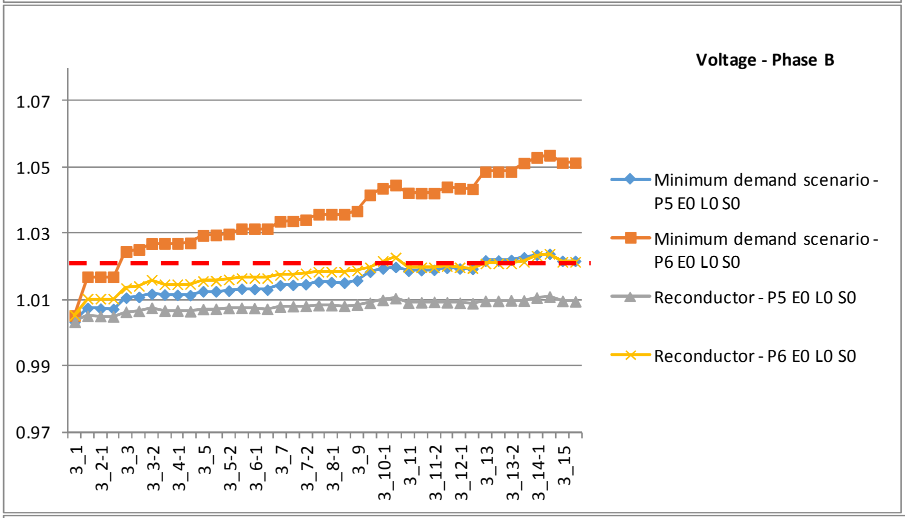


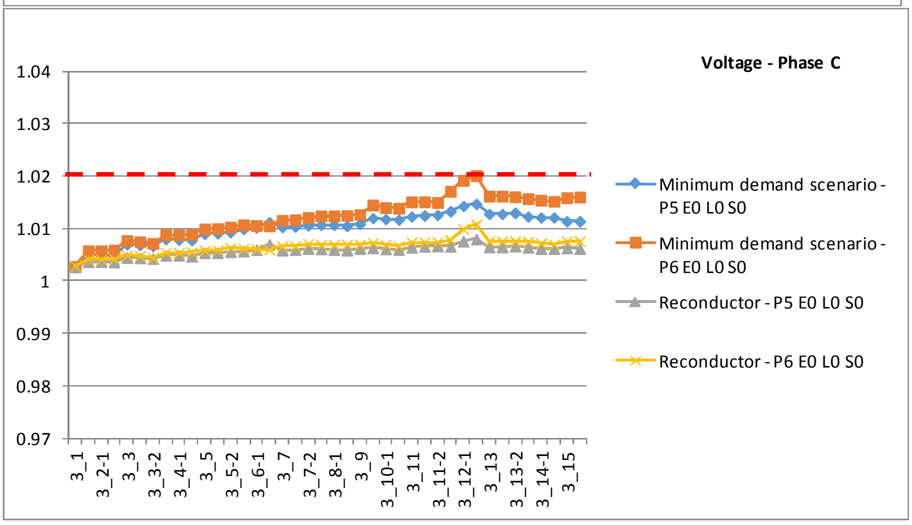




o **Leg 3 (Phase A to C)**





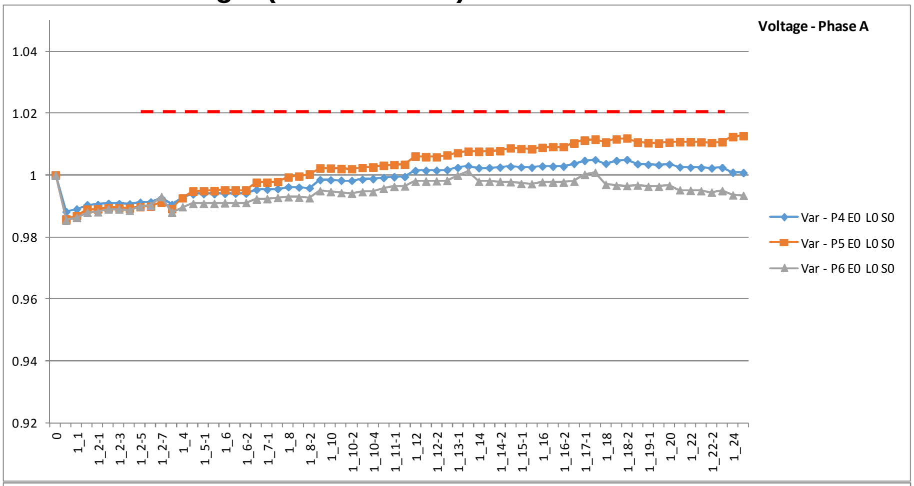


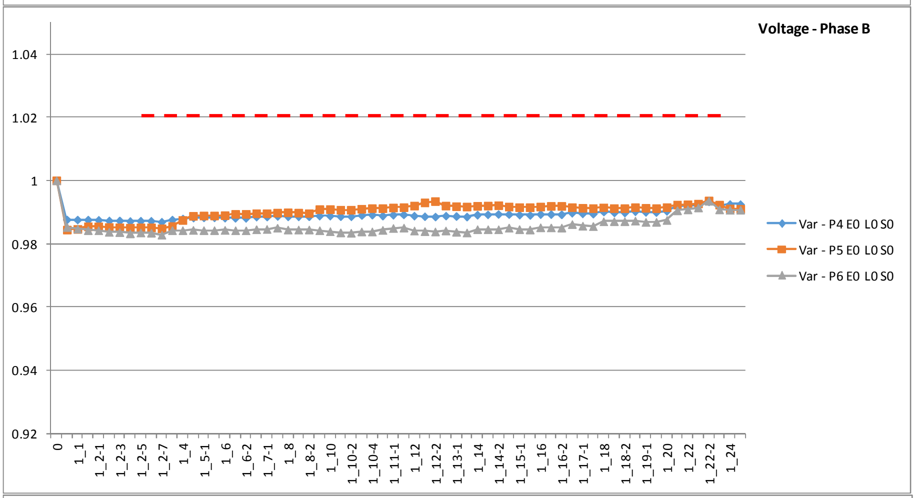
3. Dynamic VAr Control

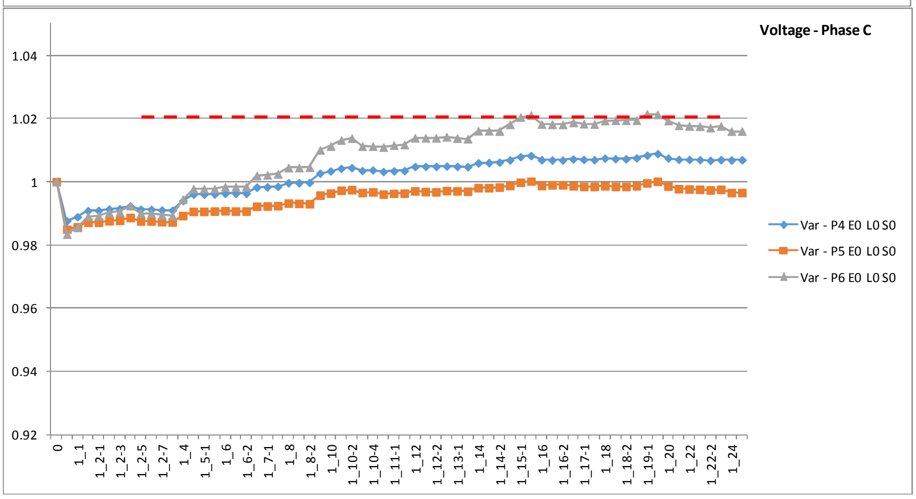
This section assesses the impact of dynamic VAr support on the voltage under minimum and peak demand scenarios. The amount of var support required to reduce the overvoltages on each of the distribution Legs as well as the resulting voltage profiles are given below:

- Leg 1 – 77 kVAr
- Leg 2 – 46 kVAr
- Leg 3 – 23 kVAr

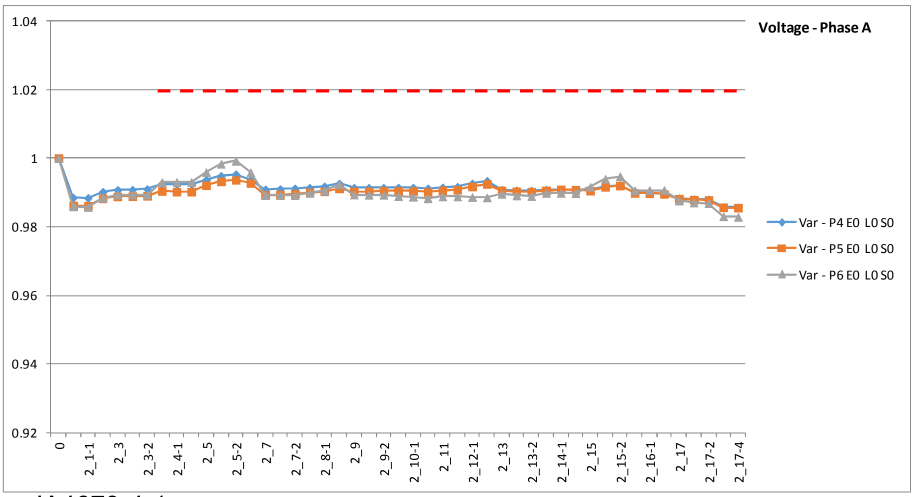
o **Leg 1 (Phase A to C)**

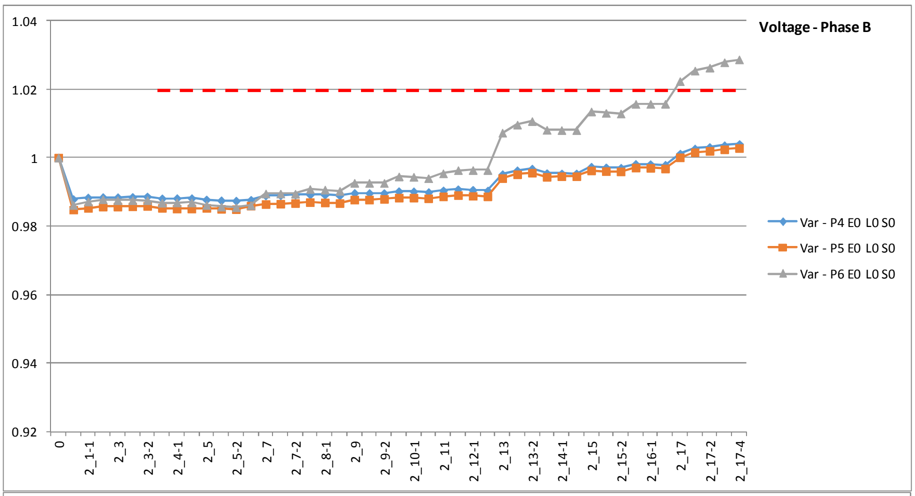


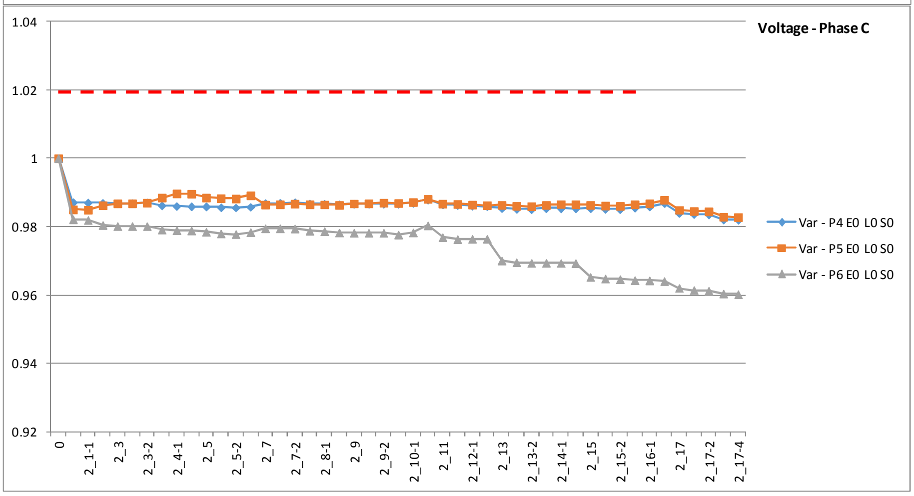




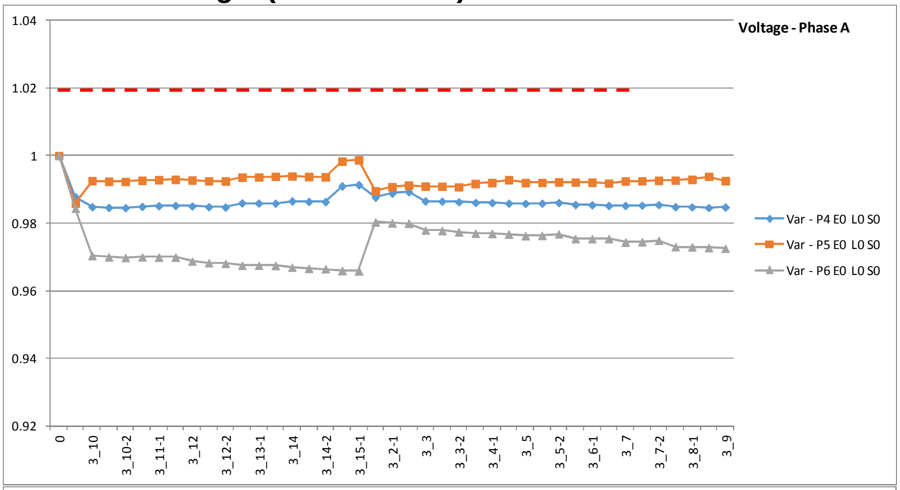
o **Leg 2 (Phase A to C)**

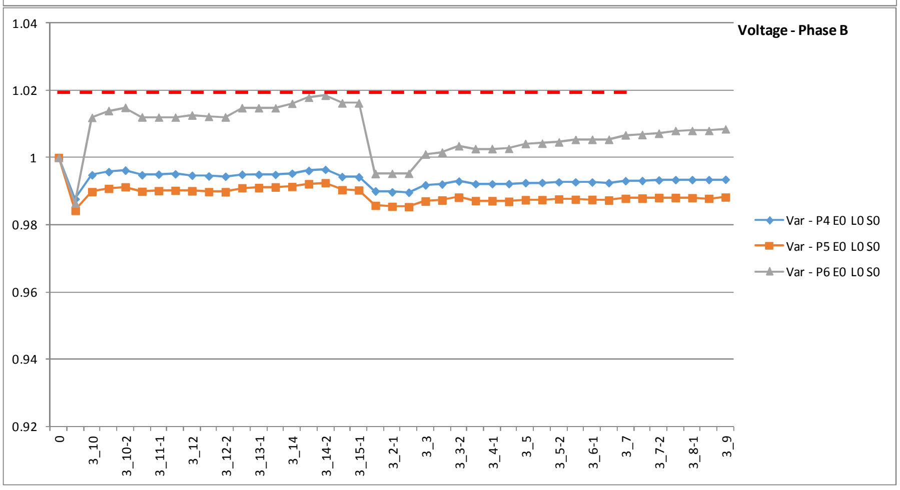


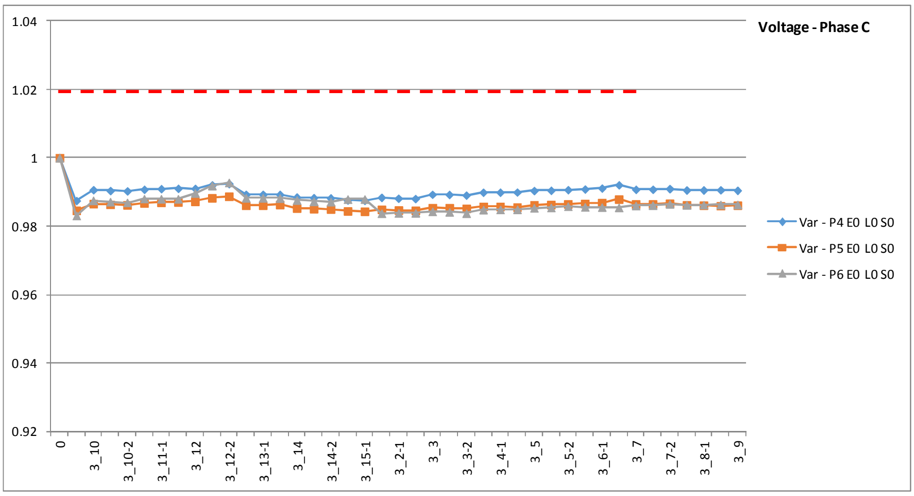




- **Leg 3 (Phase A to C)**





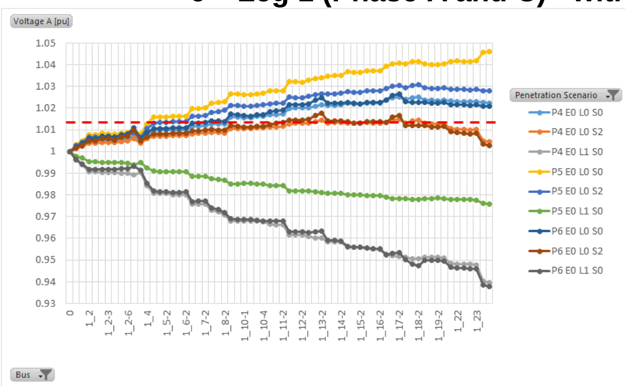


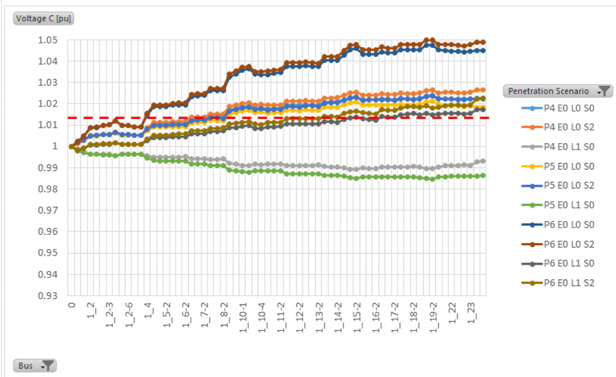
4. Controllable load and storage

For the overvoltage issue on this feeder, the controllable load measures that may assist in mitigation are controlled hot water load and battery storage (charging mode).

- In Leg 1, the Phase A boundary penetration scenario before overvoltages occur is P3. The controllable loads (L1) could be switched on to increase the penetration to P4, P5 or P6. Charging storage loads (S2) alone is insufficient to keep the voltage within limits.
- In Leg 1, the Phase C boundary penetration scenario before overvoltages occur is P3. The controllable loads (L1) could be switched on to increase the penetration to P4 or P5. Charging storage loads (S2) alone is insufficient to keep the voltage within limits. PV penetration level P6 cannot be achieved within the voltage limit even with both the controllable loads (L1) and storage loads (S2) switched on.

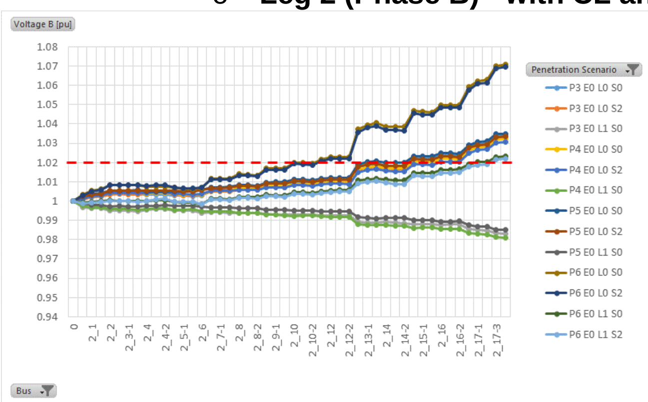
  - **Leg 1 (Phase A and C) - with CL and ST to control overvoltages**





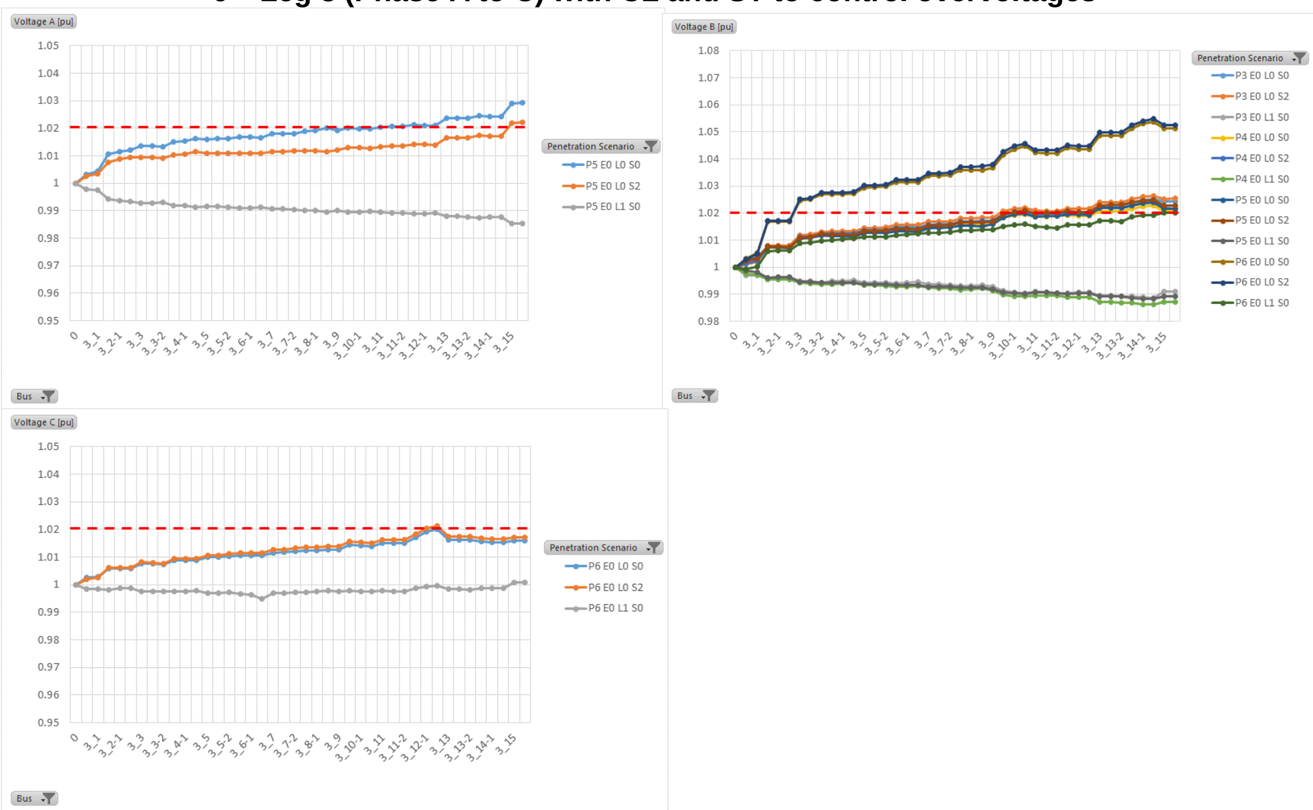
- In Leg 2, the Phase B boundary penetration scenario before overvoltages occur is P2. The controllable loads (L1) could be switched on to increase the penetration to P3, P4 or P5. The storage loads (S2) alone is insufficient to keep the voltage within limit. Penetration level P6 cannot be achieved within the voltage limit even with both the controllable loads (L1) and storage loads (S2) switched on

  - **Leg 2 (Phase B) - with CL and ST to control overvoltages**



- In Leg 3, the Phase A overvoltages occur under the P5 penetration scenario. The controllable loads (L1) could be switched on to resolve the issues for P5. Connecting the storage loads (S2) alone is insufficient to keep the voltage within limit.
- In Leg 3, the Phase B boundary penetration scenario before overvoltages occur is P2. The controllable loads (L1) could be switched on to increase the penetration to P3, P4, P5 or P6. The storage loads (S2) alone is insufficient to keep the voltage within limit.
- In Leg 3, the Phase C overvoltages occur under the P6 penetration scenario. Either the controllable loads (L1) or storage loads could be switched on to resolve the issues.

  - **Leg 3 (Phase A to C) with CL and ST to control overvoltages**

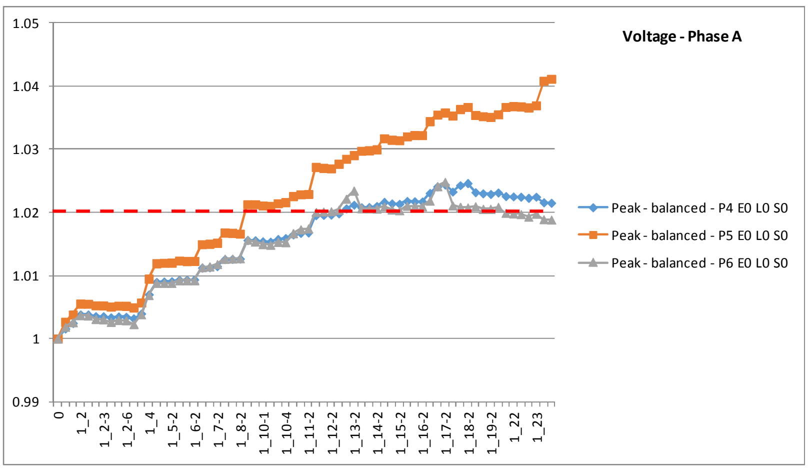


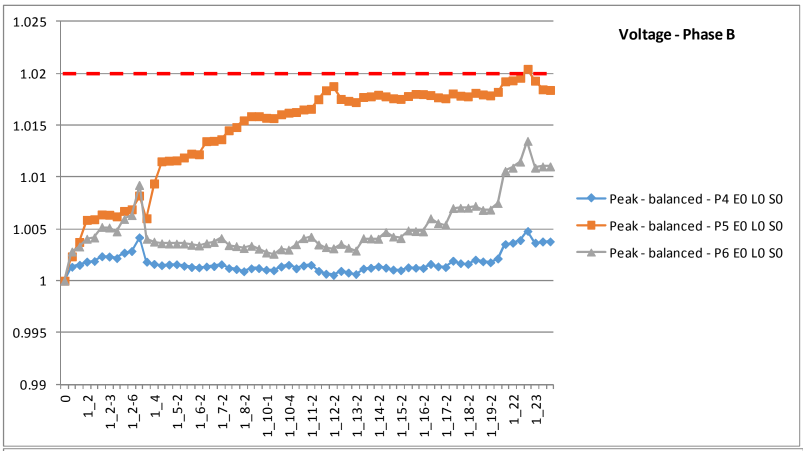
For the undervoltage issue on this feeder, the controllable load measure that may assist in mitigation is battery storage (discharging mode). Analysis shows that using storage as generation is insufficient to support the low voltages in the distribution legs.

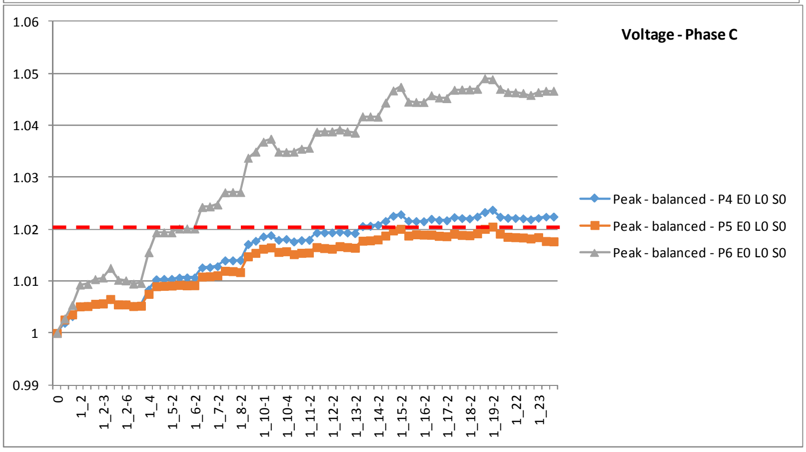
5. Feeder load balancing

This section assesses the impact of balancing the feeder load on the voltage under minimum and peak demand scenarios. The load was distributed as evenly as possible across each of the phases of each of the feeder distribution legs.

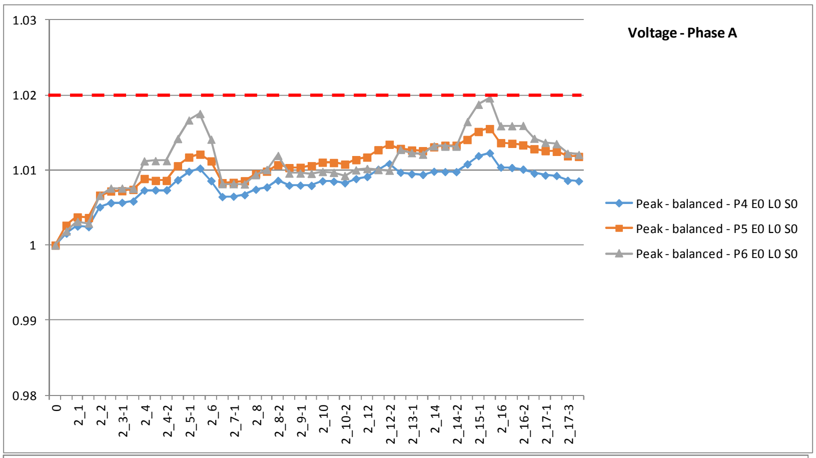
  - **Leg 1 (Phase A to C)**

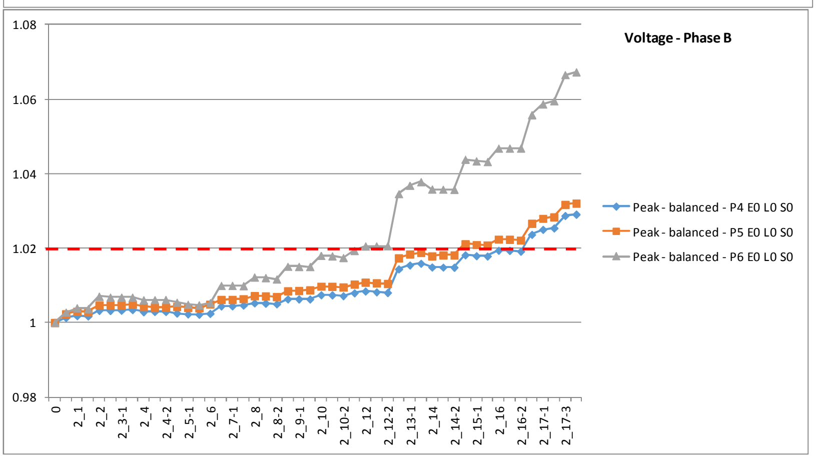


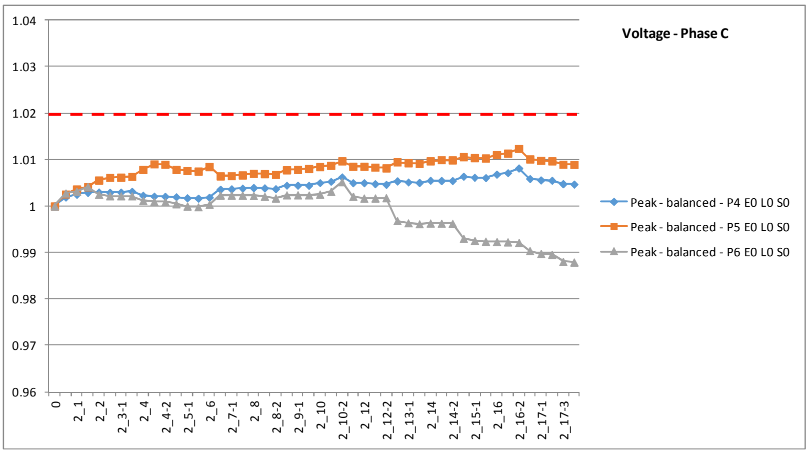




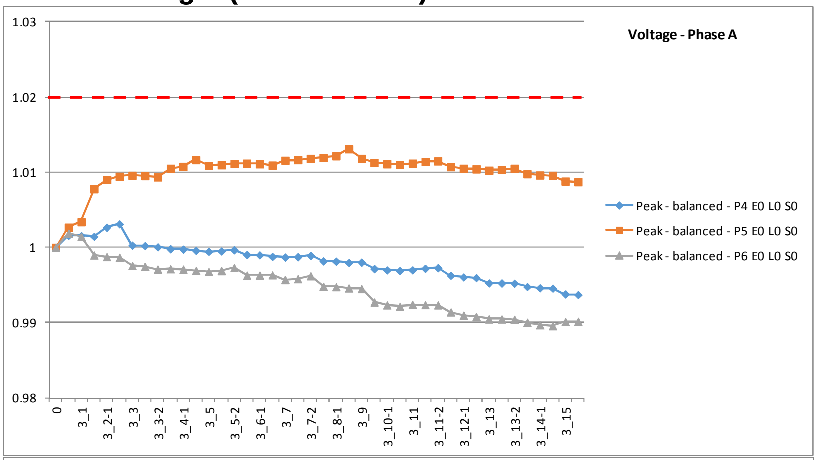
- **Leg 2 (Phase A to C)**

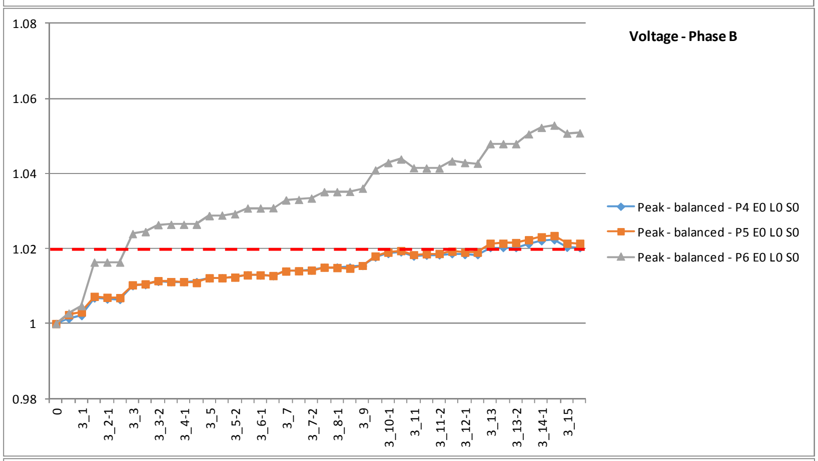


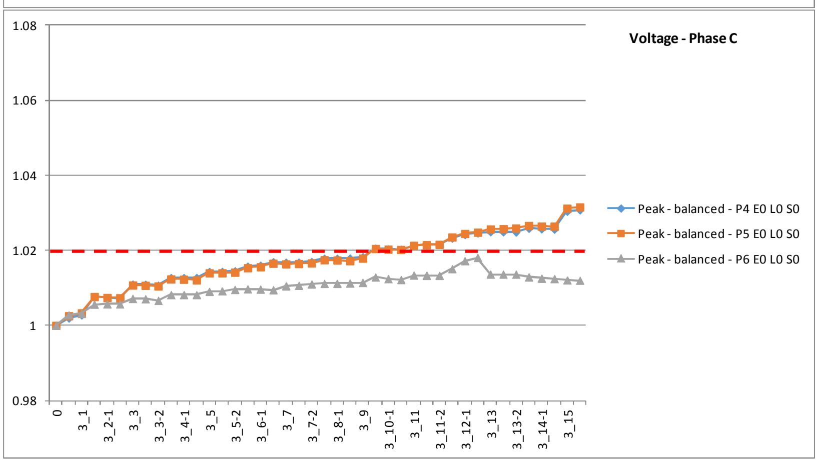




- **Leg 3 (Phase A to C)**



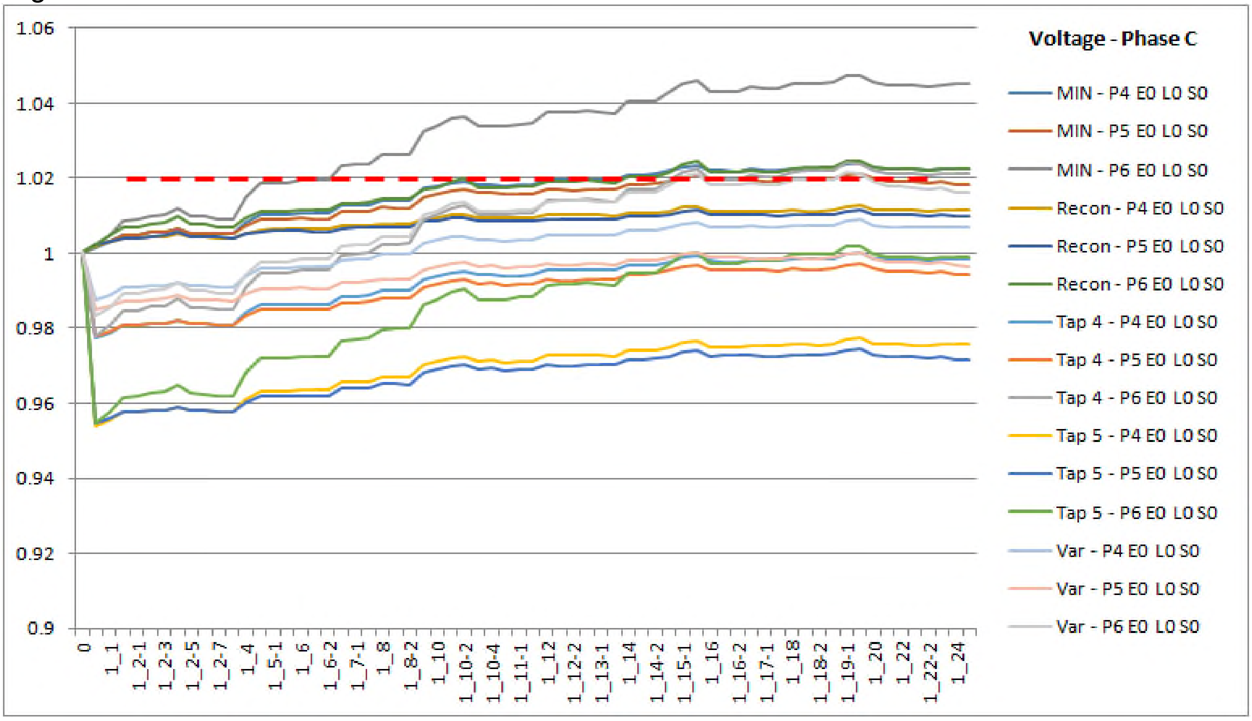




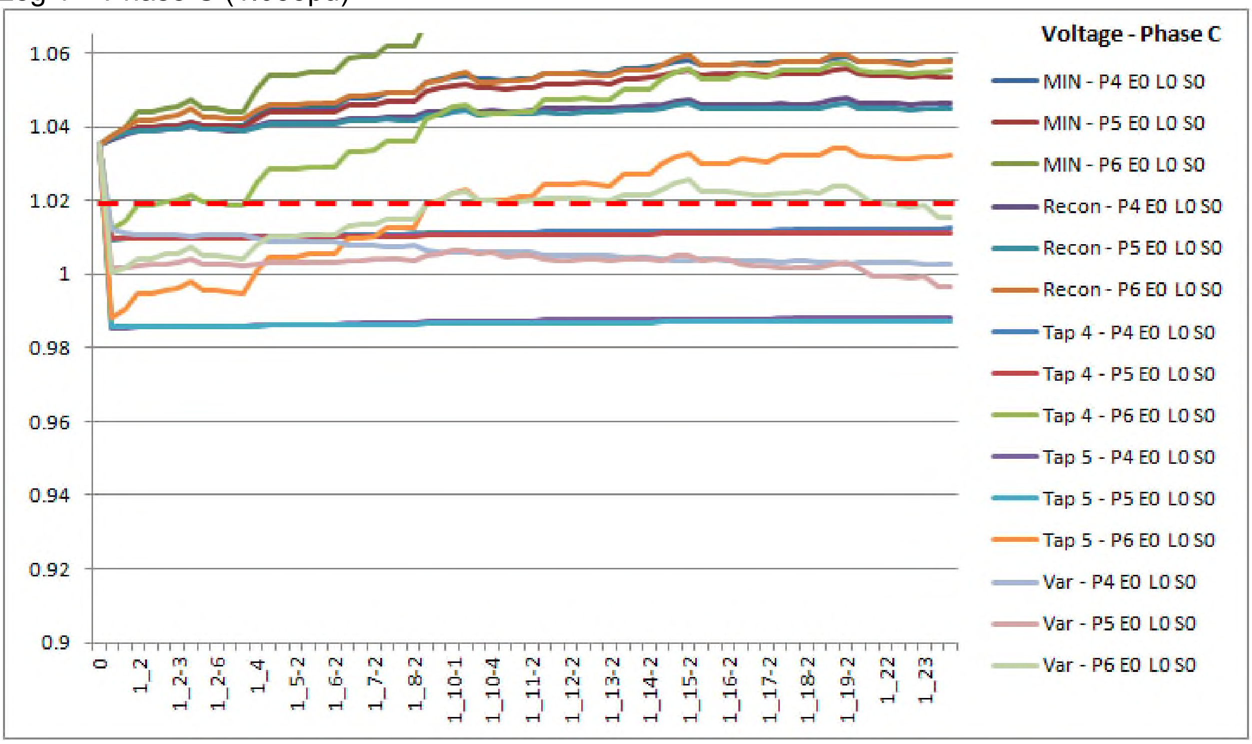
Aggregated results

The graphs below summarise all the mitigation measures investigated and the impact they have on the worst phase of each distribution Leg on the feeder under a minimum demand scenario. The results are shown for each of the assumed MV voltages of 1 pu, 1.035 pu and 0.965 pu.

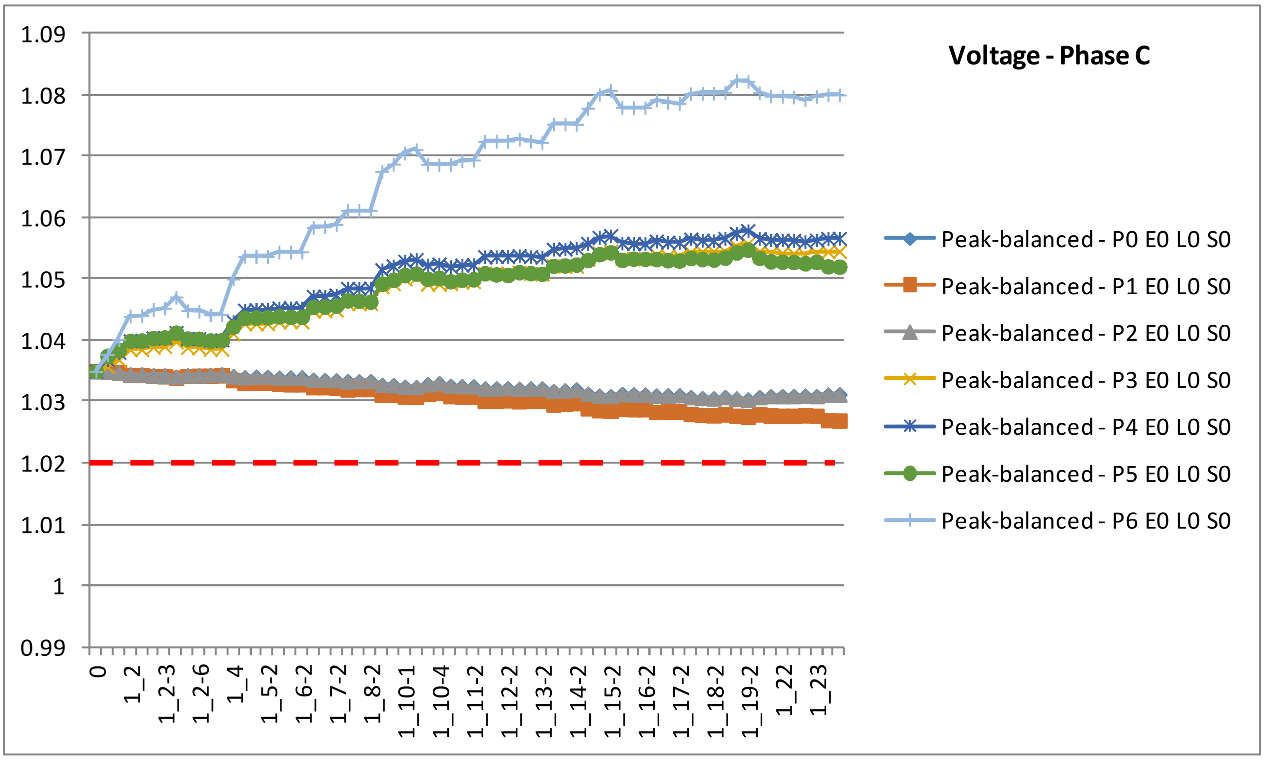
Leg 1 – Phase C



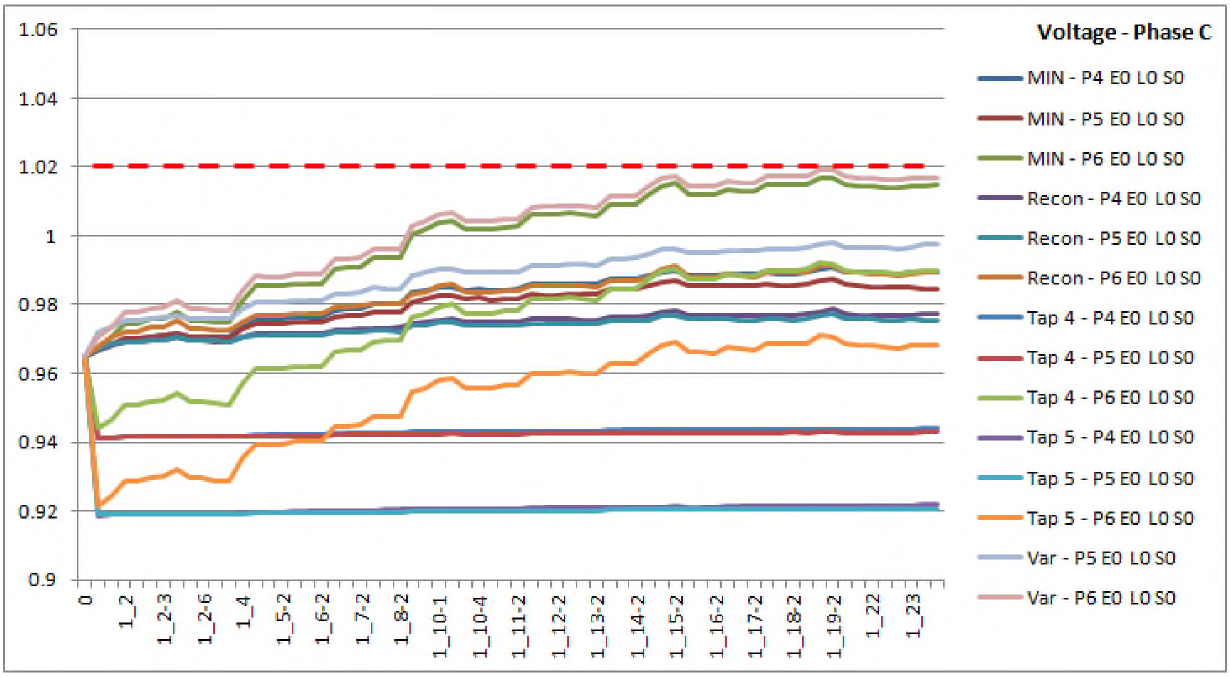
Leg 1 – Phase C (1.035pu)



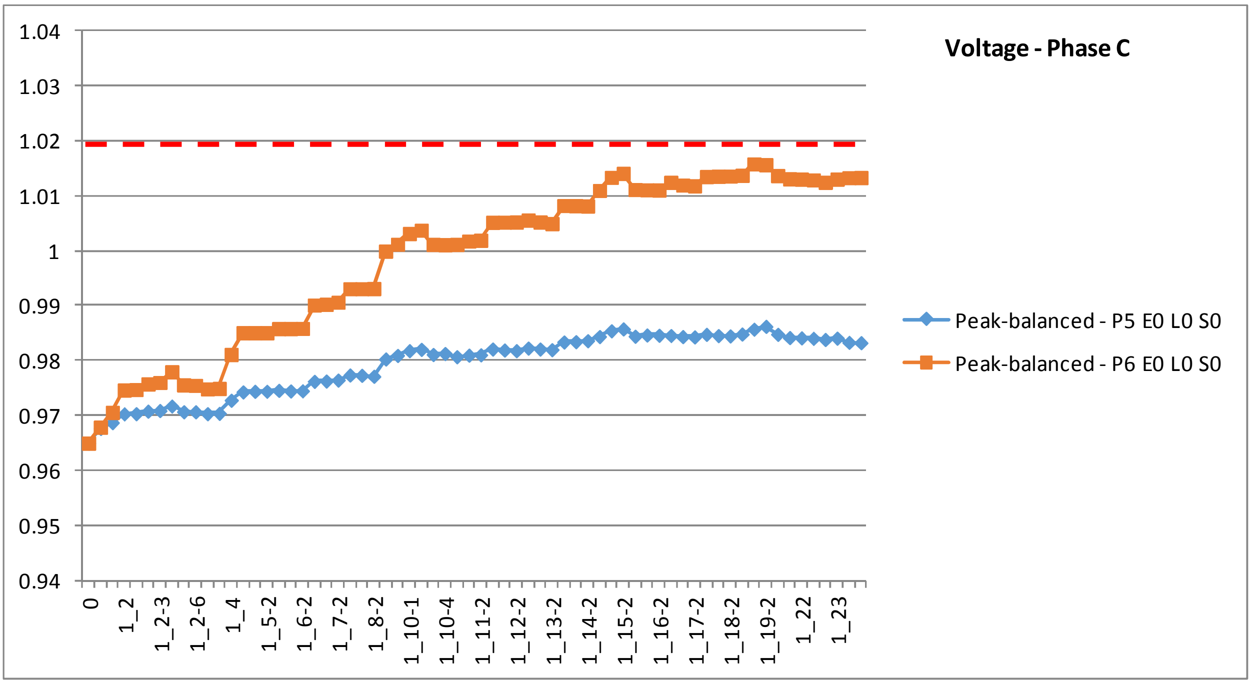
Leg 1 – Phase C (1.035pu) – balanced feeder load



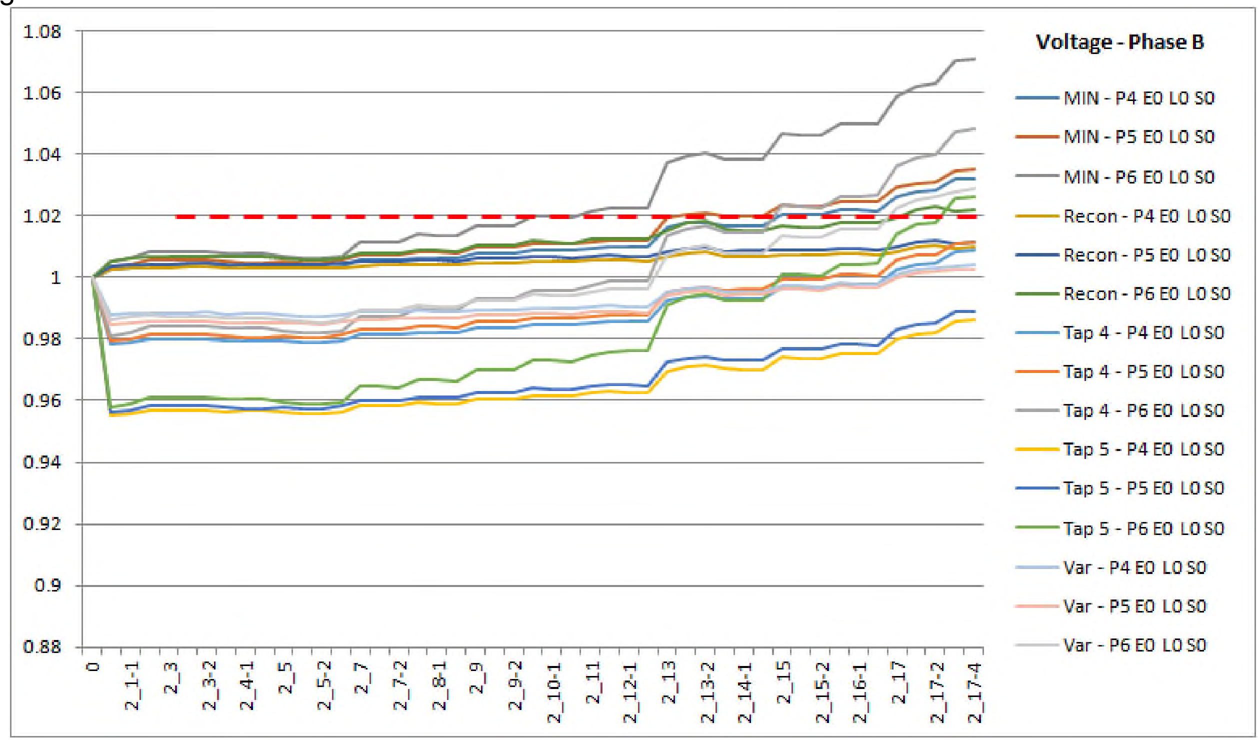
Leg 1 – Phase C (0.965pu)



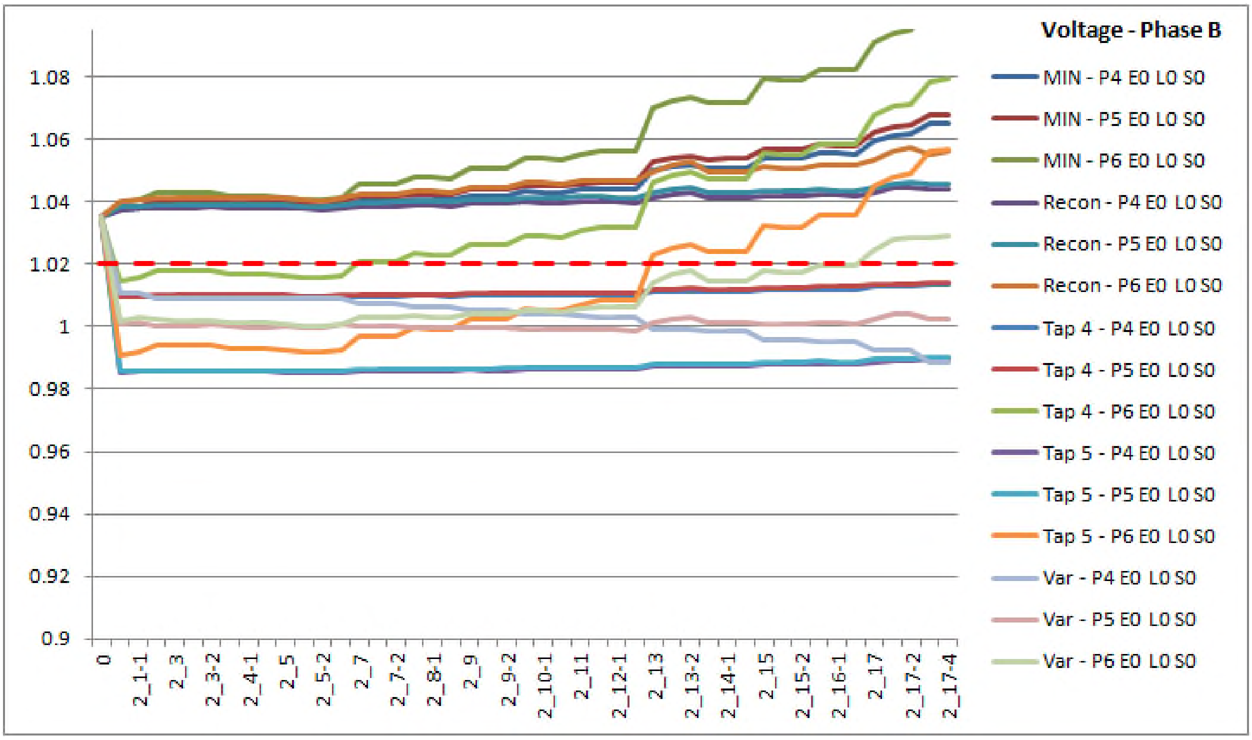
Leg 1 – Phase C (0.965pu) – Balanced feeder load



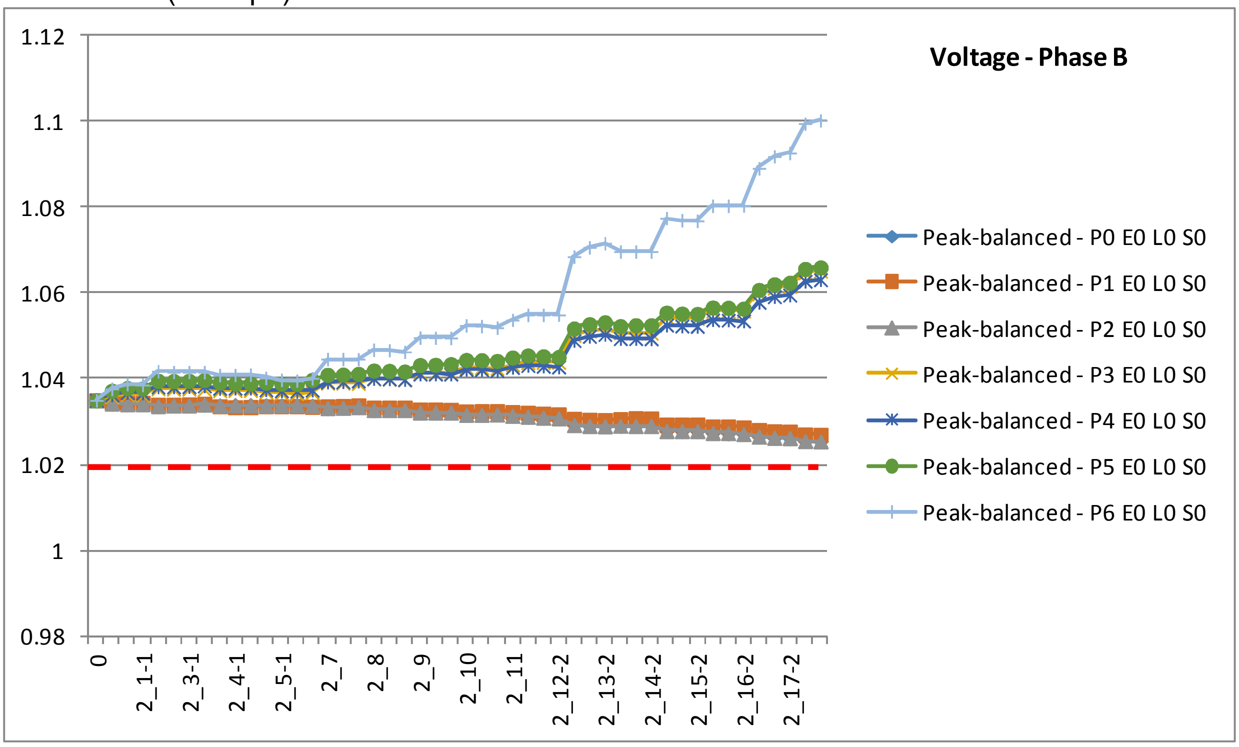
Leg 2 – Phase B



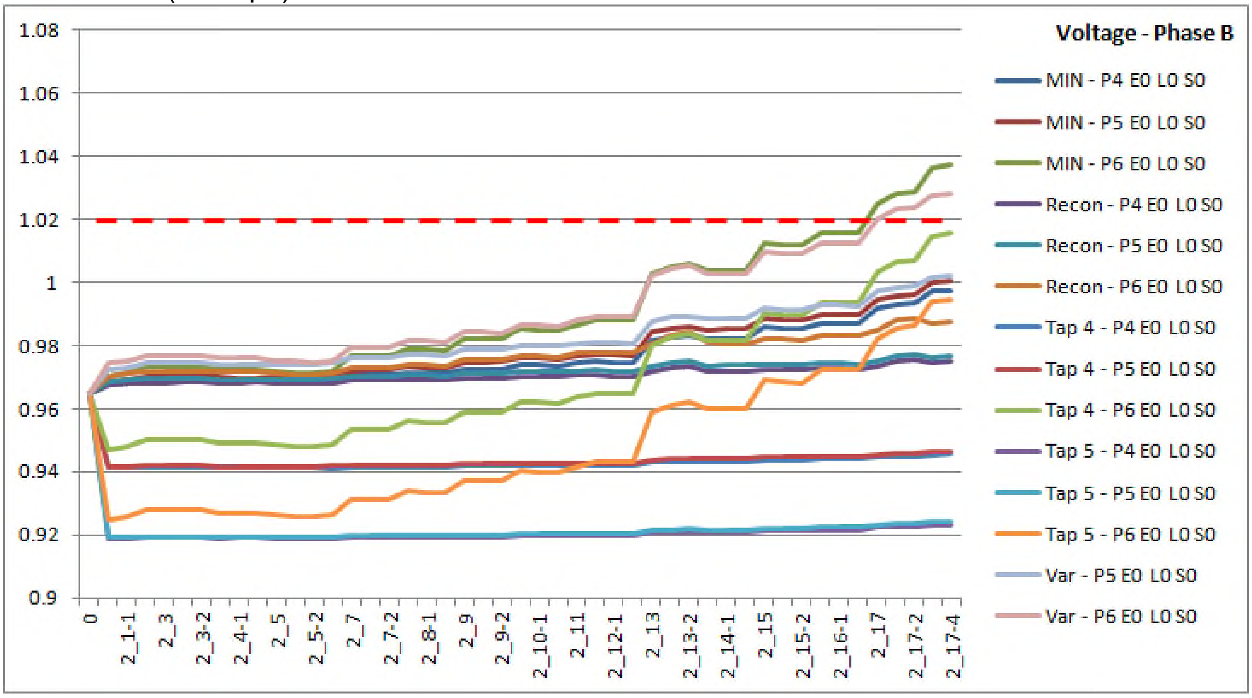
Leg 2 – Phase B (1.035pu)



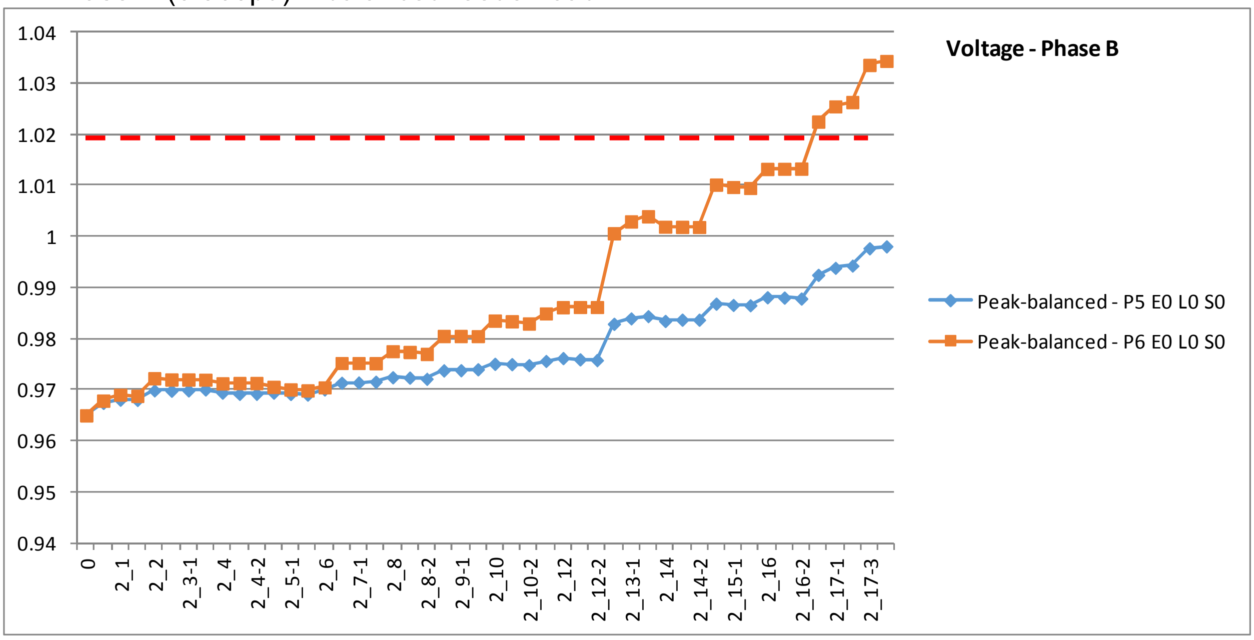
Leg 2 – Phase B (1.035pu) – balanced feeder load



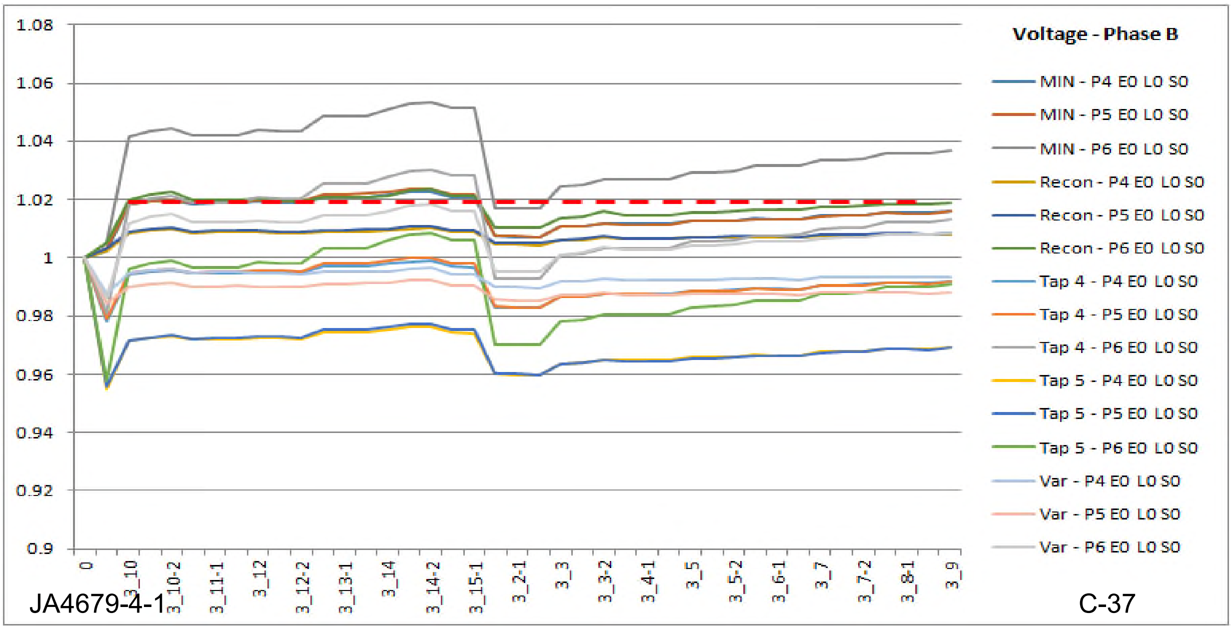
Leg 2 – Phase B (0.965pu)



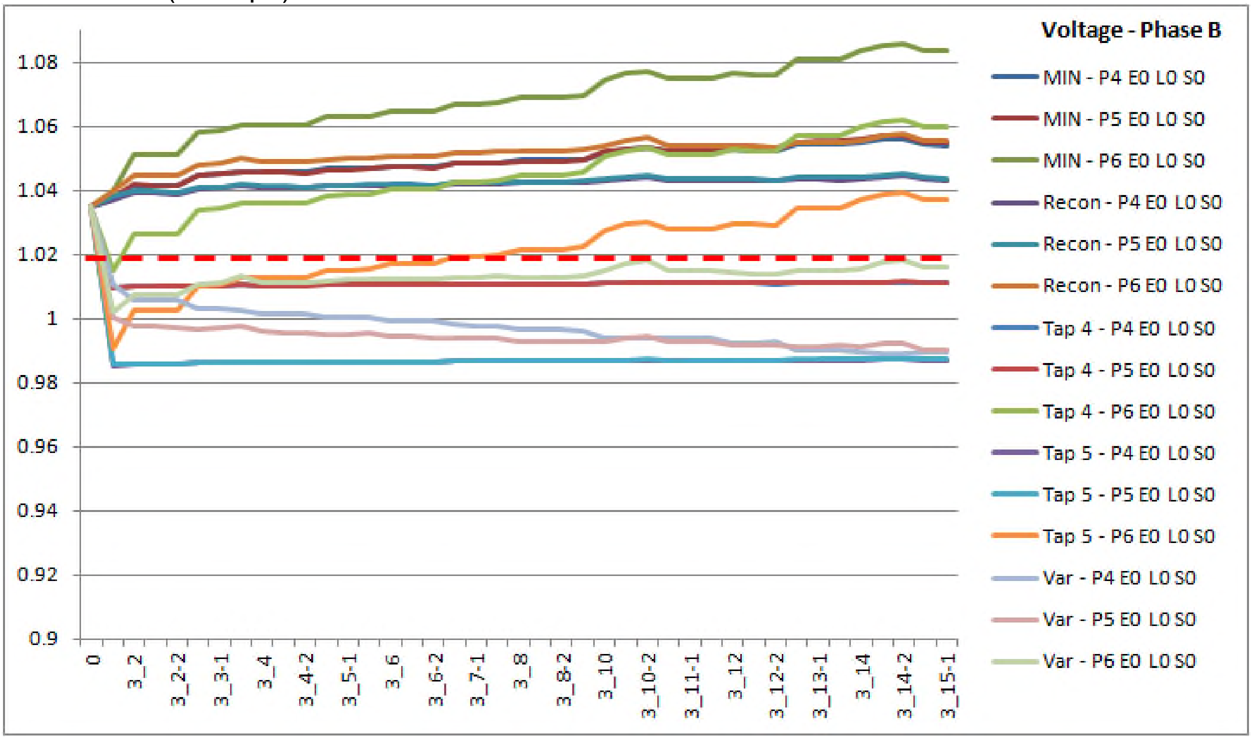
Leg 2 – Phase B (0.965pu) – balanced feeder load



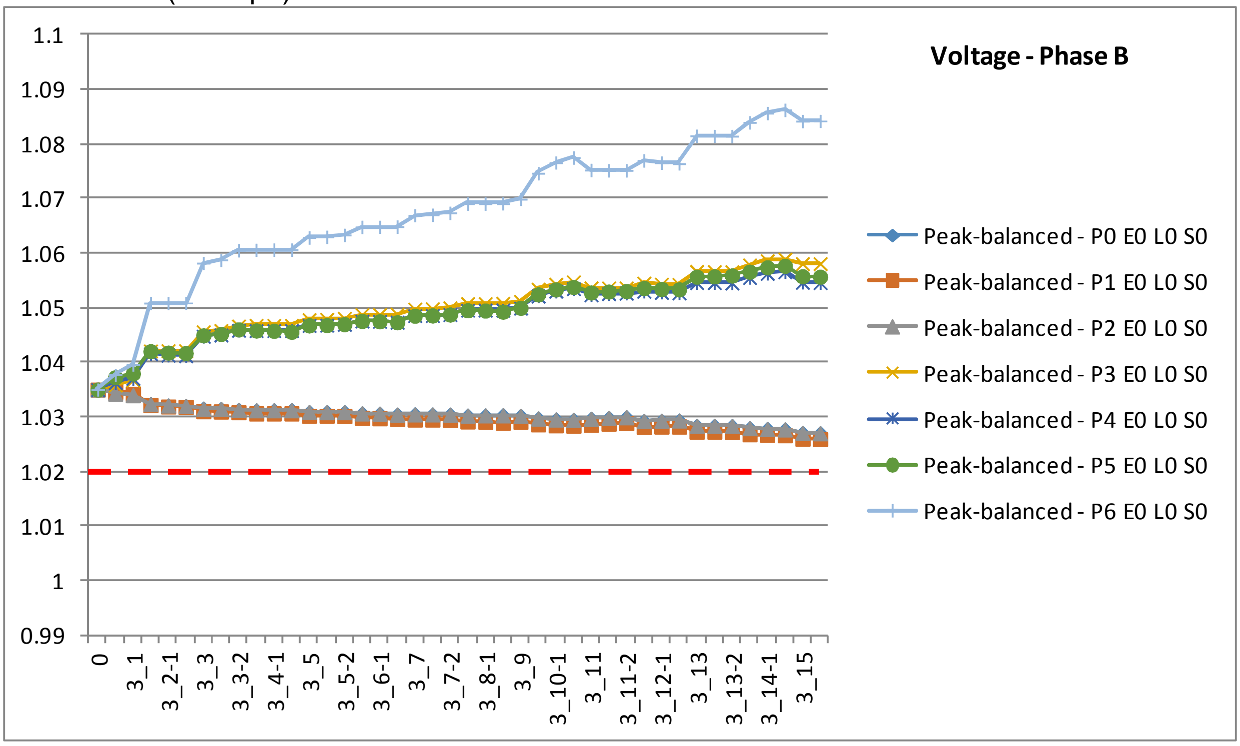
Leg 3 – Phase B



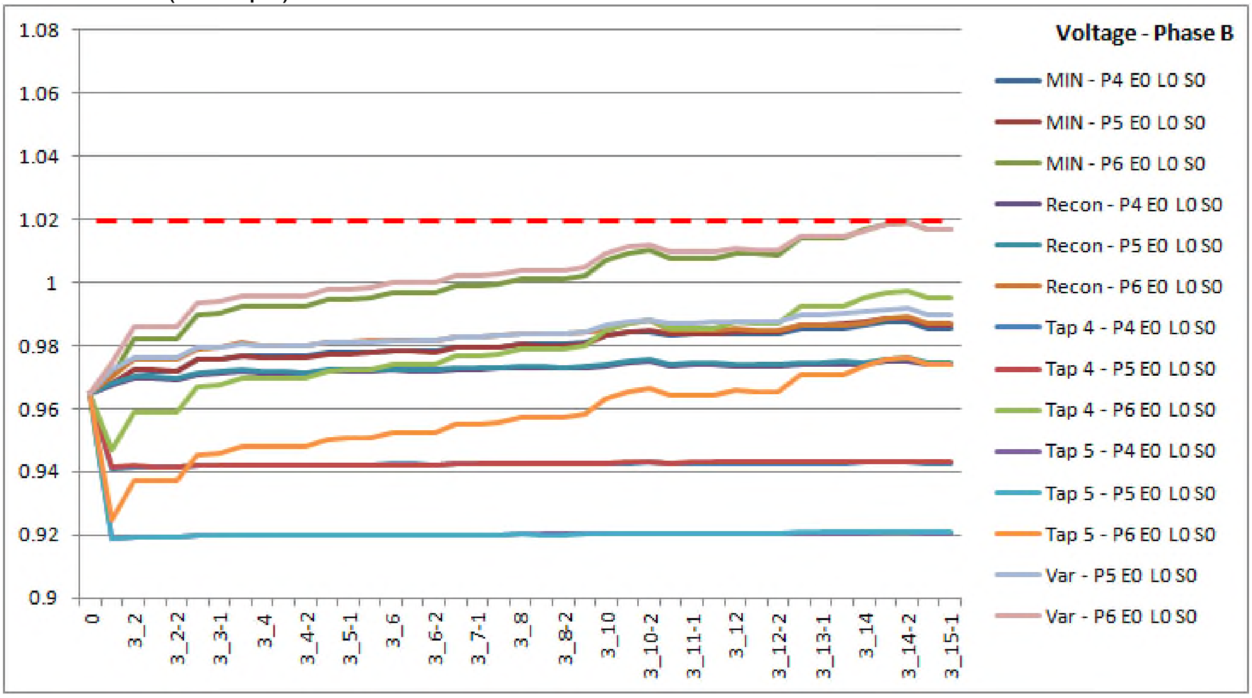
Leg 3 – Phase B (1.035pu)



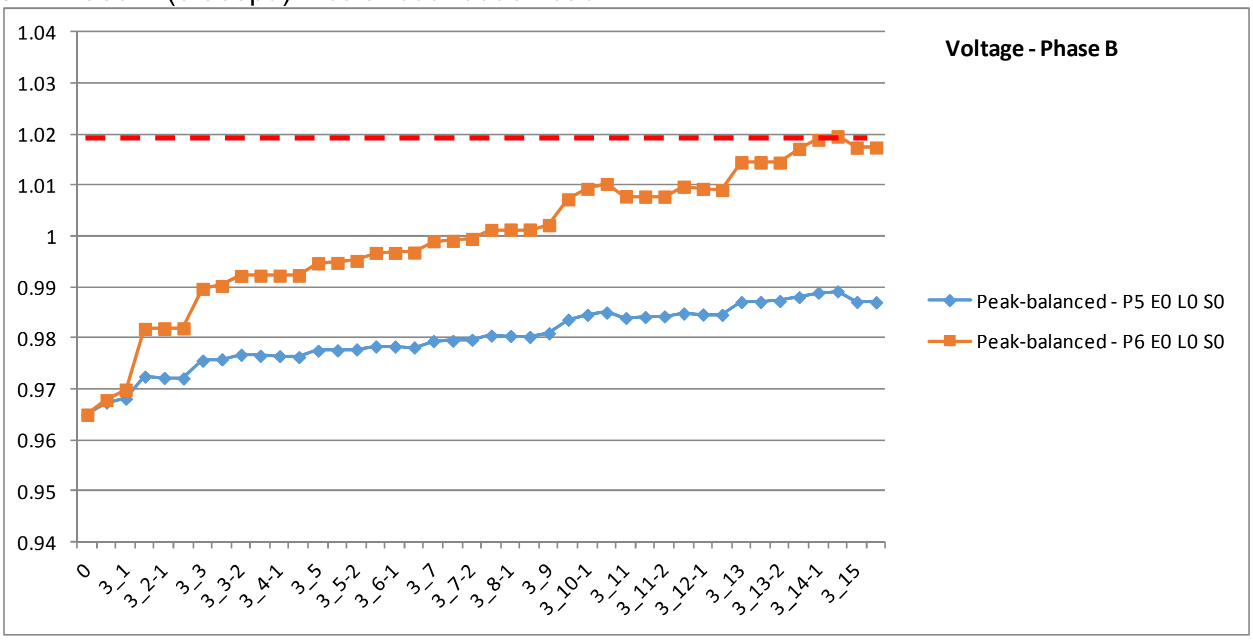
Leg 3 – Phase B (1.035pu) – balanced feeder load



Leg 3 – Phase B (0.965pu)

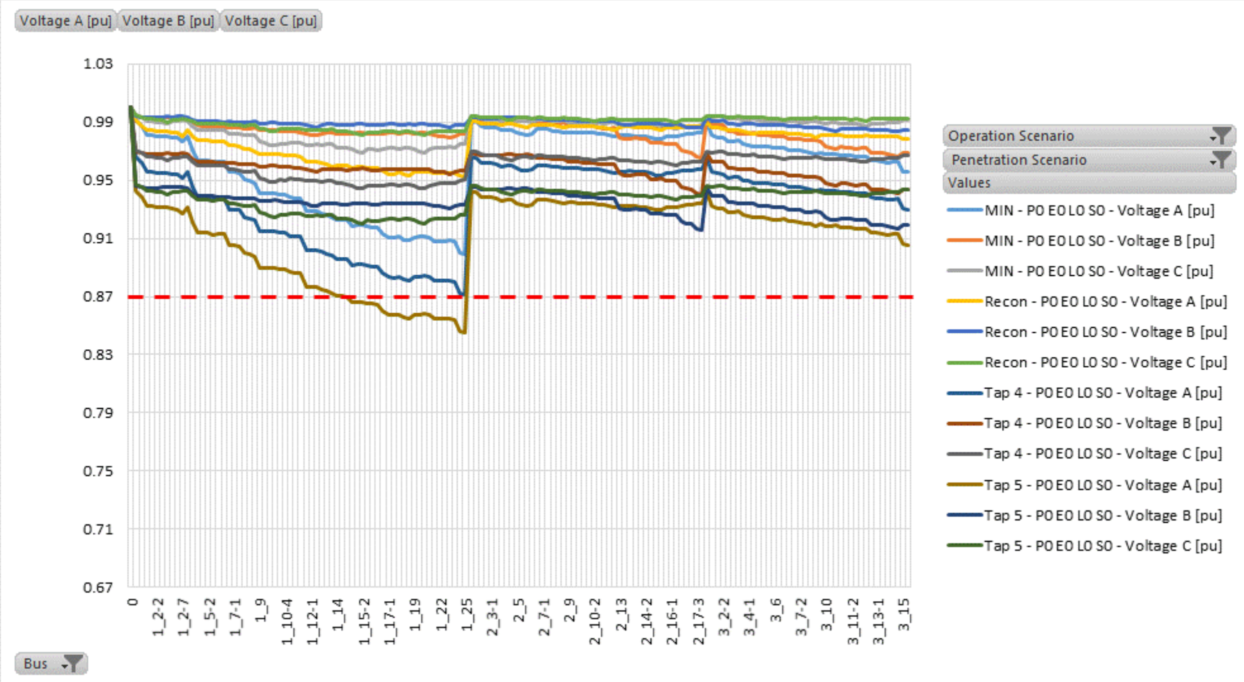


Leg 3 – Phase B (0.965pu) – balanced feeder load

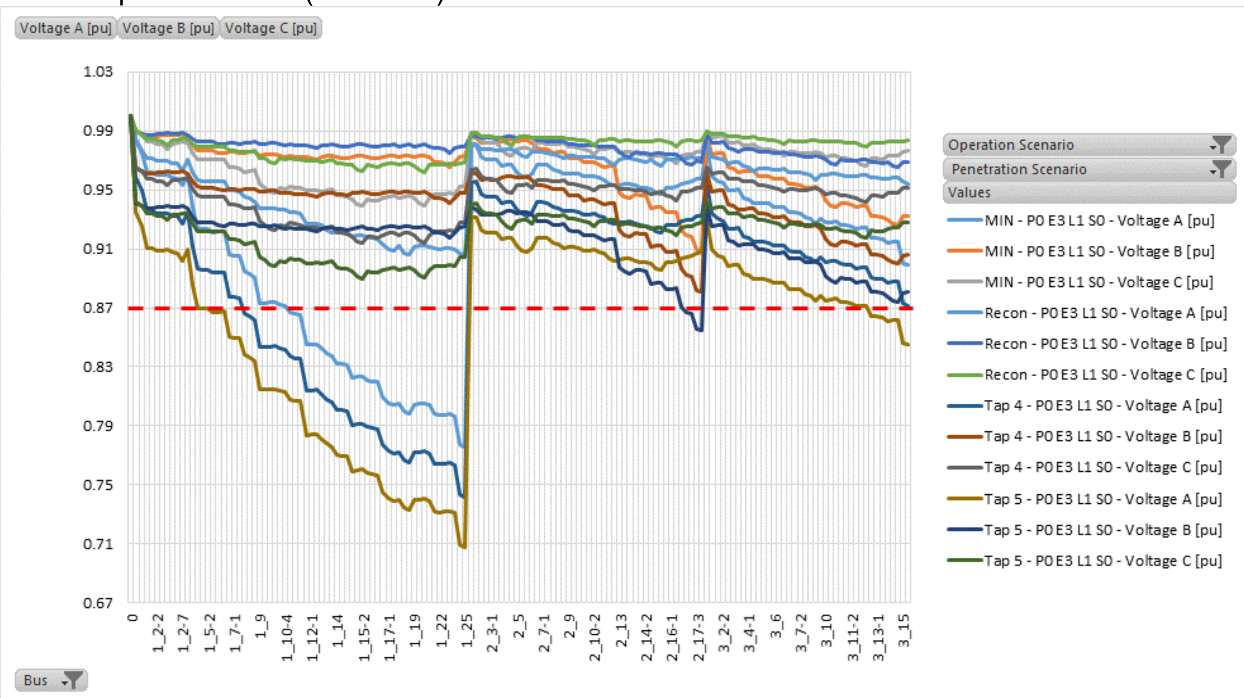


The graphs below summarise all the mitigation measures investigated and the impact they have on the worst phase of each distribution Leg on the feeder under a peak demand scenario, with and without DERs.

Impact under peak demand



Impact under peak demand (with DER)



SWER M-23 – MITIGATION ANALYSIS

1. Details

- Rockleigh 19 kV SWER
- 11/19 k V 200 kVA transformer
- Comprised of the following overhead conductor:
  - 3/12 SCGZ
- Total feeder length – 52 km
- 132 customers
- Has one meter point to one distribution leg.
- Max. consumer load assumed = 280 kVA (obtained from actual data). Note that the max. load exceeds the rating of the transformer.
- Min. consumer load = 101.6 kVA (obtained from actual data assuming existing PV utilisation factor of 80%)
- Existing PV penetration = 77.5 kW 31 customers (assuming a 2.5 kW inverter size)
- Existing customers with controllable load = 67 (51 %)

Mitigation measures

1. Transformer taps

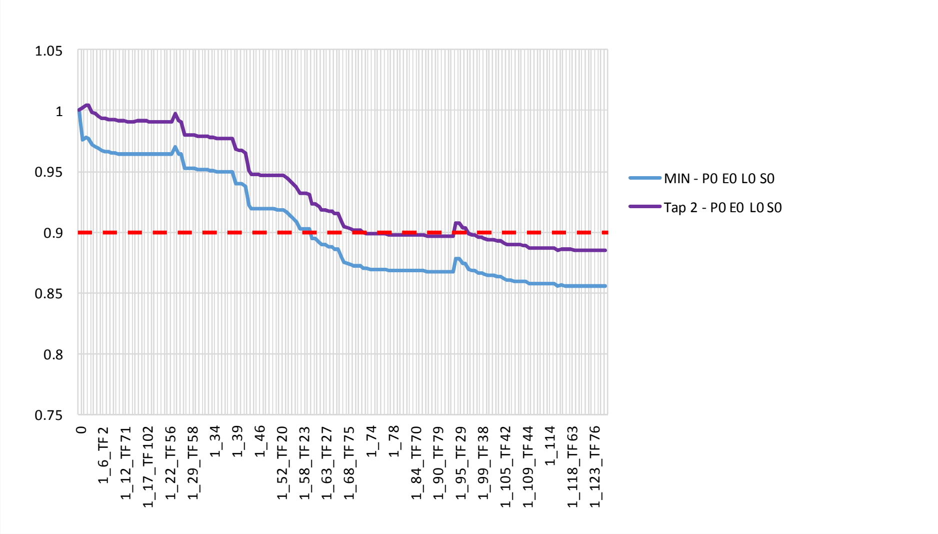
In the original analysis, with the MV/LV transformer at nominal tap (tap 3), undervoltages were observed. This section assesses the impact of changing the tap position on the voltage under peak and minimum demand scenarios.

Tap 2

Undervoltage check

- To check the worst undervoltage – consider the max. consumer load with the lowest PV utilisation factor of 20%.
- The PV-only DER penetration scenarios were considered.
- Undervoltages (<0.90pu) were observed due to the heavy loading on this feeder.

a) Max. consumer load with 20% PV utilisation factor



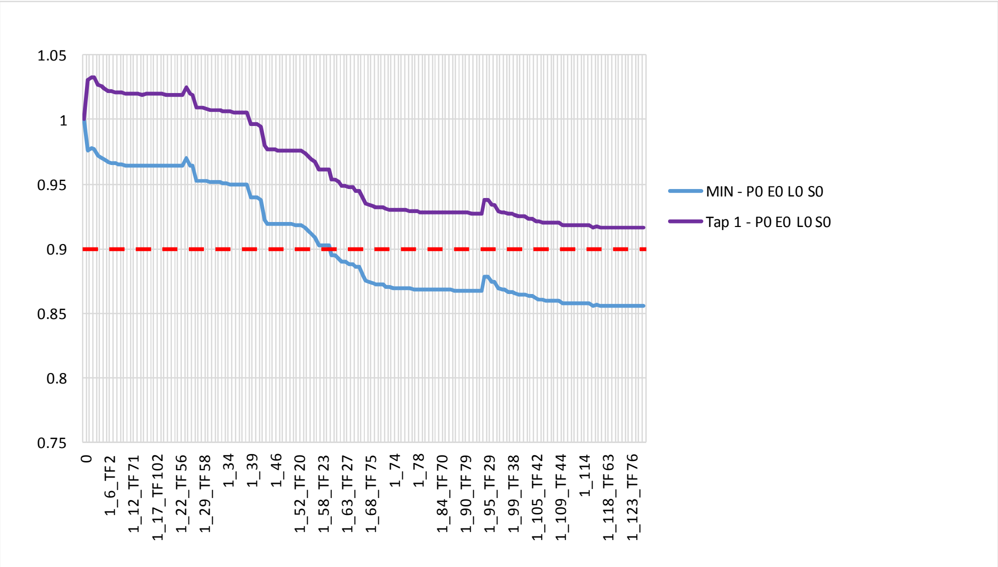
Overvoltage check

- To check the worst overvoltage – consider the min. consumer load with the highest PV utilisation factor of 80% for the PV-only DER penetration scenarios, which are most onerous for overvoltage issues.
- No overvoltages (>1.06 pu) were observed in this feeder.

Tap 1

Undervoltage check

- No undervoltages (<0.90pu) were observed.

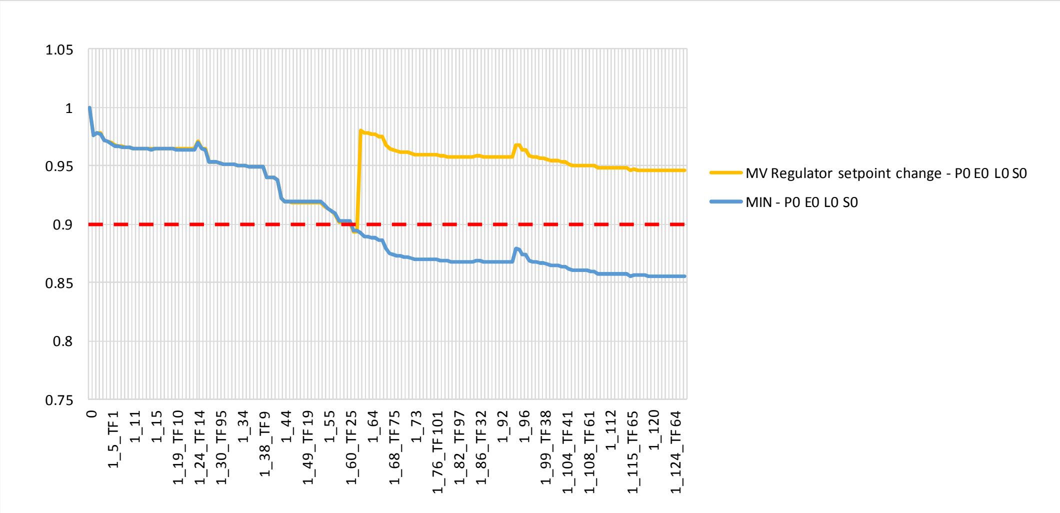


Overvoltage check

- To check the worst overvoltage – consider the min. consumer load with the highest PV utilisation factor of 80% for the PV only DERs penetration scenarios. The PV only DERs penetration scenarios are most onerous for overvoltage issues.
- No overvoltages (>1.06 pu) were observed in this feeder.

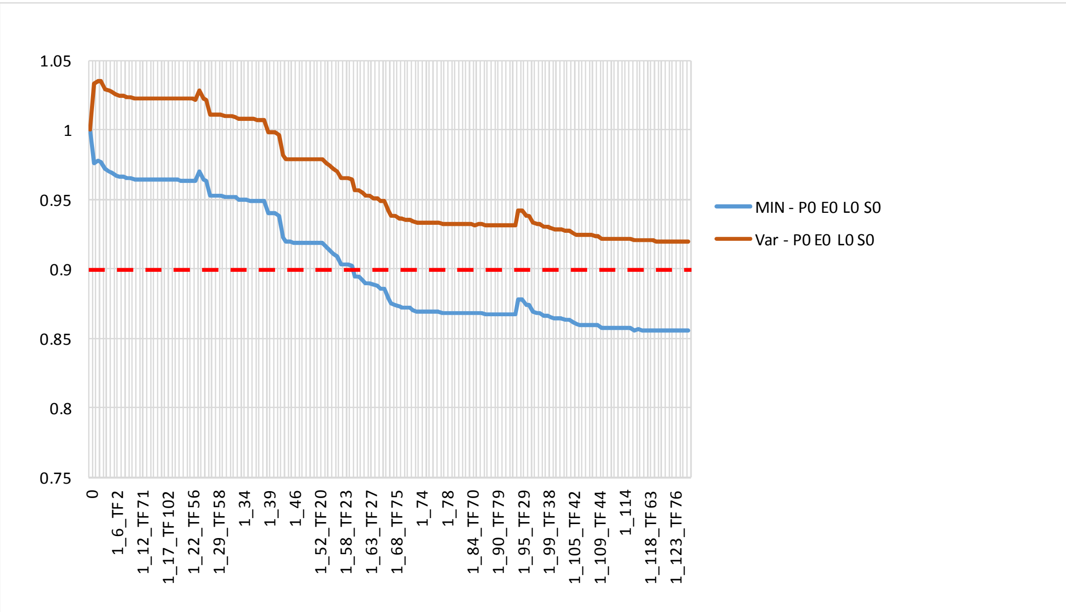
2. MV voltage regulation

This section assesses the impact existing voltage regulator settings or position changes have on the voltage under a peak demand scenario. By changing the voltage regulator setpoint, i.e. allowing the voltage regulator to tap automatically results in the voltage profile below. To achieve this voltage profile, the regulator would however need to be set at maximum tap position (tap 16). It can be seen below that one customer immediately before the voltage regulator will experience voltage below the limit.



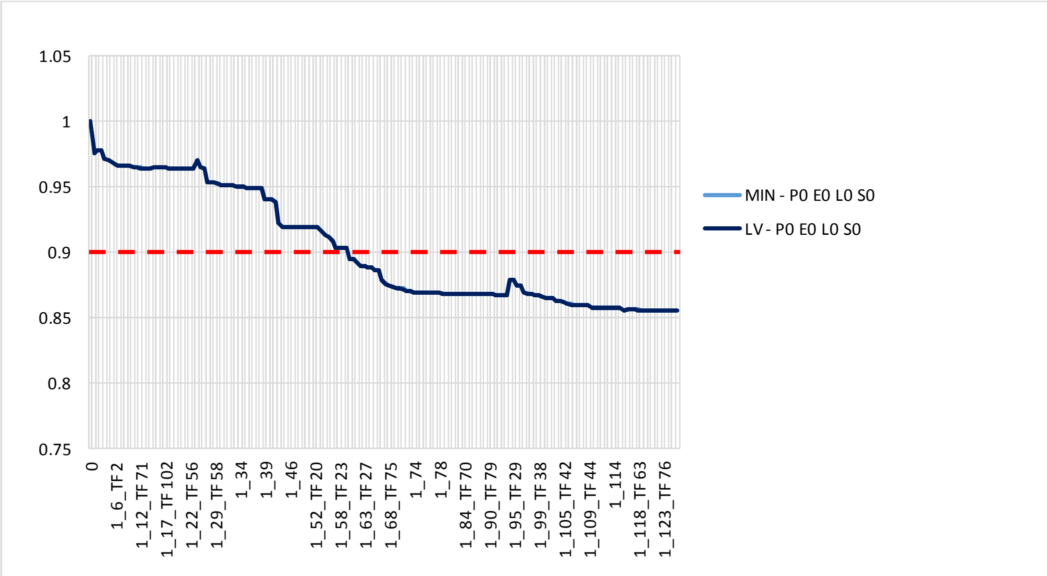
3. Dynamic VAr support

This section assesses the impact dynamic VAr support has on the voltage under a peak demand scenario. The addition of dynamic VAr support raises the voltage to within limits.



4. LV voltage regulation

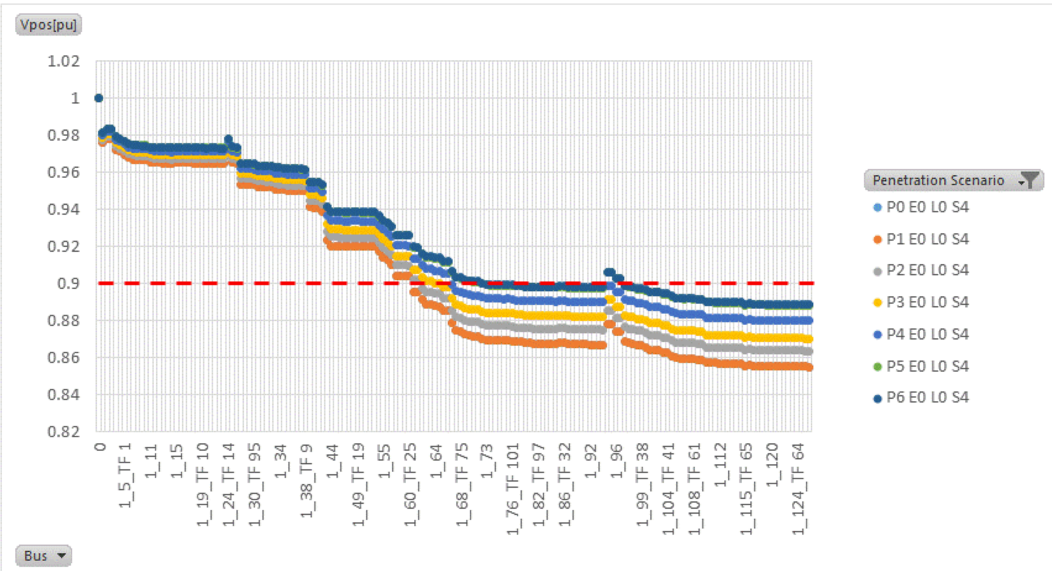
This section assesses the impact of LV voltage regulation (at the consumer level) has on the voltage under a peak demand scenario. The profile below shows that approximately 50% of customers will experience voltages below the limit therefore LV voltage regulators will be required for all these customers.



5. Controllable load and storage

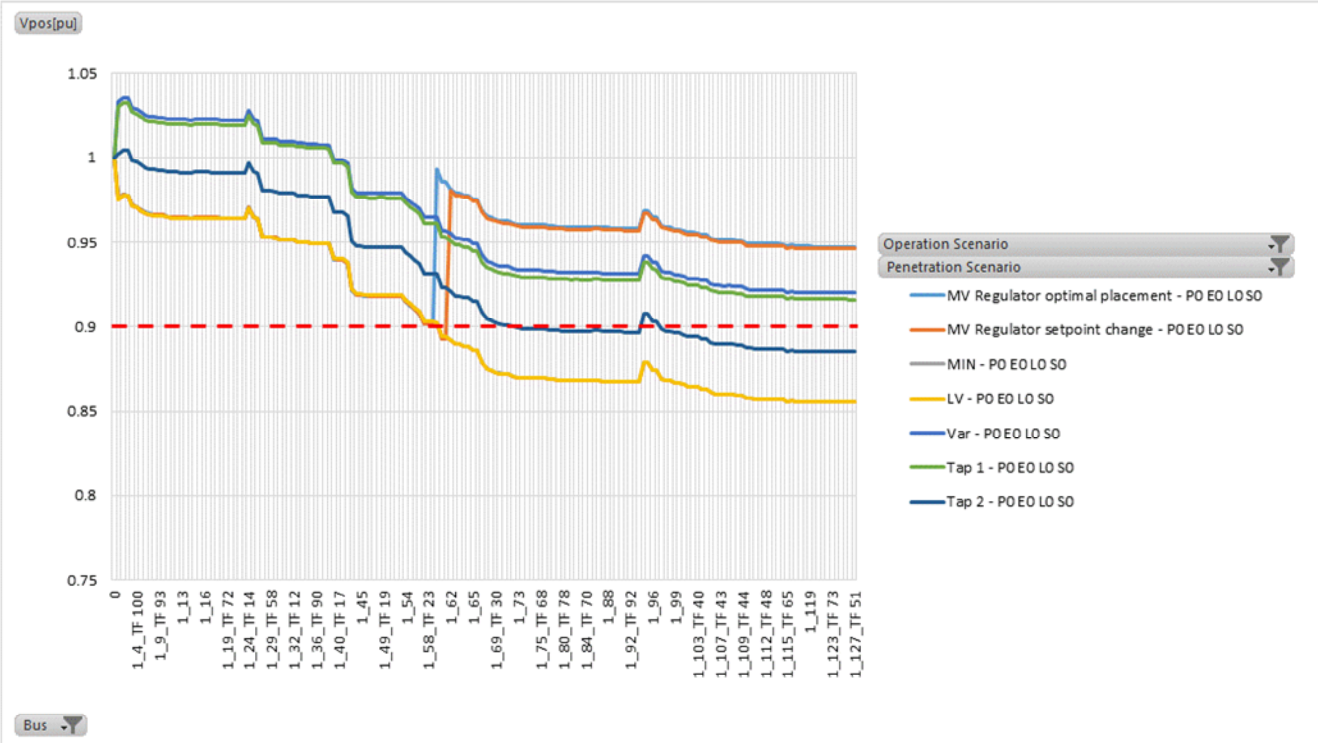
Since there is an undervoltage issue on this feeder, the only controllable load mitigation would be to use storage as generation (discharging storage batteries). The graph below implies that using storage as generation would provide insufficient mitigation to resolve the undervoltage, under all PV penetration scenarios.

- **Discharging storage loads (S4) under peak demand**

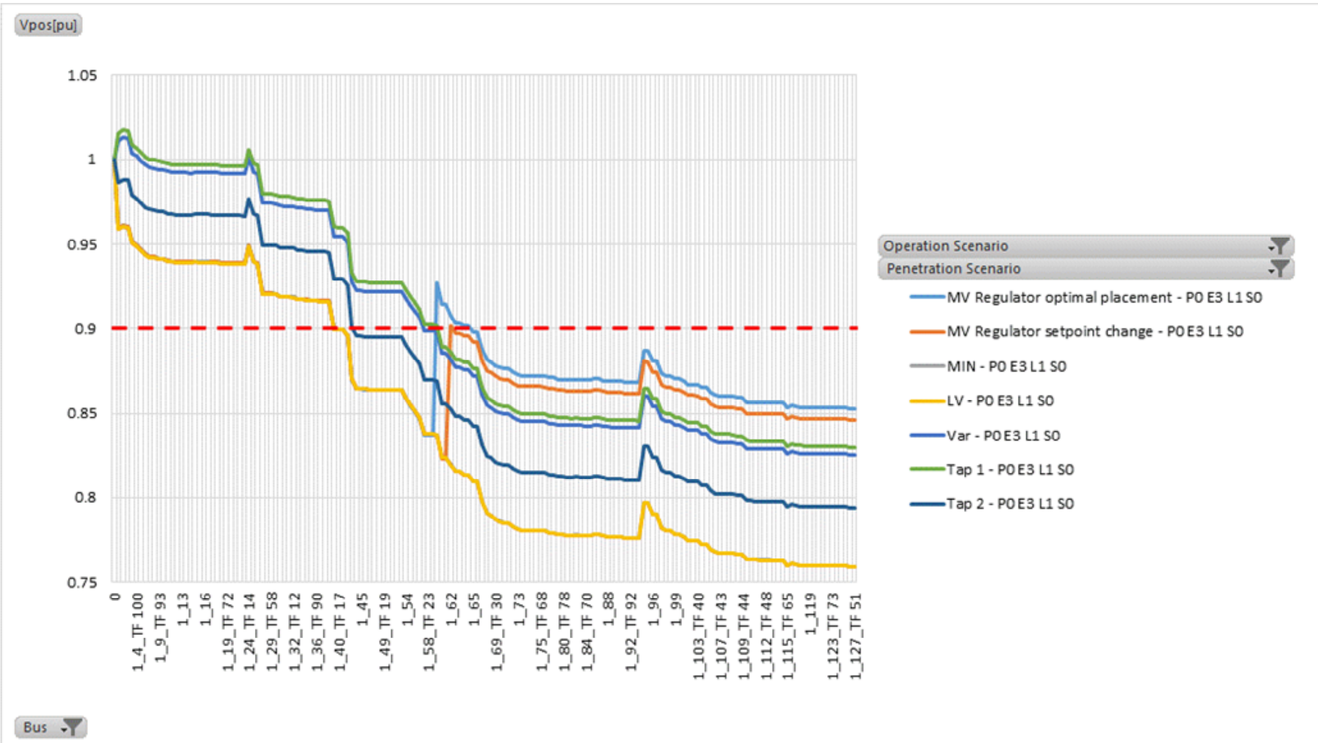


Aggregated results

The graphs below summarise all the mitigation measures investigated and the impact they have on M-23 under a peak demand scenario with and without DERs.



Impact of various mitigations on feeder voltage with DER (peak demand scenario)



The graph below summarises all the mitigation measures investigated and the impact they have on M-23 under a minimum demand scenario.