An investigation into voltage control approaches on an example distribution feeder to increase PV penetration

ENG470 Engineering Thesis Final Report

By

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Abstract

Solar power has become an increasing electricity resource in Australia's electrical energy in recent years. The increase is due to the decrease in the cost of solar Photovoltaic (PV) systems and incentives provided by the Federal Government's "Renewable Energy Target" scheme to offset carbon emissions. The existing electrical grid infrastructure was not originally designed to face high penetration levels of PV systems, so the growing embedded PV penetration levels has aroused various technical challenges and one of the key challenges is voltage rise. In order to provide methods to reduce technical barriers for achieving high penetration levels in Australian electricity networks, several approaches are studied in this report. The methods are studied with respect to prosumer (the combination of producer and consumer) aspect, utility aspect and a combination of these two aspects. The simulations were carried out using DIgSILENT PowerFactory software. Where possible, all designs and specifications are undertaken in accordance and in compliance with relevant standards and Western Power requirements and guidelines.

Three prosumers' methods which can be implemented in individual inverters are studied in chapter 6. They can be used to keep the voltage within the defined limits when the PV generation is 5kW/house, which is its assumed maximum value. But these technologies need to be upgraded to be more effective since the PV generation keeps climbing in Australian distribution networks. The utilities' methods with additional devices implemented in the network are discussed in chapter 7. These control methods can effectively and efficiently control the voltage rise problem but one disadvantage is that they are all expensive and are not economically viable options. The combination of utilities' method and prosumers' method are introduced in this report as well.

A recommendation for future studies that could be a continuation of this topic is provided at the end of the thesis report.

Acknowledgements

I would like to take this opportunity to thank my project supervisor, Dr Martina Calais, for her kind and continuous help, patience, encouragement and supervision of this thesis project. And I also thank my project co-supervisor, adjunct Professor Craig Carter, for all the help and support for the project, specifically his guidance in designing the PowerFactory system throughout the semester.

I would also like to thank all those people and friends who gave me support and helped me towards the completion of my thesis. Without them, this project could be more difficult and challenging.

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Glossary

APC	Active power curtailment
DSO	Distribution system operator
DG	Distributed generation
ElmPvsys	Photovoltaic System element
HV	High Voltage
LDC	Line Drop Compensation
LV	Low Voltage
MW	Megawatt
OLTC	On Load Tap Changer
Overvoltage	When voltage exceeds a specified upper limit
PCC	Point of Common Coupling
PF	Power Factor
PV	Photovoltaic
SMA	Solar Technology AG
Voltage Droop	Intentional loss in output voltage from a device
WP	Western Power

1 Introduction

PV generation is a form of renewable energy generation; it is one of the most effective methods to produce electricity from solar energy. In Australia, the installation of PV systems has increased substantially in recent years. The existing electrical grid infrastructure was not originally designed to face high penetration levels of PV systems, so the growing size of embedded PV generation has led to some technical issues. Key issues like voltage rise on the network will result in various problems such as difficulty in demand-supply management, so it become more and more important to find methods to manage these issues.

1.1 Aim of the project

This project aims at giving readers an introduction to some of the key technical issues caused by increased PV generation, the research is focused on voltage variations and voltage rise. Approaches from both prosumer and utility aspects that can help reduce technical barriers for achieving high penetration levels in Australian electricity networks will be discussed. An example distribution feeder in an interconnected urban network with PV generation was modelled by using the power system modelling software DigSILENT PowerFactory, which can analyse methods to increase PV generation on the sample feeder.

1.2 Thesis structure

Chapter 2 in this thesis report gives a literature review of this project, which includes Australia's solar resource and PV status, technical issues associated with the increased PV penetration and PV Inverters' voltage control strategies.

Chapter 3 presents the project methodology. A table will list the approaches that are used in this report to manage PV induced voltage rise on distribution feeders. A Gantt chart, which provides an overall timeline for the project schedule, is also discussed in this section.

Chapter 4 defines the example feeder with distributed PV generation that will be used to analyse methods to increase PV generation on a network. A description introduction of the network components is also included.

In Chapter 5, a base case and its variations are studied. Their simulation results and analyse are presented as well.

Chapter 6 to Chapter 8 describe the methods to manage the voltage rise problem on distribution feeders. Chapter 6 is focused on prosumer aspects while Chapter 7 is focused on utility aspects and Chapter 8 introduces and analyses the combinations methods of the two aspects.

Chapter 9 will conclude this project and give suggestions for future works.

2 Background

2.1 Australia Solar Resource and PV status

2.1.1 Australia Solar Resource

The Australian continent has the highest solar radiation per square metre of any continent. Consequently, Australia has some of the best solar energy resources in the world. Australia receives an average of 58 million PJ of solar radiation per year, which is approximately 10000 times larger than its total energy consumption [1].

Take WA as an example. In Figure 1, it can be seen that in Murdoch University, the maximum monthly average solar radiation incident on a horizontal surface is 8.49 kW/m^2 in December and the minimum is 2.54 kW/m^2 in June. The annual average is 5.49 kW/m^2. These figures support the claim that WA has an excellent solar resource.

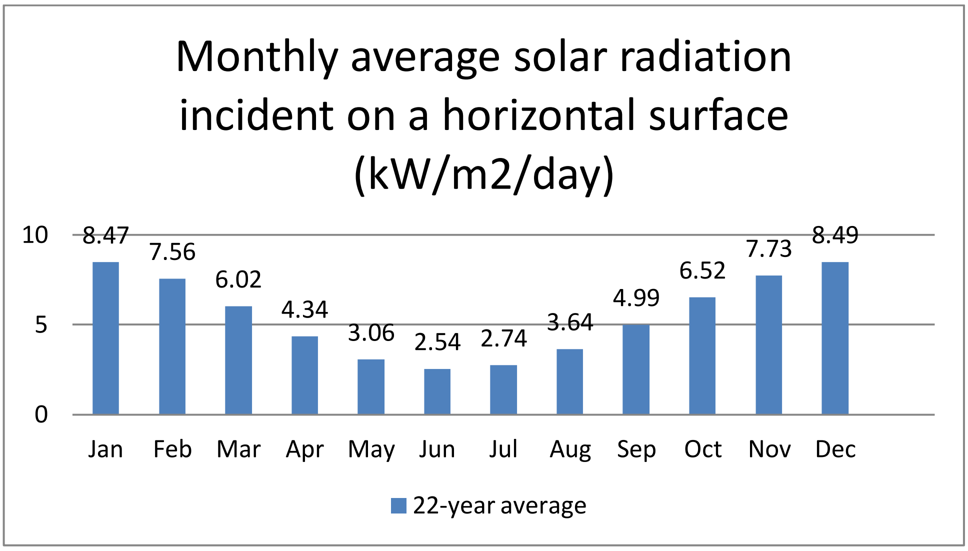

Figure 1: Monthly average solar radiation incident on a horizontal surface (kW/m2/day) at Murdoch [2]

2.1.2 Australia PV Status

In recent years, unprecedented growth has been seen in the Australian PV market, especially in residential small-scale PV systems. One of the key drivers for high growth rates in PV installation is the decline in PV system prices.

In Australia, PV systems are concentrated in major cities of each state and some rural areas, such as Alice Springs, solar resources, local industry capabilities, local government initiatives, and income levels have been the factors that have driven the emergence of high PV penetrations. A number of isolated remote grids, such as the towns of Carnarvon and Alice Springs, have also seen significant household-driven PV system deployment [3]. The largest percentage of PV systems in Australia comes from small-scale rooftop installations.

Table 1 shows a summary of small-scale PV generation in Australia in August 2015. It can be seen that Queensland has the most number of PV systems in Australia.

Table 1: Small-scale PV generation in Australia in August 2015 [4]

	Percentage of dwellings with a PV system by State/Territory (%)	Installed PV generation capacity by State/Territory (MW)	Annual energy generated from PV by State/Territory (MWh)
QLD	27.9	1,294	1,790,958
SA	27.6	535	737,156
WA	20.90	439	607,320
NSW	13.2	753	1,043,847
VIC	13.1	714	856,365
ACT	12.5	48	65,929
TAS	11.4	76	90,197
NT	7.3	15	24,118
Total		3,874	5,215,890

2.2 Technical issues associated with the increased PV penetration

2.2.1 Voltage rise

Power systems may experience over-voltage problems during the operation. The power flow on distribution feeders reverses when local PV generation is more than the local demand.

This situation often manifests itself in voltage rises along the distribution feeders, since additional power will flow from the distribution system to the transmission system. The voltage rises can result in voltages exceeding normal operation values [5], which could cause different problems such as: damage to electrical/electronic equipment and causing solar inverters to trip when they exceed an acceptable voltage range, for example 270V, AC.

Example from Carnarvon:

Two instances have been reported where over voltages have caused multiple PV inverters to disconnect from the network. Aggregated effects of a cluster of PV systems and low loads on a distribution transformer have caused the network voltage levels to rise beyond inverter cutoff limits. One of the instances was on the Richardson 1 distribution transformer (17% nominal PV penetration of the capacity of the transformer), in which a load imbalance was identified where one phase had low load and a high amount of PV generation. This problem was rectified by switching customers to different phases to balance the load [6].

2.2.2 Voltage Variations due to cloud fluctuations

Since the solar resource is irregular, the changes in solar radiation can lead to the variability of PV systems' output. When a cloud is approaching the system, the solar irradiation will be increased by refraction and reflection from the cloud and this can increase the power output from PV. When the passing cloud has covered the system, this can lead to rapid decrease in PV system output. The combination of these effects can cause large output variations on the system.

Example from Carnarvon:

There are two examples of cloud shear that have been identified on the Carnarvon network. One of the instances was that a small cloud passed over when examining a 10 kW inverter during a survey of PV system installations, which caused the output of the inverter to decrease from 8kW to 2.2 kW in about 2 seconds as the cloud passed over resulting in a 72% change in PV output [6].

2.3 PV Inverters' Voltage Control Strategies

This section discusses some control strategies of LV inverters in order to keep the network voltages in a defined range.

- Active power Curtailment

The output active power will be limited when the inverter output terminal voltage has reached the over-voltage level. This is achieved by forcing operation from the maximum power point towards the open circuit voltage of the PV panel [7].

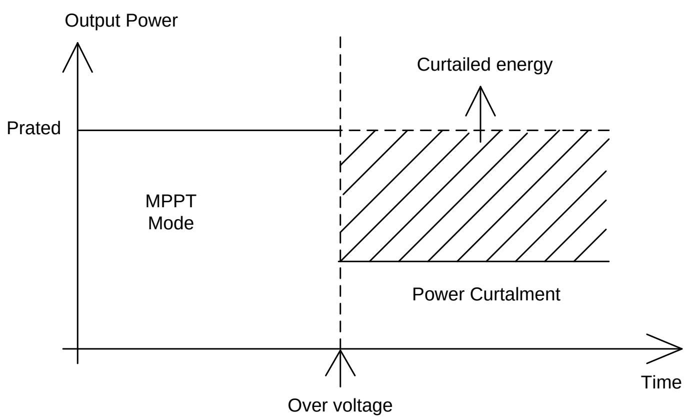

Figure 2: Power curtailment after over voltage condition [7]

- Reactive power absorption/provision as a function of real power

The German standard for low voltage, VDE-AR-N 4105, requires that PV generators operate within ±10% of the nominal voltage and up to 20% above of their maximum real power rating within the power factor ranges given in Table 2 [5] [8]:

Table 2: System solutions for the new VDE code of practice (VDE-AR-N-4105) [8]

Apparent Power S (kVA)	Power Factor	Set by network operator
S<=3.86	0.95 absorbing to 0.95 delivering	No
3.86<S<=13.8	Between 0.95 absorbing to 0.95 delivering	Yes, either by providing a fixed power factor pf or a function of P, pf(P)
13.8<S	Between 0.9 absorbing to 0.9 delivering	Yes, either by providing a fixed power factor pf or a function of P, pf(P)

- Reactive Power Support

PV inverters can contribute to lowering their impact (voltage rise) on the grid when solar irradiation is high, by using their reactive and active power control capabilities, without any additional grid reinforcement measures [9]. In order to keep network voltage in a regulated range, distributed PV based inverters can inject or absorb reactive power to control the voltage.

- Relevant voltage and frequency ranges for PV inverters

Table 3 shows the relevant voltage and frequency ranges for operation of PV inverters as given in the guidelines from AS4777 and Horizon Power. Keeping the values in these ranges can potentially reduce the number of inverter tripping instances.

Table 3: Allowable voltage and frequency ranges as per AS4777 and Horizon Power connection guidelines [10]

LV Parameter	Minimum	Maximum
AS 4777 Voltage	200-230V	230-270V
Horizon Power Voltage	225.6V	254.4V
Default SMA Voltage protection set points in Australia	200V	270V
AS 4777 Frequency	45-50Hz	50-55Hz
Horizon Power Frequency	47.5Hz	52Hz
Default SMA Frequency protection set points in Australia	45Hz	52Hz

3 Project methodology

3.1 Project investigation approaches

Table 4 shows the approaches that are used in this project to manage PV induced voltage rise on distribution feeders. This table was designed to make it easier for the readers to identify the tasks that have been carried out in this project. The details of the methods and the analysis of the simulation results are described in Chapters 5, 6 and 7.

Table 4: The approaches to manage PV induced voltage rise on distribution feeder

Prosumer / Utility	pf=1	pf=0.95 leading	Q(V)	P(V)
Do nothing	See Chapter 5	See Chapter 6.1	See Chapter 6.2	See Chapter 6.3
Implement line drop compensation in the substation transformer	See Chapter 7.1	See Chapter 8.1	See Chapter 8.2	X
Implement On Load Tap Changer (OLTC) on distribution transformers	See Chapter 7.2	X	X	X
Implement STATCOM devices	See Chapter 7.3	See Chapter 8.3	X	X

3.2 Gantt chart

The Gantt chart shown in Appendix A provides an overall timeline for the project schedule. The Gantt chart was made using GanttProject and was used throughout the project as a project management tool. It was kept up to date to show the progress to date. There was a gap week from 28th September to 2nd October 2015, which delayed work due to personal circumstances.

4 Define the example feeder

This chapter describes the approaches taken to model the example feeder with distributed PV generation in order to analyse methods to increase PV generation on a network. DigSILENT PowerFactory version 15.2 was used for this task. For the purpose of building a reasonable example distribution feeder, the feeder modelling has taken into account AS3008 [11] for the LV cable data and applied cable data taken from Nexans Olex High Voltage Catalogue for HV cable [12].

The networks elements that were created within PowerFactory will be discussed briefly in this chapter. The details of the network data and PV systems outputs will be outlined as well.

4.1 Description of the example feeder

The distribution network is shown in Figure 3 and an enlarged diagram for the network in dashed line area is shown in Figure 4. All line and transformer impedances are expressed in per unit value on a 100MVA base. These impedances are listed in section 4.2.

This system is a simulation of a residential area. This network consists of a slack generator behind a source impedance, representing the rest of the grid, which is connected to a 132/22 kV substation via two 20MVA 132/22 kV transformers in parallel.

A 22kV feeder has been modeled using 50 mm^2 aluminum 22kV cables and with six 630 kVA 22kV/415V distribution transformers connected on the 22kV side at distances of 0.5 km, 1 km, 1.5 km, 2 km, 2.5 km and 3 km from the substation. Two LV feeders have been modeled using 95 mm^2 aluminum 415V cables connected to each 630 kVA 22kV/415V transformer. Each LV feeder has three “20 house clusters” at distances of 25m, 125m and 205m from the 22kV/415V transformer.

In this project, the system is assumed to be balanced, but this would not necessarily be the case in practice. Sometimes if a load imbalance occurs, where one phase had low load and a high PV generation. The voltage rise problems on the LV feeders will be worse than for the balanced scenario. This can be rectified by switching customers to different phases so that the load becomes more balanced refer to the previous reference on page 3. This issue will not be discussed in detail in this project but may be the subject of studies in the future.

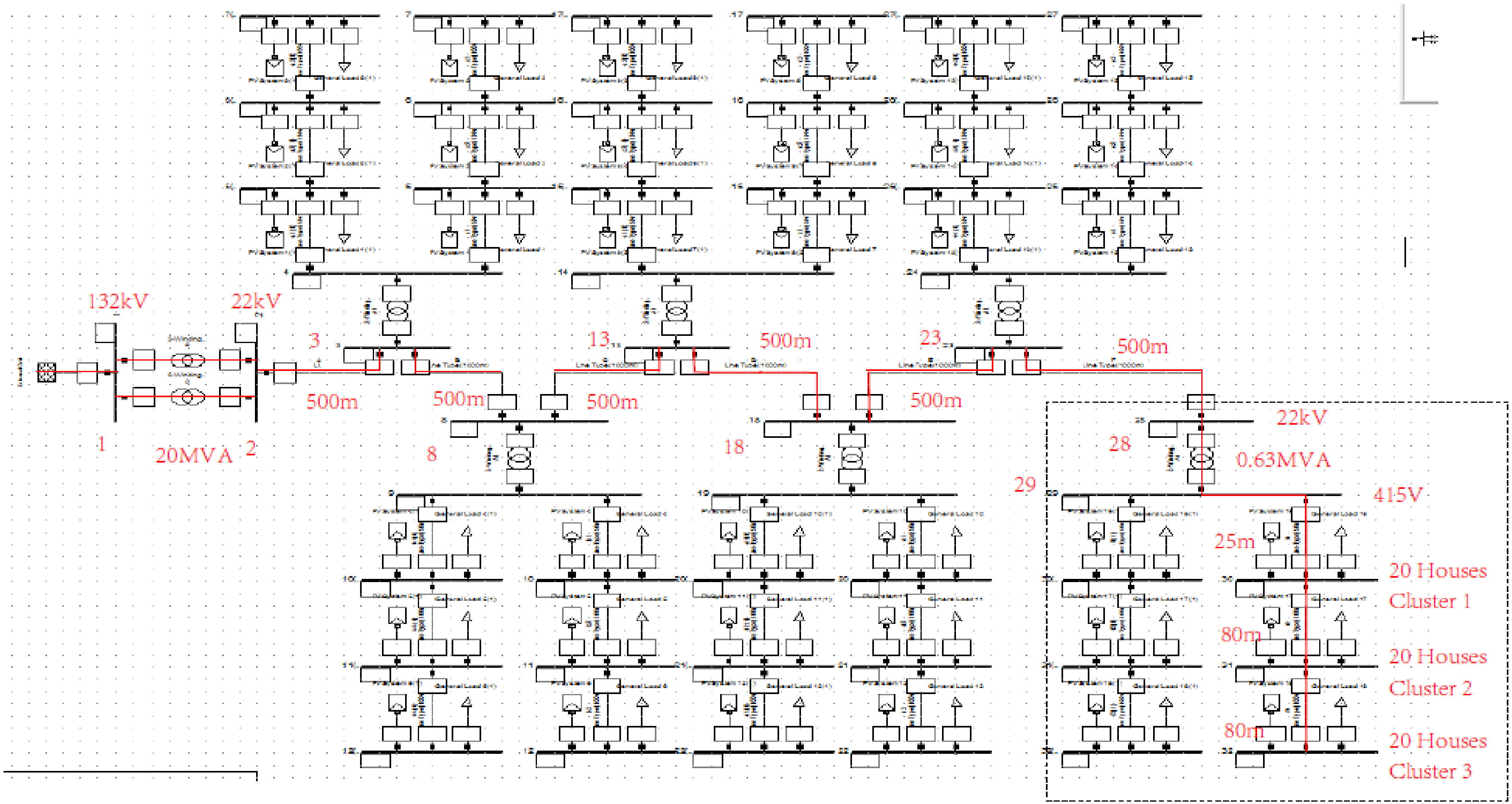

Figure 3: Example feeder modelled by PowerFactory

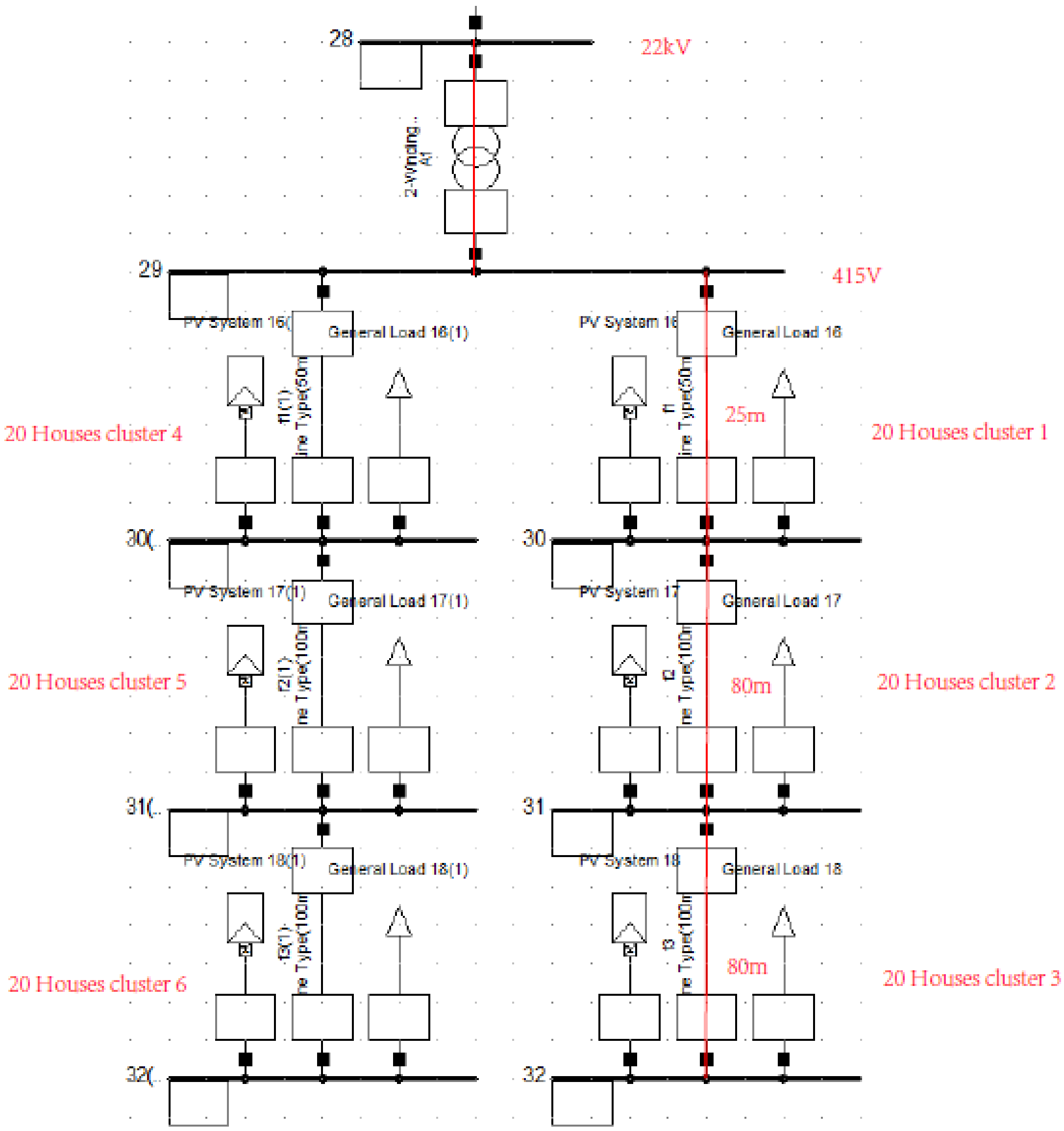

Figure 4: Enlarged diagram for the feeder

4.2 Network components

4.2.1 LV cables

Table 5 is the summary of LV line impedances of the example feeder. The rated voltage of the feeder is 0.415kV. Table 5 uses the 415V feeder in figure 4 as an example.

Table 5: LV transmission lines data

From bus	To bus	Rated voltage	Length	Material	Resistance	Reactance	System type
29	30	415V	25m	Aluminum	0.372 ohm/km	0.0766 ohm/km	AC
30	31	415V	80m	Aluminum	0.372 ohm/km	0.0766 ohm/km	AC
31	32	415V	80m	Aluminum	0.372 ohm/km	0.0766 ohm/km	AC

4.2.2 HV cables

The rated voltage of the HV feeder is 22kV, and the line impedances are summarised in Table 6.

Table 6: HV transmission lines data

From bus	To bus	Rated voltage	Length	Material	Resistance	Reactance	System type
2	3	22kV	500m	Aluminum	0.821 ohm/km	0.134 ohm/km	AC
3	8	22kV	500m	Aluminum	0.821 ohm/km	0.134 ohm/km	AC
8	13	22kV	500m	Aluminum	0.821 ohm/km	0.134 ohm/km	AC
13	18	22kV	500m	Aluminum	0.821 ohm/km	0.134 ohm/km	AC
18	23	22kV	500m	Aluminum	0.821 ohm/km	0.134 ohm/km	AC
23	28	22kV	500m	Aluminum	0.821 ohm/km	0.134 ohm/km	AC

4.2.3 Two winding transformers

Two winding transformers can be inserted as voltage regulators on long rural power distribution lines, to keep voltages within a range. The key parameters for the transformers are listed in Table 7. The 132kV/22kV transformer model including winding configuration is shown in Figure 5, the 22kV/415V transformer model is shown in Figure 6.

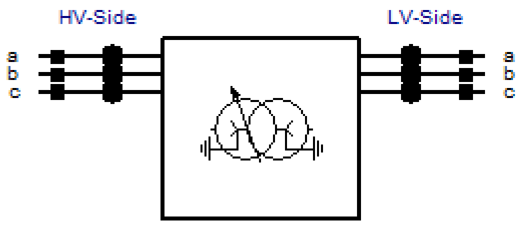

Figure 5: 132kV/22kV transformer model

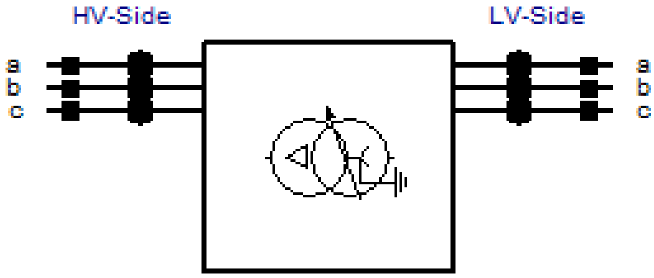

Figure 6: 22kV/415V transformer model

The 132kV/22kV Transformer is connected between buses 1 and 2, while the 22kV/415V transformers are connected between buses 3 and 4, buses 8 and 9, buses 13 and 14, buses 18 and 19, buses 23 and 24, buses 28 and 29.

Table 7: Transformer data

	132kV/22kV Transformer	22kV/415V Transformer
Rated Power	20MVA	0.63MVA
Positive Sequence Impedance	0.1+j0.5	0.01+j0.06
Tap Position	11	3
Additional Voltage Per Tap	1.4%	2.5%
Voltage Set Point	1.02	
Neutral Position	11	3
Min Position	1	1
Max Position	21	5
Tap Changer Delay (s)	60	60

5 Base case and its variations

5.1 Base case

A base case scenario was built for this project task and other study scenarios are specified variations of this case.

In the base case, each LV feeder has three “20-house clusters” at distances of 25m, 80m and 80m from the substation. Each cluster has 20 houses and the load for each house is 4kVA, which is the maximum daytime load and there is no PV generation in this case.

The data in PowerFactory for base case scenario is shown in Table 8.

Table 8: Base case scenario data

Names	Apparent Power	Power Factor	PV generation
Cluster 1	0.08MVA	0.85	None
Cluster 2	0.08MVA	0.85	None
Cluster 3	0.08MVA	0.85	None
Cluster 4	0.08MVA	0.85	None
Cluster 5	0.08MVA	0.85	None
Cluster 6	0.08MVA	0.85	None

The voltage profile for the base case scenario is shown in Figure 7. The conducting of the voltage profile is taken along the red path shown in Figure 3.

The positive sequence voltage magnitudes are expressed in p.u., starting from the 132kV ‘grid’ bus. In accordance with Clause 2.2.2 of Western Power Technical Rules, for those parts of the distribution system operating below voltages of 6kV, the steady state voltage must be within +/- 6 % of the nominal voltage during normal operating state [13]. The voltage profile of the base case has a voltage at the end of the LV feeder connected to the furthest 22kV/415V transformer of around 0.95 p.u.. This is because a fully loaded feeder would have LV voltages at its end around 5% below nominal so that the houses connected to the end of the feeder are supplied with voltage no lower than 6% below nominal, which allows for a +/- 1% voltage variation along the LV connection from the LV cable between the street to the houses’ LV switchboards. So in this project, the network is required to operate within voltage limits of +/- 5% of the nominal network voltage, which is 0.95p.u.to 1.05p.u.

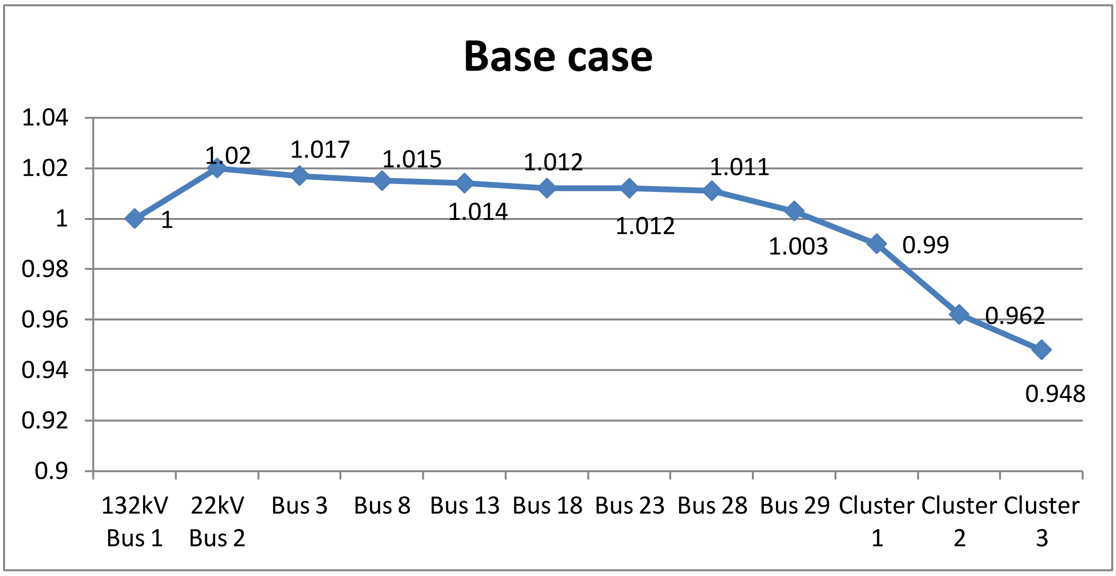

Figure 7: Base case scenario voltage profile

5.2 Minimum daytime load cases

In order to determine the impact on the voltage at the end of the LV feeder by an increase in PV penetration, the following cases are studied. The minimum daytime load is assumed to be 2kVA per house, or 0.04MVA per load cluster. The purpose of studying the following cases is to find out the voltage at the end of the LV feeder for the worst case scenario.

5.2.1 Minimum daytime load with no solar generation

The data in PowerFactory for minimum daytime load with no solar generation scenario is shown in Table 9.

Table 9: Minimum daytime load with no solar data

Names	Apparent Power	Power Factor	PV generation
Cluster 1	0.04MVA	0.85	None
Cluster 2	0.04MVA	0.85	None
Cluster 3	0.04MVA	0.85	None
Cluster 4	0.04MVA	0.85	None
Cluster 5	0.04MVA	0.85	None
Cluster 6	0.04MVA	0.85	None

The voltage profile for this case is given in Figure 8.

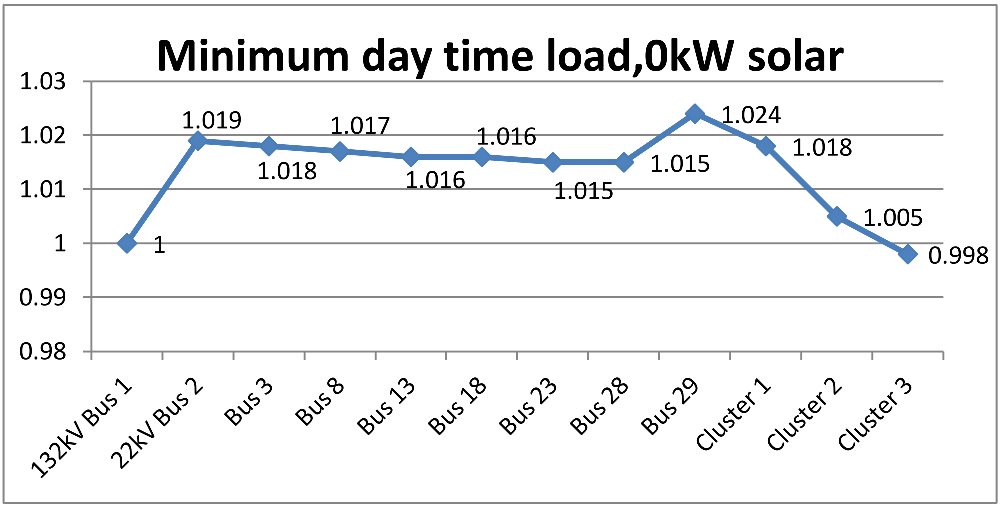

Figure 8: Minimum day time load, no solar voltage profile

5.2.2 Minimum daytime load with 1kW solar/house generation

The data in PowerFactory for minimum daytime load with 1kW solar/house generation scenario is shown in Table 10.

Table 10: Minimum daytime load with 1kW solar/house data

Names	Apparent Power	Power Factor	PV generation	PV Power Factor
Cluster 1	0.04MVA	0.85	20kW	1
Cluster 2	0.04MVA	0.85	20kW	1
Cluster 3	0.04MVA	0.85	20kW	1
Cluster 4	0.04MVA	0.85	20kW	1
Cluster 5	0.04MVA	0.85	20kW	1
Cluster 6	0.04MVA	0.85	20kW	1

The voltage profile for this case is given in Figure 9.

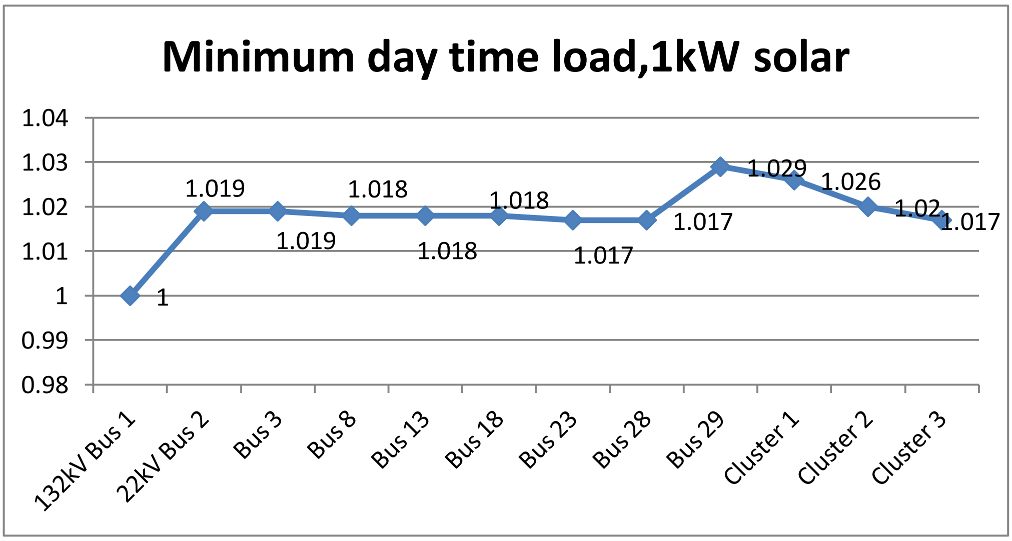

Figure 9: Minimum daytime load, 1kW solar/house voltage profile

5.2.3 Minimum daytime load with 2kW solar/house generation

The data in PowerFactory for minimum daytime load with 2kW solar/house generation scenario is shown in Table 11.

Table 11: Minimum daytime load with 2kW solar/house data

Names	Apparent Power	Power Factor	PV generation	PV Power Factor
Cluster 1	0.04MVA	0.85	40kW	1
Cluster 2	0.04MVA	0.85	40kW	1
Cluster 3	0.04MVA	0.85	40kW	1
Cluster 4	0.04MVA	0.85	40kW	1
Cluster 5	0.04MVA	0.85	40kW	1
Cluster 6	0.04MVA	0.85	40kW	1

The voltage profile for this case is given in Figure 10.

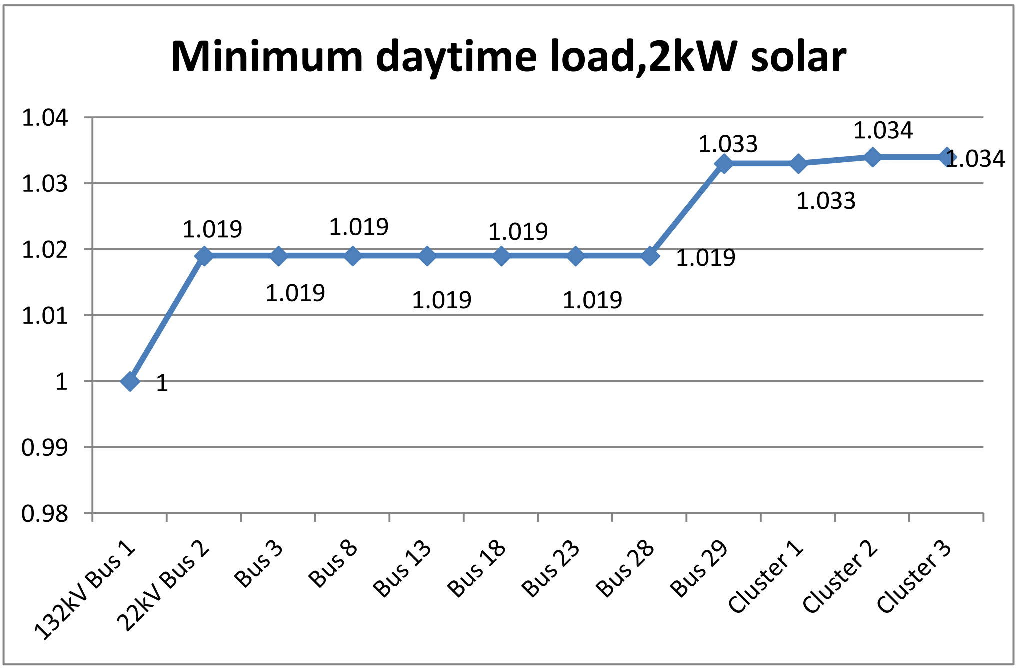

Figure 10: Minimum daytime load, 2kW solar/house voltage profile

5.2.4 Minimum daytime load with 3kW solar/house generation

The data in PowerFactory for minimum daytime load with 3kW solar/house generation scenario is shown in Table 12.

Table 12: Minimum daytime load with 3kW solar/house data

Names	Apparent Power	Power Factor	PV generation	PV Power Factor
Cluster 1	0.04MVA	0.85	60kW	1
Cluster 2	0.04MVA	0.85	60kW	1
Cluster 3	0.04MVA	0.85	60kW	1
Cluster 4	0.04MVA	0.85	60kW	1
Cluster 5	0.04MVA	0.85	60kW	1
Cluster 6	0.04MVA	0.85	60kW	1

The voltage profile for this case is given in Figure 11.

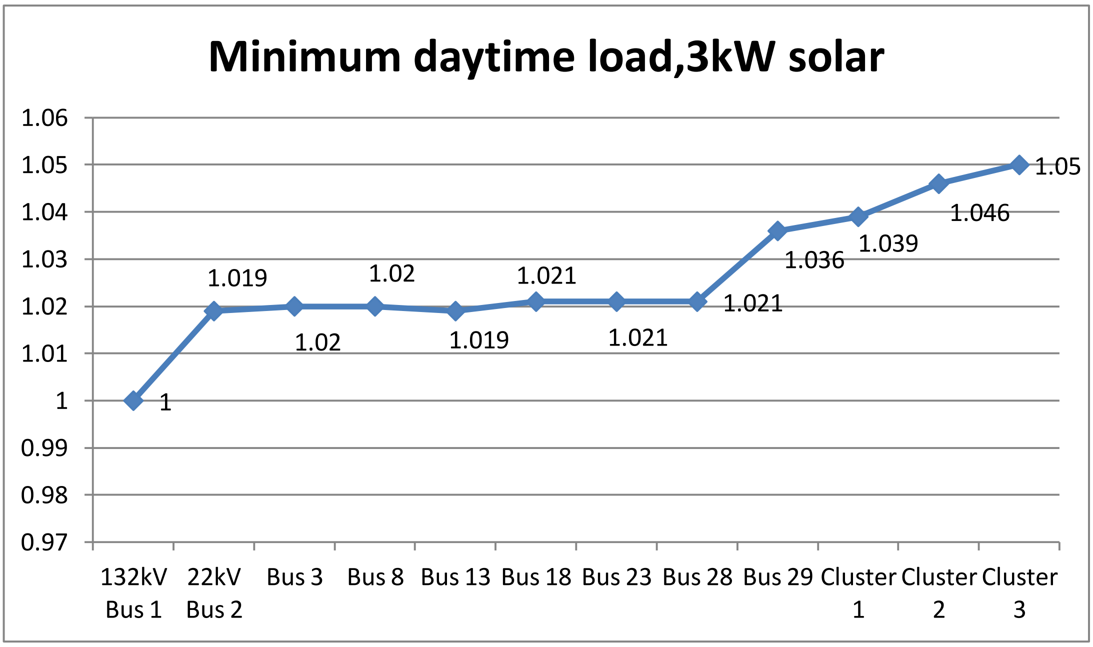

Figure 11: Minimum daytime load, 3kW solar/house voltage profile

5.2.5 Minimum daytime load with maximum PV generation

The maximum PV generation for per house is assumed to be 5kW since most of the residential systems' sizes are under 5 kW.

The data in PowerFactory for minimum daytime load with maximum PV generation scenario is shown in Table 13.

Table 13: Minimum daytime load with 5kW solar/house data

Names	Apparent Power	Power Factor	PV generation	PV Power Factor
Cluster 1	0.04MVA	0.85	100kW	1
Cluster 2	0.04MVA	0.85	100kW	1
Cluster 3	0.04MVA	0.85	100kW	1
Cluster 4	0.04MVA	0.85	100kW	1
Cluster 5	0.04MVA	0.85	100kW	1
Cluster 6	0.04MVA	0.85	100kW	1

The voltage profile for this case is given in Figure 12.

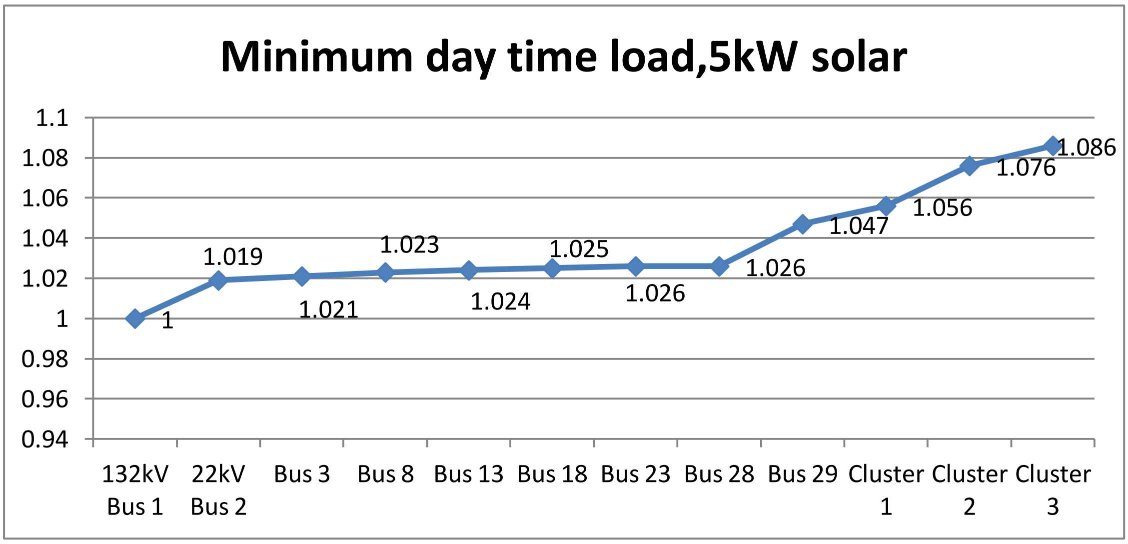

Figure 12: Minimum daytime load, 5kW solar/house voltage profile

5.3 Discussion

Figure 13 shows the combination of the voltage profiles for the different scenarios listed above. As mentioned earlier, the voltage at the end of the LV feeder (20 houses in cluster 3) connected to the furthest 22kV/415V transformer should not be outside the range: 0.95 p.u.- 1.05 p.u. It can be seen from figure 14 that the voltage at the end of the LV feeder (20 houses cluster 3) has reached the upper limit value, when the PV generation is increased to 3kW/house. In order to keep the voltage in the defined range at the maximum PV penetration of 5kW/house case, some form of compensation will need to be considered. Different methods will be introduced and discussed in the next chapter.

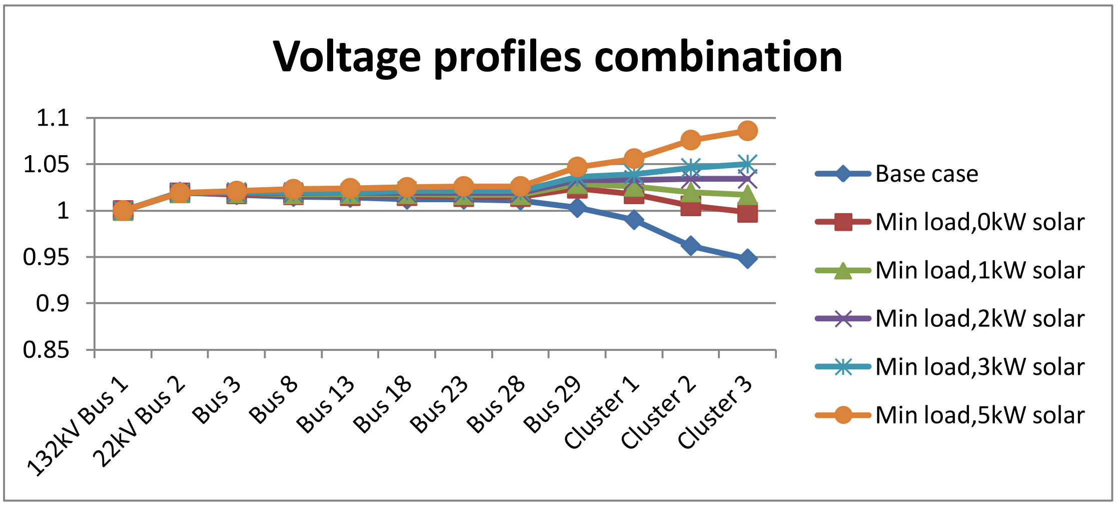

Figure 13: Combination of the voltage profiles

Figure 14 shows the voltages at "20 houses cluster 3" for the different scenarios.

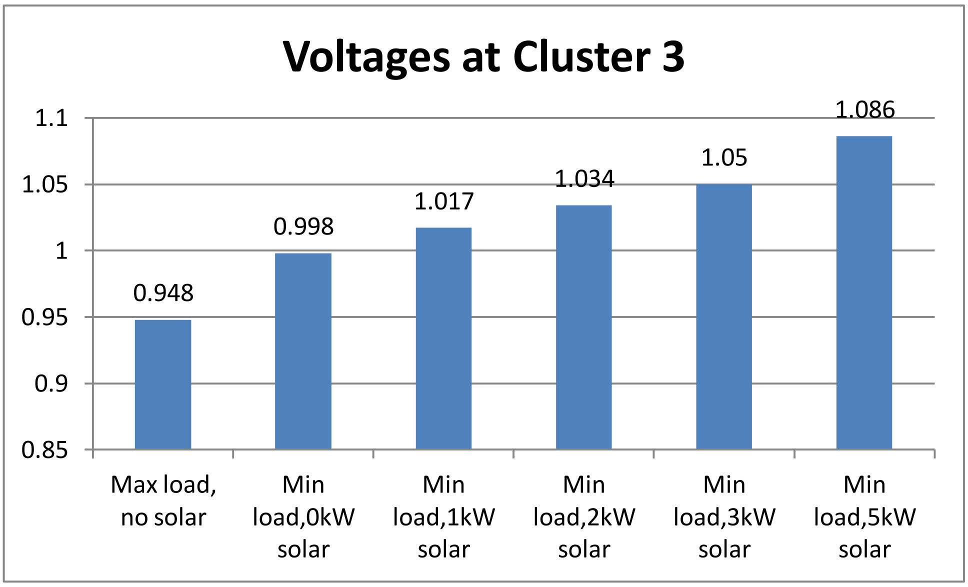

Figure 14: Voltages at "20 houses cluster 3"

6 The approaches to manage voltage rise on distribution feeders using PV inverters (prosumer aspect)

The penetration of grid-connected PV systems tends to raise the voltage in the LV network. As noted in the previous chapters, this could become a problem, since over voltages on the network can have an impact on utility regulatory compliance, and could lead to increases in equipment power consumption and cause the disconnection of PV inverters [6]. The purpose of this chapter is to list the approaches prosumers can take to manage the voltage rise on distribution feeders by using PV inverters with different reactive power characteristics. Also, different levels of PV penetration are applied in the example model and the simulation results of different scenarios will be discussed as well.

In this chapter, the minimum daytime load is assumed to be 2kVA/house and this minimum load is applied to all the simulation cases.

The approaches that will be discussed are:

- Change the power factor of PV inverter from 1 to 0.95 leading
- Use the Q (V) voltage control function of the PV inverter
- Use the P (V) voltage control function of the PV inverter

6.1 Change the power factor of PV inverter from 1 to 0.95 leading

Fixed power factor operation could be a simple and low cost method of managing voltage. Operators often use non-unity power factor to achieve system requirements where a system voltage is affected by the variability of the inverter real power output.

In this case, the load for each house is 2kVA at 0.85 pf. So the load for each cluster is 0.04MVA. In PowerFactory simulation, the PV generation increases from no solar to 5kW solar/house, in order to see the impact on the voltage at cluster 3 with the increased PV generation.

Scenarios	Apparent Power (per cluster)	Power Factor	PV Generation (per cluster)	PV Power Factor
0kW solar/house	0.04MVA	0.85	0kW	0.95leading
1kW solar/house	0.04MVA	0.85	20kW	0.95leading
2kW solar/house	0.04MVA	0.85	40kW	0.95leading
3kW solar/house	0.04MVA	0.85	60kW	0.95leading
4kW solar/house	0.04MVA	0.85	80kW	0.95leading
5kW solar/house	0.04MVA	0.85	100kW	0.95leading

Figure 15: 0.95 pf scenario data

6.1.1 Simulation results

Table 14: 0.95 pf scenario simulation results

	0kW Solar	1kW Solar	2kW Solar	3kW Solar	4kW Solar	5kW Solar
132kV Bus 1	1	1	1	1	1	1
22kV Bus 2	1.019	1.019	1.019	1.019	1.019	1.02
Bus 3	1.018	1.019	1.019	1.02	1.0201	1.021
Bus 8	1.017	1.018	1.019	1.02	1.021	1.022
Bus 13	1.016	1.018	1.019	1.02	1.0217	1.024
Bus 18	1.016	1.017	1.019	1.021	1.0222	1.024
Bus 23	1.015	1.017	1.019	1.021	1.0225	1.025
Bus 28	1.015	1.017	1.019	1.021	1.0227	1.025
Bus 29	1.024	1.025	1.025	1.025	1.0242	1.024
20 Houses Cluster 1	1.018	1.022	1.025	1.027	1.0297	1.032
20 Houses Cluster 2	1.005	1.015	1.024	1.033	1.0414	1.05
23 Houses Cluster 3	0.998	1.012	1.024	1.036	1.0473	1.059

The voltage profile is shown in Figure 16.

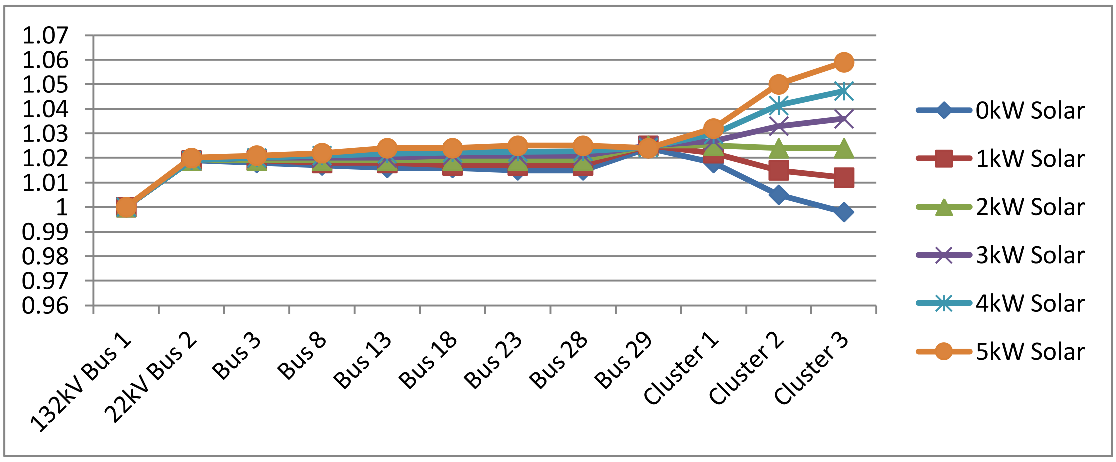

Figure 16: 0.95 pf scenario simulation result

6.1.2 Discussion

Figure 17 shows the voltages at cluster 3 for the cases of different PV penetration.

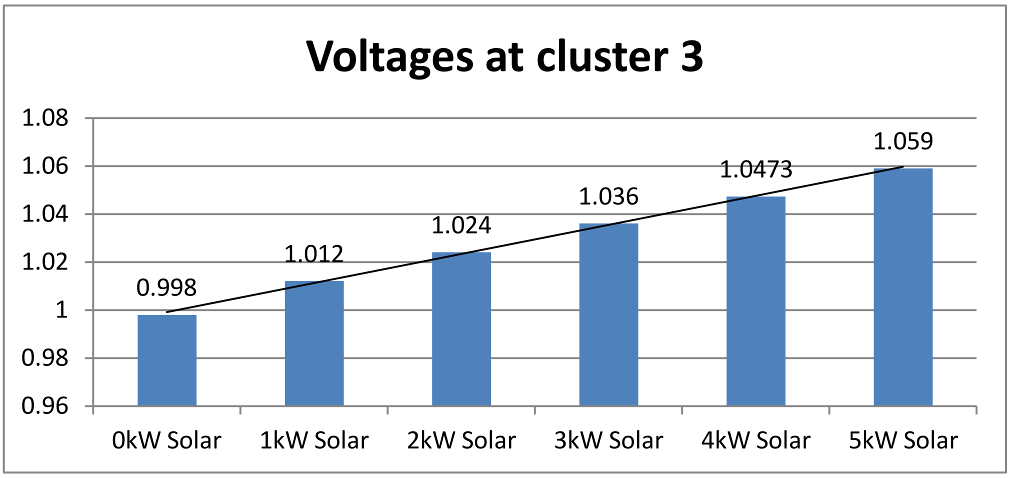

Figure 17: Voltages at cluster 3

As we can see from Figure 17, it is clear that the voltages at cluster 3 are within the specified voltage operation limits until the PV generation has reached a value between 4kW and 5kW. In the section 5.2 with minimum load, the voltage at cluster 3 has reached the limit (1.05 p.u.) when the solar generation is 3kW/house. Compared with this, the voltage changes have been moderated by using inverters with a fixed power factor added.

6.2 Use the Q (V) voltage control function of PV inverters

Reactive power control is important in electrical systems. Through controlling the production, absorption, and flow of reactive power at all levels in the system, voltage/Var control can maintain the voltage profile within acceptable limits and reduce the transmission losses [14].

In this case, the load for each house is 2kVA at 0.85 pf. So the load for each cluster is 0.04MVA. In PowerFactory simulation, the PV generation increases from no solar to 5kW solar/house. The data for each scenario is shown at Table 15.

Table 15: Q (V) method scenario

Scenarios	Apparent Power (per cluster)	Power Factor	PV Generation (per cluster)	PV Power Factor
0kW solar/house	0.04MVA	0.85	0kW	1
1kW solar/house	0.04MVA	0.85	20kW	1
2kW solar/house	0.04MVA	0.85	40kW	1
3kW solar/house	0.04MVA	0.85	60kW	1
4kW solar/house	0.04MVA	0.85	80kW	1
5kW solar/house	0.04MVA	0.85	100kW	1

In accordance with Clause 6.3.2.3 of Draft AS/NZ4777:2015, the volt-VAr response mode varies the reactive power output of the inverter in response to the voltage at its grid-interactive port. The response curve required for the volt-VAr response is defined by the volt response reference values specified in Table 16 and corresponding VAr levels. These are listed in Table 17 and shown in Figure 18 [15].

Table 16: Volt response reference values [15]

Reference	Aus. default value (volts)	NZ default value (volts)	Range (volts)
V_1	207	207	Not applicable
V_2	220	220	216 to 230
V_3	250	240	240 to 255
V_4	265	255	253 to 265

Table 17: Volt-var response set-point values for reference voltages [15]

Reference	Default values for VAr level (% rated VA)	Range
V_1	30% leading	0 to 60% leading
V_2	0%	0%
V_3	0%	0%
V_4	30% lagging	0 to 60% lagging

NOTE: The percentage VAr/VA level leading is supplying VArs to the grid, whereas the percentage VAr/VA level lagging is drawing VAr from the grid.

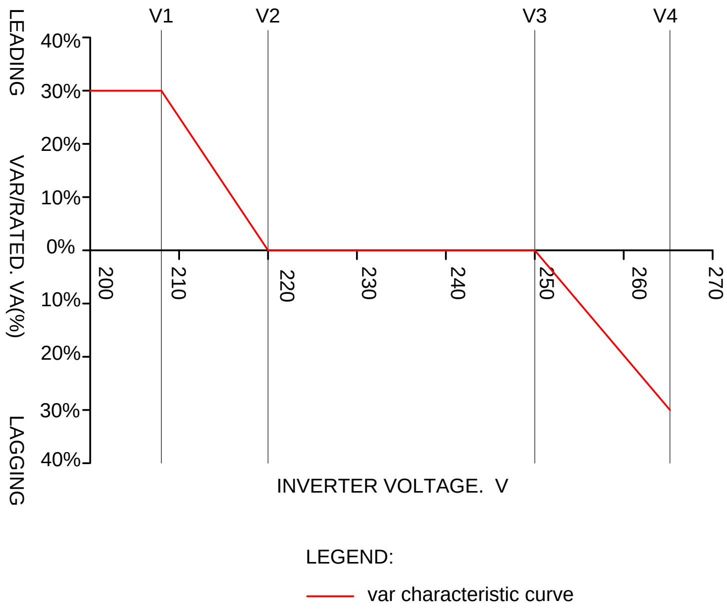

Figure 18: Example curve for a possible volt-Var control mode (Australia) [15]

In this control method, the inverter operates as a voltage regulator. If the measured voltage is below the limit, the inverter supplies reactive power to boost the voltage. If the measured voltage is above the limit, the inverter absorbs reactive power to reduce the voltage to keep it in the defined range.

6.2.1 Simulation results

- Without a deadband

The Q (V) characteristics data is shown in Table 18

Table 18: Q (V) characteristics data (without a deadband)

Voltage Droop	Lower Voltage Limit of deadband	Upper Voltage Limit of deadband
5%	1 p.u.	1 p.u.

The simulation results are shown in Table 19.

Table 19: Q (V) method scenario simulation results (without a deadband)

	0kW Solar	1kW Solar	2kW Solar	3kW Solar	4kW Solar	5kW Solar
132kV Bus 1	1	1	1	1	1	1
22kV Bus 2	1.02	1.019	1.02	1.019	1.019	1.019
Bus 3	1.018	1.019	1.02	1.02	1.02	1.021
Bus 8	1.018	1.018	1.02	1.02	1.021	1.022
Bus 13	1.017	1.018	1.02	1.021	1.022	1.023
Bus 18	1.016	1.017	1.02	1.021	1.023	1.024
Bus 23	1.016	1.017	1.02	1.021	1.023	1.024
Bus 28	1.016	1.017	1.02	1.021	1.023	1.025
Bus 29	1.025	1.027	1.027	1.025	1.023	1.02
20 Houses Cluster 1	1.019	1.024	1.027	1.028	1.028	1.028
20 Houses Cluster 2	1.006	1.017	1.027	1.034	1.04	1.044
20 Houses Cluster 3	0.999	1.014	1.027	1.037	1.045	1.053

The voltage profile for this case is given in Figure 19.

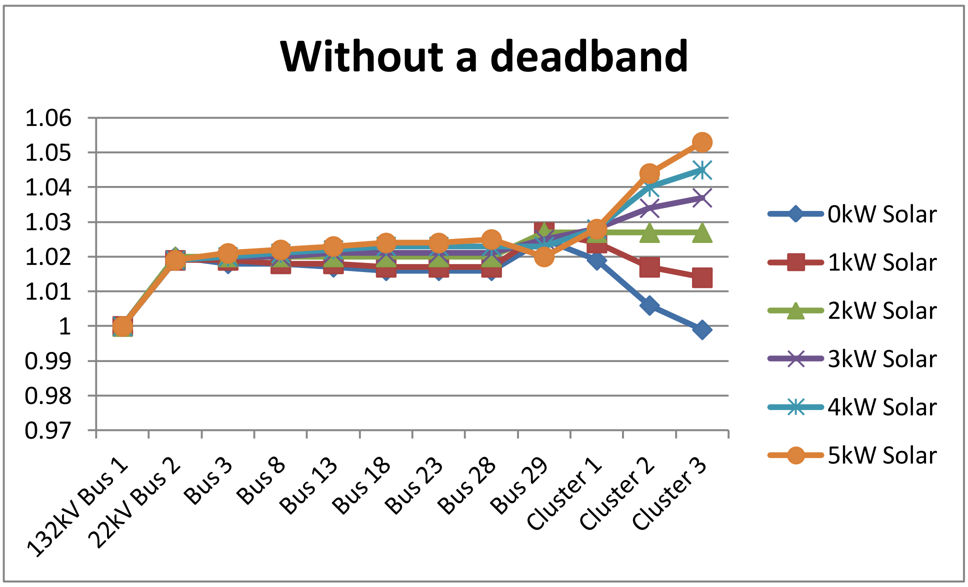

Figure 19: Q (V) method scenario simulation results (without a deadband)

- With a deadband

Figure 20 shows the Q (V) control curve, which is also called deadband control.

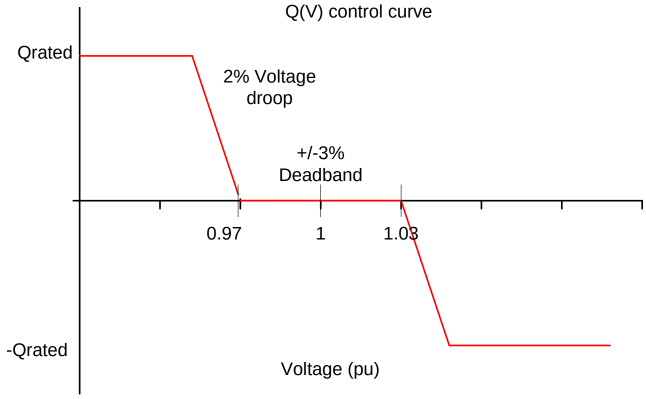

Figure 20: Q (V) control curve

The Q (V) characteristics data is shown in Table 20.

Table 20: Q (V) characteristics data (with a deadband)

Voltage Droop	Lower Voltage Limit	Upper Voltage Limit
2%	0.97 p.u.	1.03 p.u.

The deadband control only starts above or below a certain voltage limit and the reactive power is only used when grid voltage shifts significantly from the setpoint. Deadband is an interval where no action occurs. In this range of voltages, no changes are made.

The simulation results are shown in Table 21.

Table 21: Q (V) method scenario simulation results (with a deadband)

	0kW Solar	1kW Solar	2kW Solar	3kW Solar	4kW Solar
132kV Bus 1	1	1	1	1	1
22kV Bus 2	1.019	1.019	1.019	1.019	1.019
Bus 3	1.018	1.019	1.019	1.02	1.021
Bus 8	1.017	1.018	1.019	1.021	1.021
Bus 13	1.016	1.018	1.019	1.021	1.022
Bus 18	1.016	1.018	1.019	1.021	1.023
Bus 23	1.015	1.017	1.019	1.022	1.023
Bus 28	1.015	1.017	1.019	1.022	1.023
Bus 29	1.024	1.029	1.032	1.03	1.027
20 Houses Cluster 1	1.018	1.026	1.032	1.033	1.032
20 Houses Cluster 2	1.005	1.02	1.032	1.039	1.044
23 Houses Cluster 3	0.998	1.017	1.032	1.042	1.049

The voltage profile for this case is given in Figure 21.

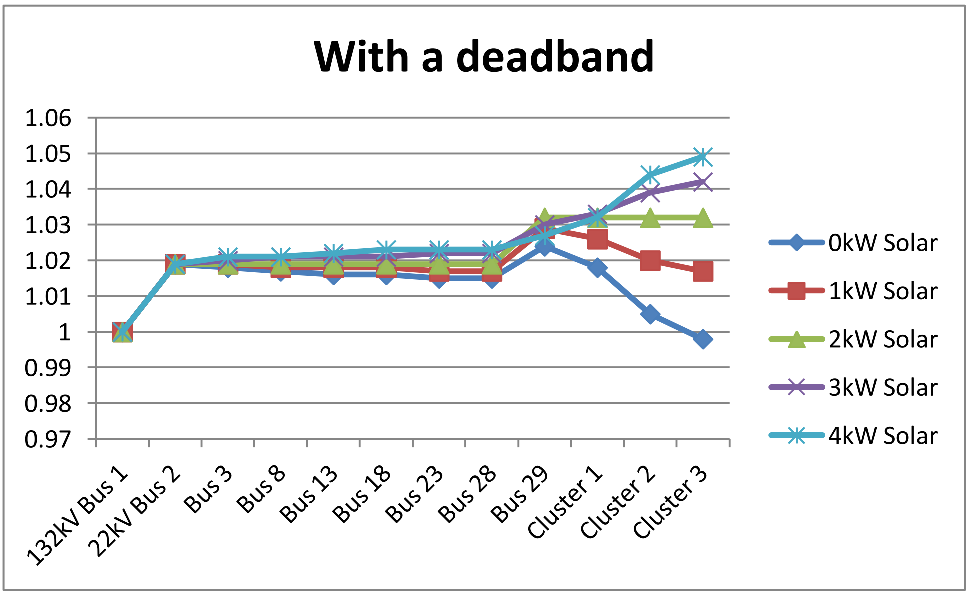

Figure 21: Q (V) method scenario simulation results (with a deadband)

6.2.2 Discussion

Figure 22 and Figure 23 show the voltages at the end of LV feeder for the two cases with Q(V) control and different PV penetrations.

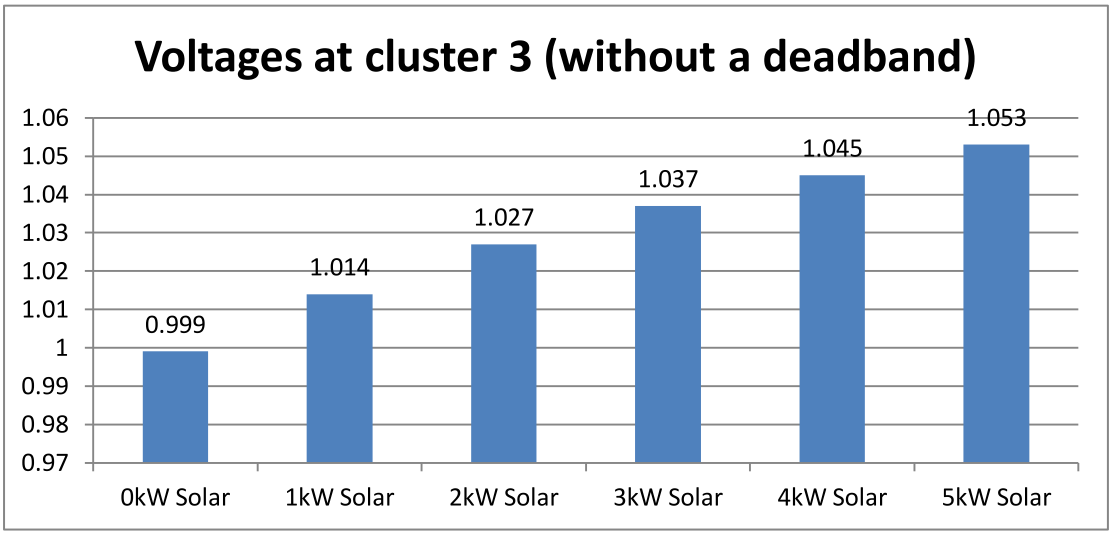

Figure 22: Voltages at cluster 3 (without a deadband)

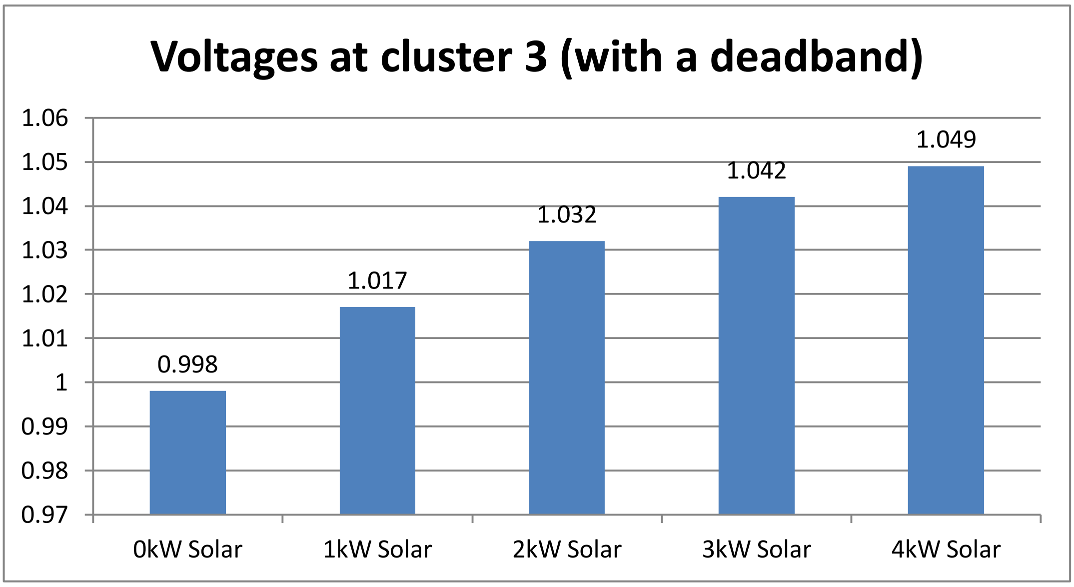

Figure 23: Voltages at cluster 3 (with a deadband)

It can be seen from Figure 22 that the voltage at cluster 3 does not reach the limit until the PV generation increases to about 5 kW per house. Compared with the minimum load cases in section 5.2, the overvoltage problem has been reduced.

6.3 Use P (V) voltage control function of PV inverter

Fixed Active power curtailment (APC) is an easy and quick way to solve the overvoltage problems on feeders and the unbalanced phase problem can be improved as well.

Curtailment or droop is a method to force evaluation parameters within their set boundaries, which is to keep the voltage under 1.05 p.u. in this project. In order to reduce the voltage at a given location, the power injected at that location will be decreased. Due to its fixed character, the method requires no communication and is easy to implement on inverters. This method is also called a 'fixed droop' scheme since the droop set point (the minimum voltage where the algorithm starts regulating) does not change at any time [16].

The Volt-watt response mode in a PV inverter can vary the output power of the inverter in response to the voltage at its terminal.

In accordance with Clause 6.3.2.2 of Draft AS/NZ4777:2015, the response curve required for the volt-watt response mode is defined by the volt response reference values in Table 16 and the corresponding power levels. These are listed in Table 22 and shown in Figure 24.

Table 22: Volt-watt response maximum set-point values for reference voltages [15]

Reference	Maximum value (P/P_{rated}%)
V_1	100%
V_2	100%
V_3	100%
V_4	20%

After a volt-watt response, the inverter shall power rate limit for any required decrease in output power.

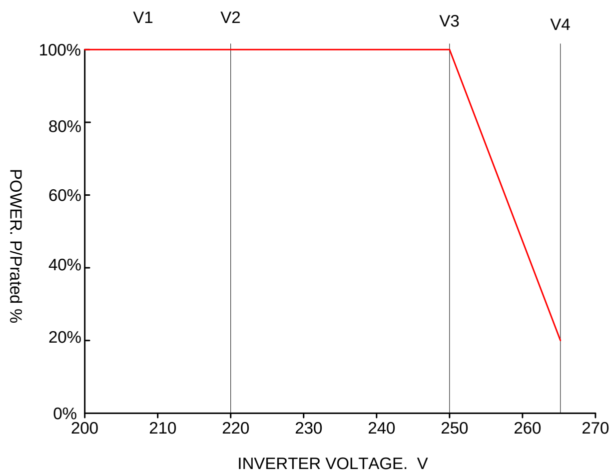

Figure 24: Example curve for a volt-watt response mode (Australia) [15]

This method is not simulated in this project as it defeats the purpose of trying to increase the amount of solar PV power that can be injected.

7 The approaches to manage voltage rise on distribution feeders using PV inverters (utility aspect)

In this task, the focus will now turn to the methods available to utilities for managing the voltage rise on distribution feeders. The methods are listed below:

- Implement line drop compensation in the substation transformer
- Implement On Load Tap Changer (OLTC) on distribution transformers
- Implement STATCOM devices

In this chapter, the minimum daytime load is assumed to be 2kVA/house and this minimum load is applied to all the simulation cases.

7.1 Implement line drop compensation (LDC) in the substation transformers

The purpose of using LDC is to allow a constant voltage to be maintained at a point along the feeder remote from the transformer [17]. With LDC, the transformer increases its output voltage as the load increases to maintain acceptable voltages at the end of the feeder. The LDC devices are installed in the 132kV/22kV transformers between bus 1 and bus 2.

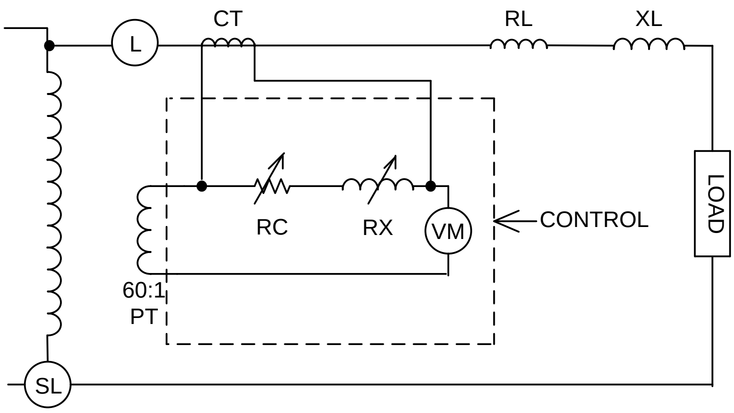

Figure 25: Line Drop Compensation Diagram adapted from Copper Power System [17]

Figure 25 shows a LDC model diagram. In this model, a reactive and resistive element can simulate the reactance and resistance of the line from the substation transformers to about 50% along the line to the next voltage regulator. The regulated voltage sensed by the sensing circuit can be reduced by the additional voltage drop in the LDC and the increased voltage can let the tap change controller to tap up the output of transformer [17].

The data being used in this case is shown below:

Table 23: 132kV/22kV Transformer data

Voltage set point	Rset	Xset
1.00 p.u.	7	1.4

Table 24: Line drop compensation scenario data

Scenarios	Apparent Power (per cluster)	Power Factor	PV Generation (per cluster)	PV Power Factor
0kW solar/house	0.04MVA	0.85	0kW	1
1kW solar/house	0.04MVA	0.85	20kW	1
2kW solar/house	0.04MVA	0.85	40kW	1
3kW solar/house	0.04MVA	0.85	60kW	1
4kW solar/house	0.04MVA	0.85	80kW	1
5kW solar/house	0.04MVA	0.85	100kW	1

7.1.1 Simulation results

Table 25: Line drop compensation scenario simulation results

	0kW Solar	1kW Solar	2kW Solar	3kW Solar	4kW Solar	5kW Solar
132kV Bus 1	1	1	1	1	1	1
22kV Bus 2	1.01	1.004	0.999	0.994	0.99	0.985
Bus 3	1.008	1.004	0.999	0.994	0.991	0.987
Bus 8	1.007	1.003	0.999	0.995	0.992	0.989
Bus 13	1.007	1.003	0.999	0.995	0.993	0.99
Bus 18	1.006	1.003	0.999	0.996	0.994	0.991
Bus 23	1.006	1.003	0.999	0.996	0.994	0.991
Bus 28	1.005	1.002	0.999	0.996	0.995	0.992
Bus 29	1.014	1.014	1.012	1.011	1.011	1.009
20 Houses Cluster 1	1.008	1.011	1.012	1.014	1.017	1.019
20 Houses Cluster 2	0.995	1.004	1.013	1.021	1.031	1.039
20 Houses Cluster 3	0.988	1.001	1.013	1.025	1.038	1.049

The voltage profile for this case is given in Figure 26.

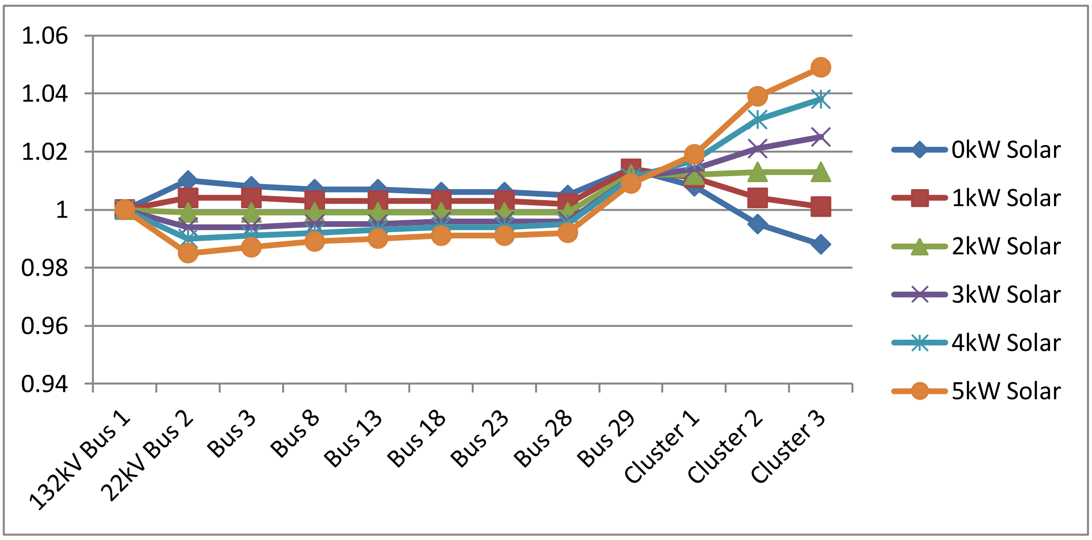

Figure 26: Line drop compensation scenario simulation result

7.1.2 Discussion

Figure 27 shows the voltages at the end of LV feeder for the cases with different PV penetration.

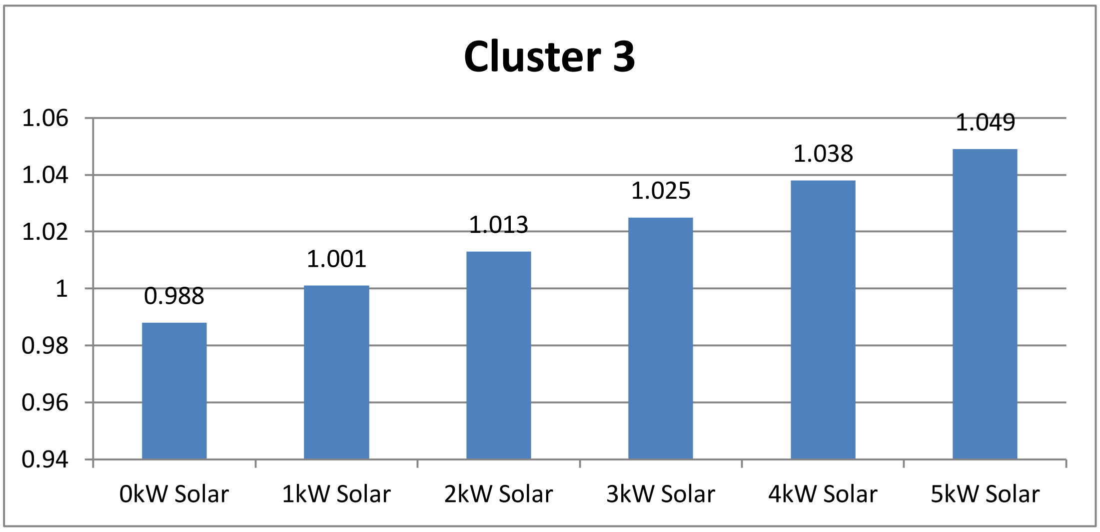

Figure 27: Voltages at cluster 3 (with LDC)

It can be seen from Figure 27 that the voltage at cluster 3 is still within the voltage limit when the solar generation increases to 5kW, which indicates that implementing the LDC device can help to regulate the voltage at a load center on a feeder remote from the transformer.

7.2 Implement On Load Tap Changer (OLTC) on distribution transformers

A tap changer along a power transformer can allow different turns to be selected in separate steps. OLTC is usually done on the HV winding. "The OLTC changes the ratio of a transformer by adding or subtracting turns from either the primary or the secondary winding. The transformer is therefore equipped with a regulating or tap winding which is connected to the OLTC." [18]

When the network voltage increases, the OLTC now has to adjust the voltage level to maintain it in the defined range. A switching pulse will be released if the voltage level has been exceeded its limitation for a long period, which means a mechanical switching process to be activated. The transformer's windings are set to a new transmission ratio in order to control the voltage level [19].

In this project, the OLTC device is not simulated because of its complexity and high cost. However this is still a good solution and worth doing more simulation studies in the future.

7.3 Implement STATCOM devices

The static synchronous compensator (STATCOM) is a shunt connected device which generates a balanced set of three-phase sinusoidal voltages at the fundamental frequency, with rapidly controllable amplitude and phase angle [20]. It is used for voltage control and reactive power compensation on the grid. The STATCOM uses self-commutated power electronics to synthesize the reactive power output rather than using conventional capacitors and inductors combined with thyristors [13].

The advantage of using a device like STATCOM is that it can provide a very fast solution, by providing dynamic voltage control. It is an effective method to maintain the steady state voltage profile of the network.

The STATCOM device will not be used alone in this project but it will be used with the fixed power control method which is discussed in section 8.4.

8 Different combinations of the methods

8.1 Combination one

The first combination is to implement line drop compensation devices in the substation transformer and change the power factor of the PV inverters from 1 to 0.95 leading.

In PowerFactory simulation, the PV generation increases from no solar to 9kW solar/house (the highest PV generation in this case that keeps the voltage under 1.05 p.u). The load for per house is 0.02kVA at 0.85 pf. The data for each scenario is shown in Table 26.

Table 26: Combination one scenario data

Scenarios	Apparent Power (per cluster)	Power Factor	PV Generation (per cluster)	PV Power Factor
0kW solar/house	0.04MVA	0.85	0kW	0.95
1kW solar/house	0.04MVA	0.85	20kW	0.95
2kW solar/house	0.04MVA	0.85	40kW	0.95
3kW solar/house	0.04MVA	0.85	60kW	0.95
4kW solar/house	0.04MVA	0.85	80kW	0.95
5kW solar/house	0.04MVA	0.85	100kW	0.95
6kW solar/house	0.04MVA	0.85	120kW	0.95
7kW solar/house	0.04MVA	0.85	140kW	0.95
8kW solar/house	0.04MVA	0.85	160kW	0.95
9kW solar/house	0.04MVA	0.85	180kW	0.95

8.1.1 Simulation results

Table 27: Combination one scenario simulation results

	0kW	1kW	2kW	3kW	4kW	5kW	6kW	7kW	8kW	9kW
132kV Bus 1	1	1	1	1	1	1	1	1	1	1
22kV Bus 2	1.01	1.005	1	0.995	0.991	0.986	0.982	0.978	0.974	0.97
Bus 3	1.008	1.004	1	0.995	0.992	0.988	0.984	0.98	0.977	0.973
Bus 8	1.007	1.004	1	0.996	0.993	0.989	0.986	0.982	0.979	0.976
Bus 13	1.007	1.003	1	0.996	0.994	0.99	0.987	0.984	0.981	0.979
Bus 18	1.006	1.003	1	0.996	0.994	0.991	0.988	0.986	0.983	0.98
Bus 23	1.006	1.003	1	0.997	0.995	0.991	0.989	0.986	0.984	0.982
Bus 28	1.005	1.003	1	0.997	0.995	0.992	0.989	0.987	0.984	0.982
Bus 29	1.014	1.01	1.005	0.999	0.995	0.989	0.983	0.977	0.971	0.965
20 Houses Cluster 1	1.008	1.007	1.005	1.002	1	0.997	0.995	0.992	0.988	0.985
20 Houses Cluster 2	0.995	1	1.004	1.008	1.012	1.016	1.019	1.022	1.025	1.027
23 Houses Cluster 3	0.988	0.996	1.004	1.011	1.019	1.025	1.031	1.037	1.043	1.048

The voltage profile for this case is given in Figure 28.

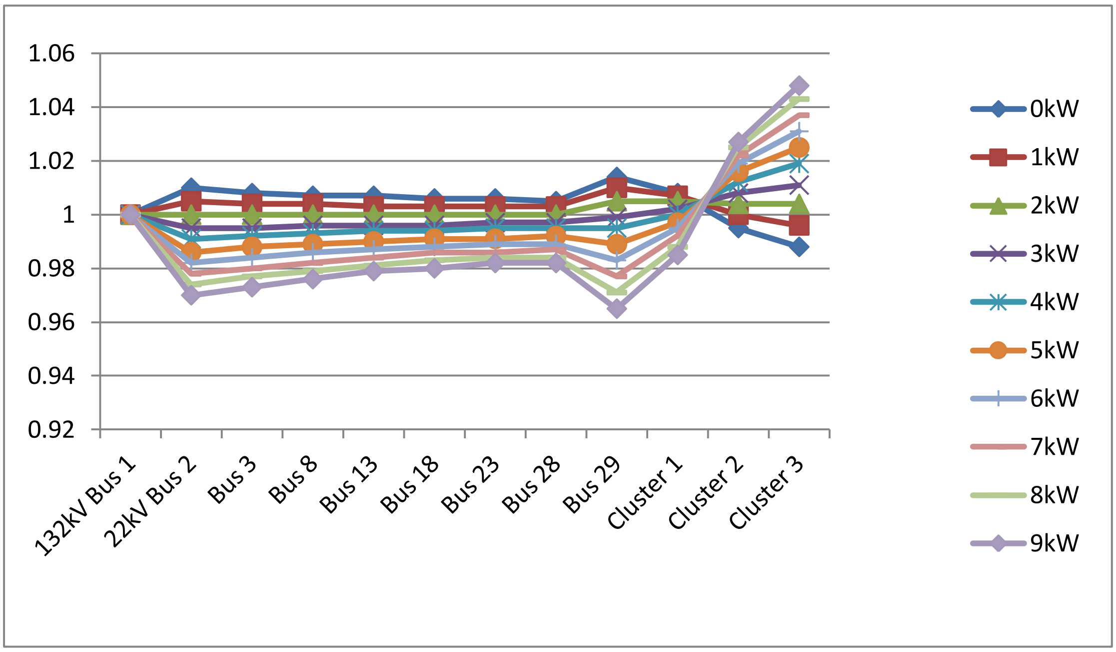

Figure 28: Combination one scenario simulation result

8.1.2 Discussion

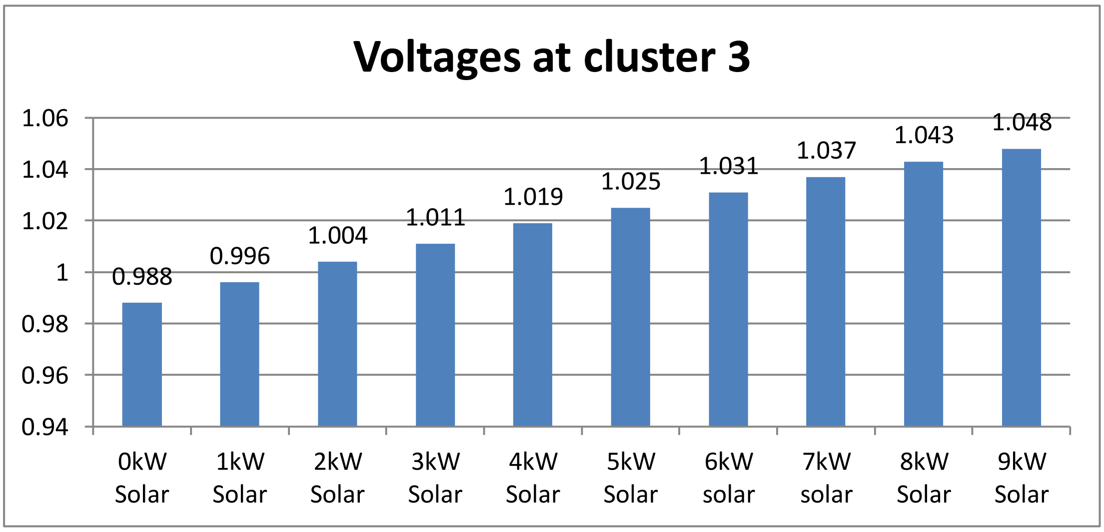

Figure 29: Voltages at cluster 3

Figure 29 shows that, with the LDC device in combination with the fixed power factor control method, the voltages at cluster 3 are within the limit even when the solar generation has increased to 9kW per house, which is a very high penetration level. The combination of these two methods is an effective and efficient way to manage the voltage rise in distribution feeders.

As we can seen from the voltage profiles in Figure 28, there is a voltage drop at bus 29 while linked to the LV feeder along the circuit going to the house loads, when the PV generation is lower than or equal to 2kW/house. And there is a voltage rise at bus 29 when the PV generation increases, which is because with each house generating more and more solar PV (for example at 5kW/house), the net power flow is in the opposite direction and this leads to a voltage rise.

This can be explained by the equation below [21]:

$$\triangle V = (PR+QX)/V$$

Where P is real power injected;

Q is reactive power injected;

R is line resistance;

X is line reactance;

V is (nominal) voltage.

8.2 Combination two

The second combination is to implement line drop compensation devices in the substation transformer and use the Q (V) voltage control function of the PV inverter.

In PowerFactory simulation, the PV generation increases from no solar to 7kW solar/house (the highest PV generation in this case that keeps the voltage under 1.05 p.u). The data for each scenario is shown at Table 28.

Table 28: Combination two scenario data

Scenarios	Apparent Power (per cluster)	Power Factor	PV Generation (per cluster)	PV Power Factor
0kW solar/house	0.04MVA	0.85	0kW	1
1kW solar/house	0.04MVA	0.85	20kW	1
2kW solar/house	0.04MVA	0.85	40kW	1
3kW solar/house	0.04MVA	0.85	60kW	1
4kW solar/house	0.04MVA	0.85	80kW	1
5kW solar/house	0.04MVA	0.85	100kW	1
6kW solar/house	0.04MVA	0.85	120kW	1
7kW solar/house	0.04MVA	0.85	140kW	1

8.2.1 Simulation results

- Without a deadband

Table 29: Combination two scenario simulation results (without a deadband)

	0kW Solar	1kW Solar	2kW Solar	3kW Solar	4kW Solar	5kW Solar	6kW solar	7kW solar
132kV Bus 1	1	1	1	1	1	1	1	1
22kV Bus 2	1.01	1.005	0.999	0.995	0.989	0.985	0.981	0.977
Bus 3	1.008	1.004	0.999	0.996	0.99	0.987	0.983	0.979
Bus 8	1.007	1.003	0.999	0.996	0.991	0.988	0.985	0.982
Bus 13	1.007	1.003	0.999	0.996	0.992	0.989	0.987	0.983
Bus 18	1.006	1.003	0.999	0.997	0.993	0.99	0.988	0.985
Bus 23	1.006	1.003	0.999	0.997	0.993	0.991	0.988	0.986
Bus 28	1.005	1.003	0.999	0.997	0.993	0.991	0.989	0.986
Bus 29	1.014	1.013	1.01	1.006	1.001	0.996	0.991	0.985
20 Houses Cluster 1	1.008	1.01	1.01	1.01	1.007	1.005	1.003	1
20 Houses Cluster 2	0.995	1.004	1.01	1.016	1.02	1.024	1.027	1.029
23 Houses Cluster 3	0.988	1.001	1.01	1.019	1.026	1.033	1.039	1.044

The voltage profile is shown in figure 30.

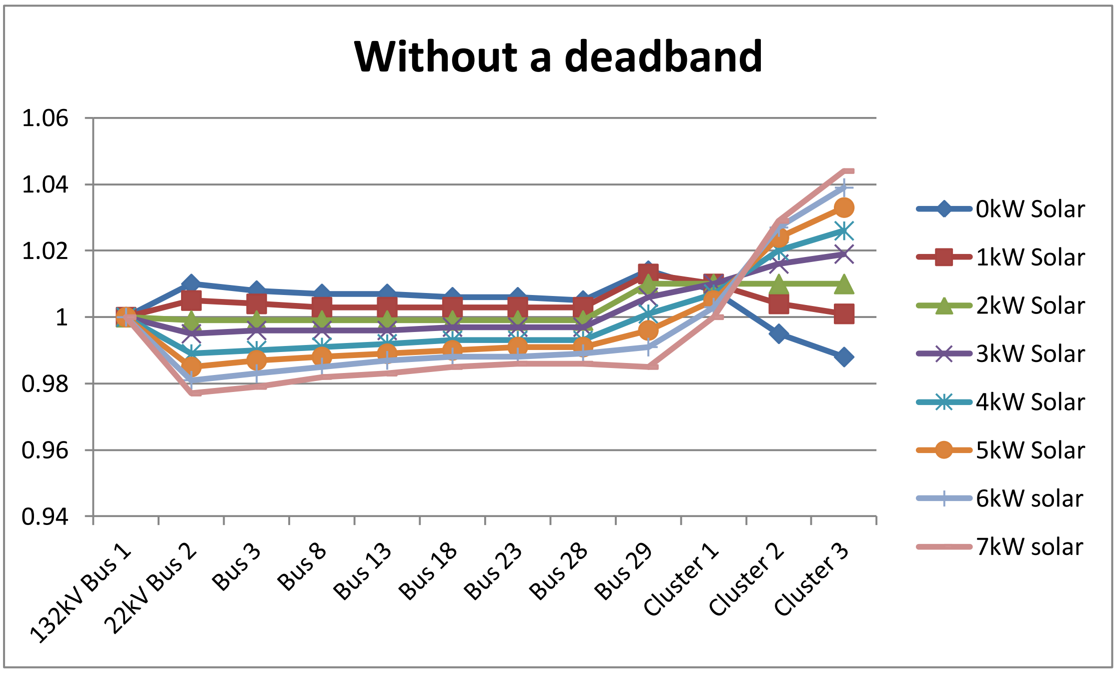

Figure 30: Combination two scenario simulation result (without a deadband)

- With a deadband

Table 30: Combination two scenario simulation results (with a deadband)

	0kW Solar	1kW Solar	2kW Solar	3kW Solar	4kW Solar	5kW Solar	6kW Solar
132kV Bus 1	1	1	1	1	1	1	1
22kV Bus 2	1.01	1.004	0.999	0.994	0.99	0.985	0.98
Bus 3	1.009	1.004	0.999	0.994	0.991	0.987	0.982
Bus 8	1.008	1.003	0.999	0.995	0.992	0.99	0.984
Bus 13	1.007	1.003	0.999	0.995	0.993	0.99	0.986
Bus 18	1.007	1.003	0.999	0.996	0.993	0.99	0.987
Bus 23	1.006	1.003	0.999	0.996	0.994	0.991	0.988
Bus 28	1.006	1.002	0.999	0.996	0.994	0.991	0.988
Bus 29	1.015	1.014	1.012	1.011	1.008	1.003	0.996
20 Houses Cluster 1	1.009	1.011	1.012	1.014	1.015	1.012	1.008
20 Houses Cluster 2	0.995	1.004	1.013	1.021	1.028	1.031	1.033
23 Houses Cluster 3	0.989	1.001	1.013	1.025	1.035	1.041	1.045

The voltage profile is shown in figure 31.

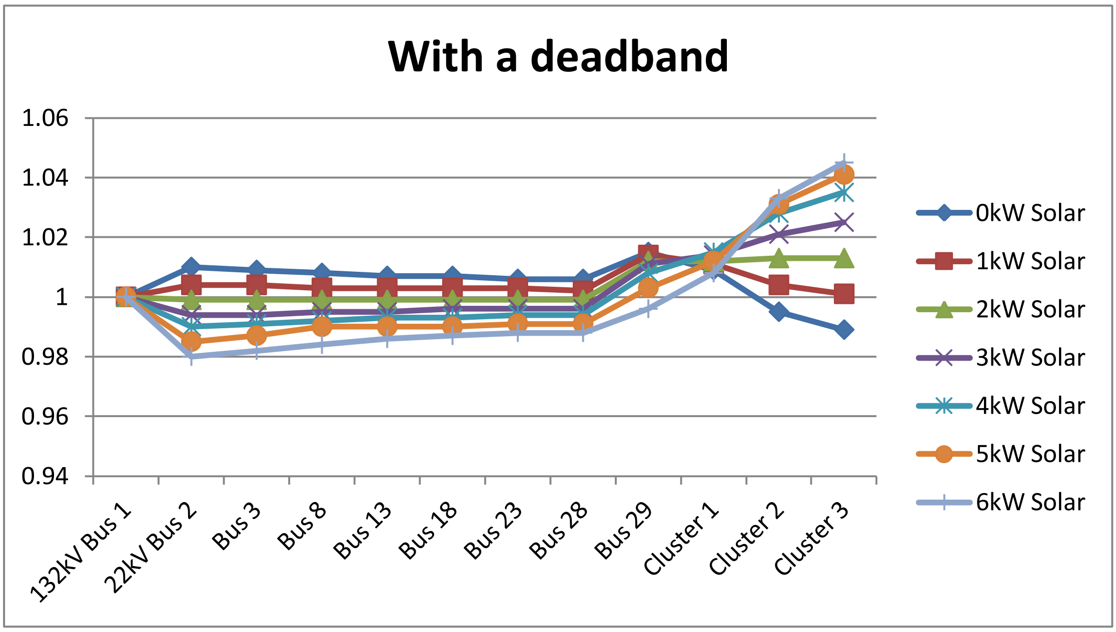

Figure 31: Combination two scenario simulation result (with a deadband)

8.2.2 Discussion

Figure 32 and Figure 33 shows the voltages at the end of LV feeder for the cases with different PV penetration.

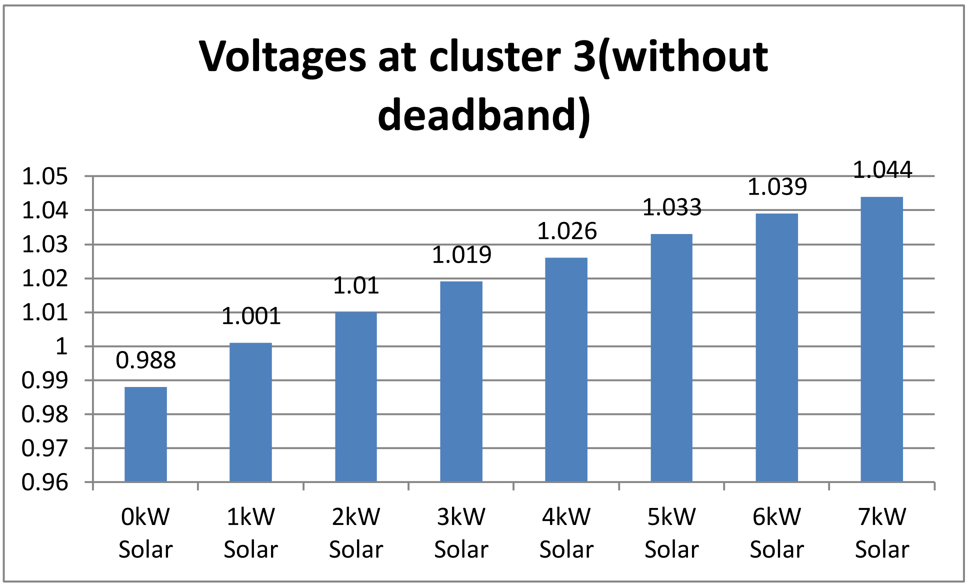

Figure 32: Voltages at cluster 3 (without a deadband)

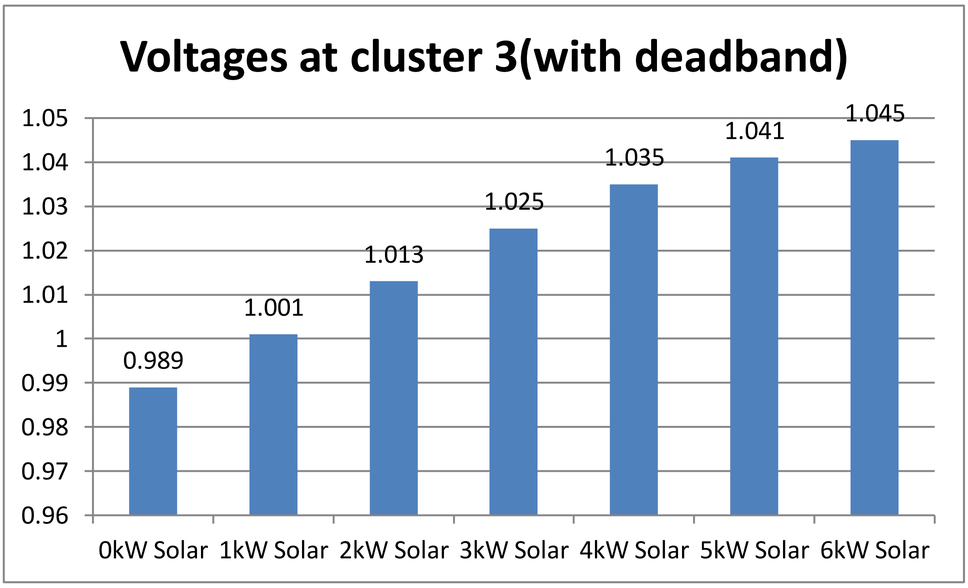

Figure 33: Voltages at cluster 3 (with a deadband)

It can be seen from Figure 32 and 33 that, with the Q (V) method and the fixed power factor control method, the voltages at cluster 3 are within the limit even when the solar generation has increased to 7kW per house (without a deadband); 6kW per house (with a deadband). This indicates that the combination of these two methods is also an effective way to manage the voltage rise in the network.

8.3 Combination three

The third combination is to implement a STATCOM device and change the power factor of the PV inverter from 1 to 0.95 leading. In this case, in order to compare the results with the fixed power factor control scenario in section 6.1, the simulation was only carried out on the 5kW case, which is the maximum solar generation per house for the fixed power factor scenario. The STATCOM device has been installed in two separate locations (bus 28 and bus 32) to see their effects respectively. The network diagram for this case is shown in Appendix B.

The data being used in this case is shown in Table 31.

Table 31: Combination three scenario data

Scenarios	Apparent Power (per cluster)	Power Factor	PV Generation (per cluster)	PV Power Factor
5kW solar/house	0.04MVA	0.85	100kW	0.95 absorbing

8.3.1 Simulation results

- Implement STATCOM at cluster 3

The voltage profiles for implementing STATCOM at cluster 3 with a fixed power factor case, and the 0.95 pf absorbing case (5kW solar/house) are shown in Figure 34.

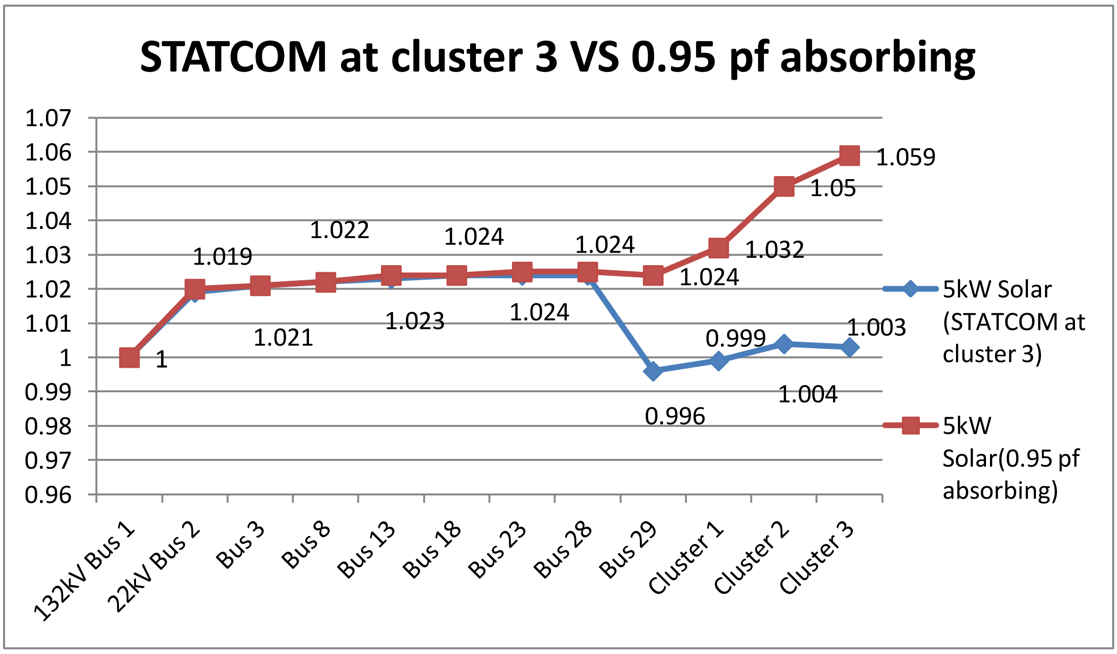

Figure 34: STATCOM at cluster 3 VS 0.95 pf absorbing

Figure 35 shows the comparison between the voltages along the red path in figure 3 and the voltages along clusters 4, 5 and 6.

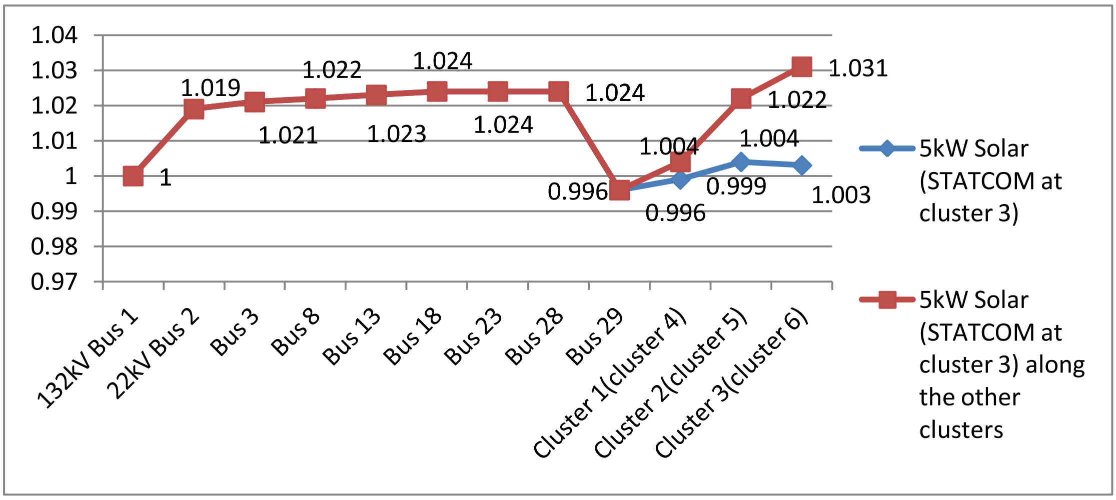

Figure 35: Voltages along the red path in Figure 3 and the voltages along clusters 4, 5 and 6

- Implement STATCOM at bus 28

The voltage profiles for implementing STATCOM at bus 28 with a fixed power factor case, and the 0.95 pf absorbing case (5kW solar/house) are shown in Figure 36.

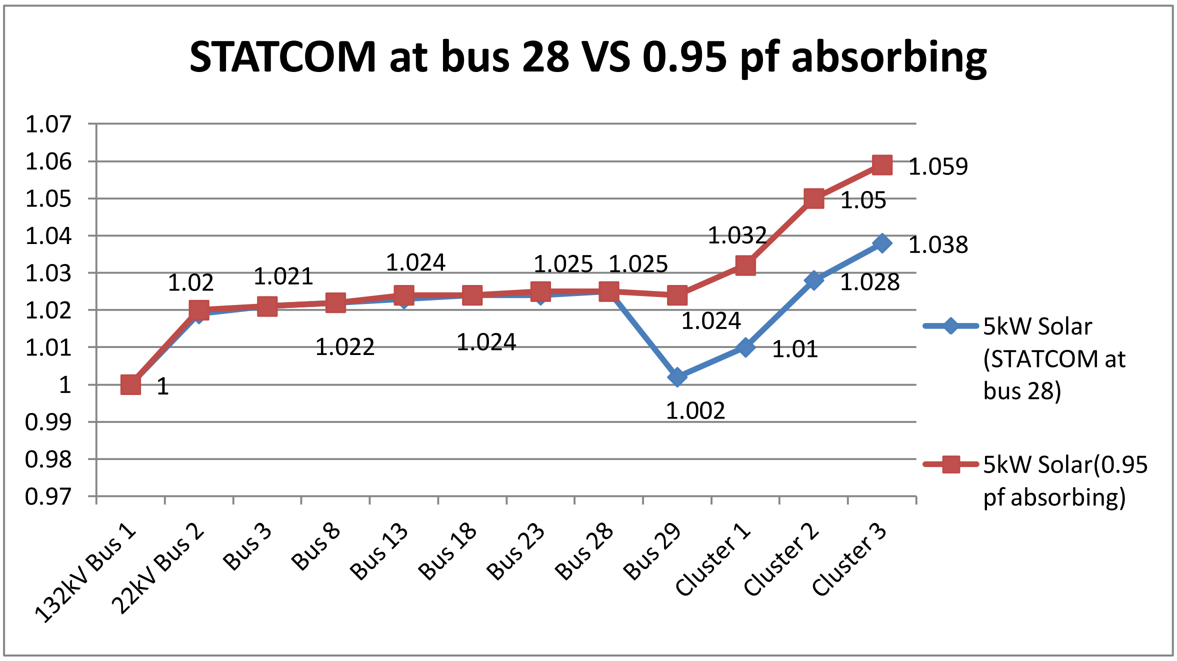

Figure 36: STATCOM at bus 28 VS 0.95 pf absorbing

8.3.2 Discussion

As it is shown in Figure 34, the STATCOM implementing at cluster 3 can have an obvious effect in regulating the voltage at the last bus compared with the method of using only the a fixed power factor control. STATCOM can have the remarkable impact on the place where it is implemented, not on the whole system. It can be seen from Figure 35 that the voltage rise problem improvement on cluster 6 in Figure 4 is less than the cluster 3 when the STATCOM is implemented at cluster 3. Although STATCOM can manage the voltage rise problem effectively, the major disadvantage of it is that it is too expensive for a household PV system so it is not an economical option.

9 Conclusion

Penetrations of PV systems within distribution networks has been growing in recent years and this has come with various technical challenges like voltage rise and voltage variations. The purpose of this thesis is to provide approaches to reduce technical barriers for achieving high PV penetration levels in Australian electricity networks. The investigation was supported by using the DIgSILENT Power Factory software version 15.2.

The thesis starts with a literature review that included Australian solar resources and PV status, technical issues associated with the increased PV penetration and PV Inverters' Voltage Control Strategies. After that, the project methodology is described in chapter 3. Chapter 4 defines an example feeder built in PowerFactory and the base case and its variations are analysed in chapter 5. Chapter 6 to chapter 8 describes methods to manage voltage the rise problem on distribution feeders. Chapter 6 is focused on prosumer aspects while chapter 7 is focused on utility aspects and chapter 8 introduces and analyses three combinations of the methods.

Table 32 shows the methods that have been studied in this report and also shows the amount of solar per house that can be accommodated for each prosumer, utility or combined method before the voltage exceeds 1.05 p.u..

Table 32: The amount of solar per house that can be accommodated before the voltage exceeds 1.05 p.u.

Prosumer / Utility	pf=1	pf=0.95 leading	Q(V)	P(V)
Do nothing	3 kW	4-5kW	5kW	
Implement line drop compensation in the substation transformer	5kW	9kW	8kW	
Implement On Load Tap Changer (OLTC) on distribution transformers				
Implement STATCOM devices				

The results for prosumer's methods show that these methods can basically be used to keep the voltage within the defined limits when the PV generation is 5kW/house, which is its assumed maximum value. But as PV penetrations climb in Australian distribution networks, it will be important that these technologies are upgraded to effectively manage the issues.

From the simulation results of the remaining cases, it can be concluded that all these control methods can effectively and efficiently control the voltage rise problem at cluster 3. But one disadvantage is that the LDC, OLTC and STATCOM devices are all expensive, and are not economically viable options.

10 Future work

- Harmonics problem

From the harmonics point of view, each inverter which is interfaced to the public LV network is considered as an electronic equipment [22]. A parallel resonance might be triggered by clustered PV inverters due to capacitance of residential units, interaction between equivalent line inductance and injected harmonic currents [23]. Further research can be carried out on the issues associated with this problem and the approaches to solve it.

- Single phase PV system installations in three phase supply

High neutral currents and nuisance tripping of the inverter can an issue associated with single phase PV system connections for three phase customers. According to Western Power's Technical Rules [13], the single phase PV systems that can be installed on a LV distribution grid cannot exceed 10kW. With the growing embedded PV generation in recent years, customers may require larger PV systems than the limit specified. This could be the next study aspect of interest in how to improve this situation.

- PV system islanding

Table 3 in section 2.3 has shown the relevant voltage and frequency ranges for PV inverters as the guidelines from AS4777 and Horizon Power. However, care needs to be taken to ensure that the limits, including the network parameters, are appropriate to avoid the situation when the main supply is disconnected while PV system stay connected to the network, and also when there is a void in the manufacturer's warranty [6]. Different protection methods to solve this problem should be studied.

11 References

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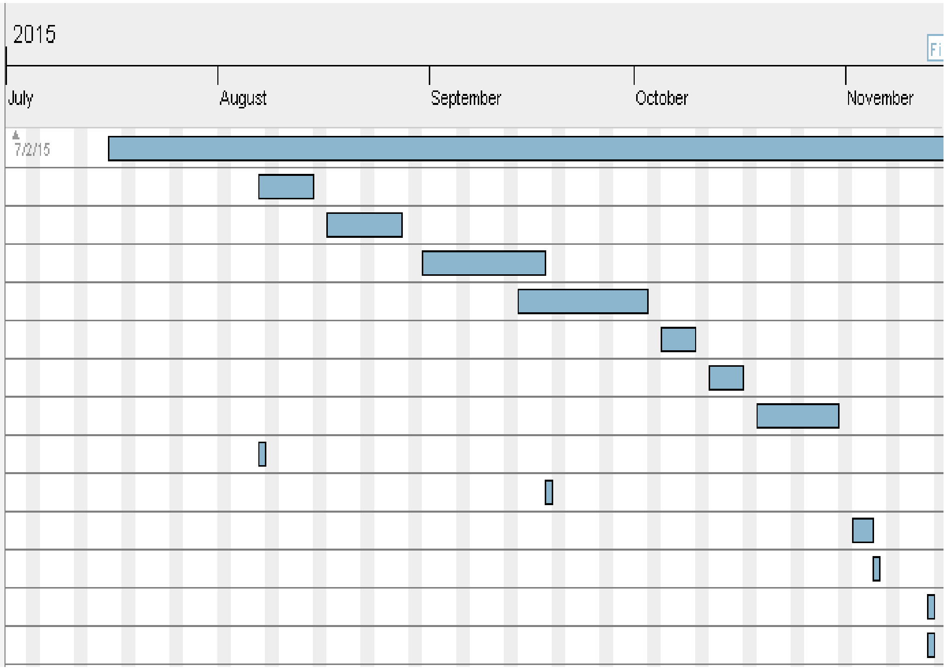
12 Appendices

12.1 Appendix A: Gantt chart

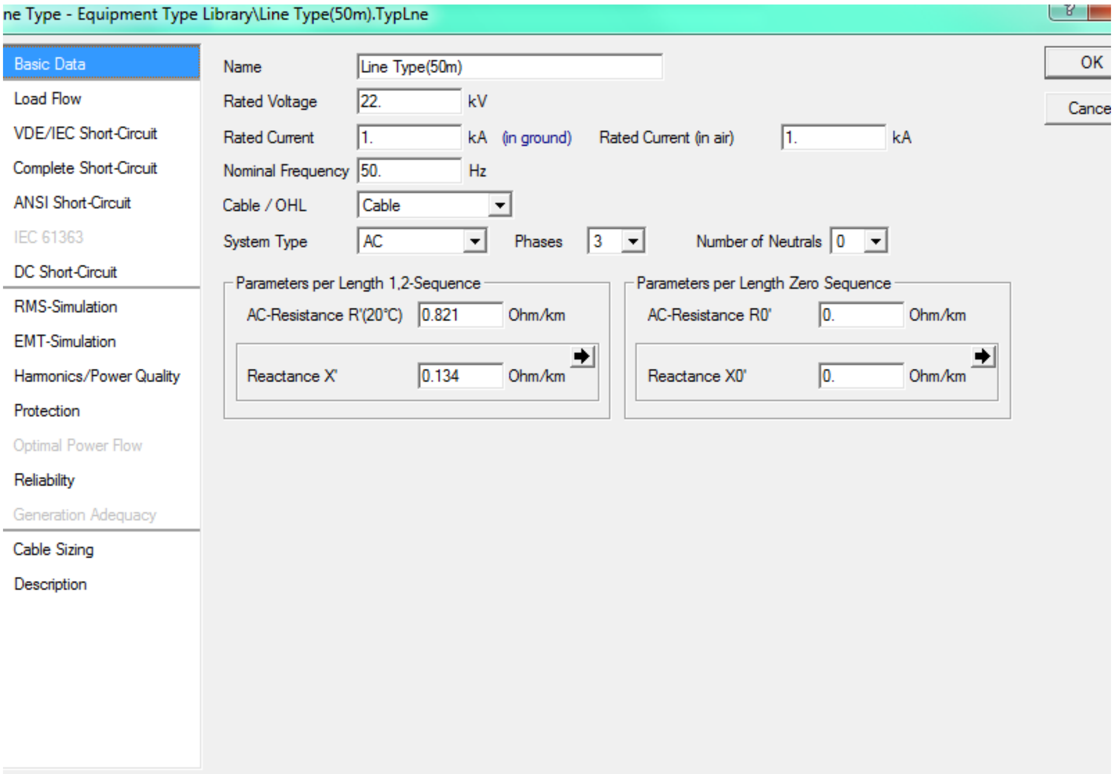
Name	Begin date	End date
Literature review and documentation of report	7/16/15	11/16/15
Familiarization with PowerFactory	8/7/15	8/14/15
Modelling example feeder	8/17/15	8/27/15
Define a base case scenario	8/31/15	9/17/15
Approaches to manage voltage variations on distribution feeders(prosumer)	9/14/15	10/2/15
Gap week	10/5/15	10/9/15
Approaches to manage voltage variations on distribution feeders(utility)	10/12/15	10/16/15
Comparison,analysis,discussion and development of new approaches	10/19/15	10/30/15
Project plan due date	8/7/15	8/7/15
Progress report due date	9/18/15	9/18/15
Preparation for presentation slides	11/2/15	11/4/15
DIscuss the presentation detaiils with supervisors	11/5/15	11/5/15
Final presentation	11/13/15	11/13/15
Final report due date	11/13/15	11/13/15



12.2 Appendix B: Network components data and diagram in PowerFactory

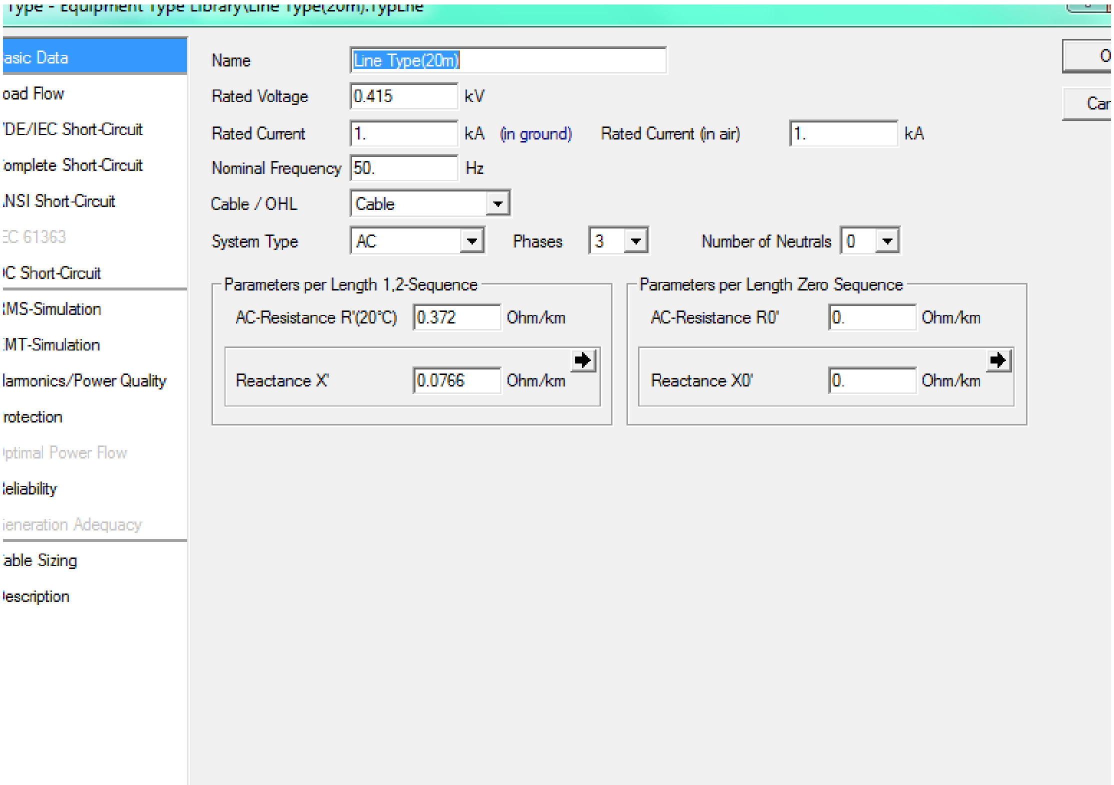
- HV cable

General table from database in PowerFactory:



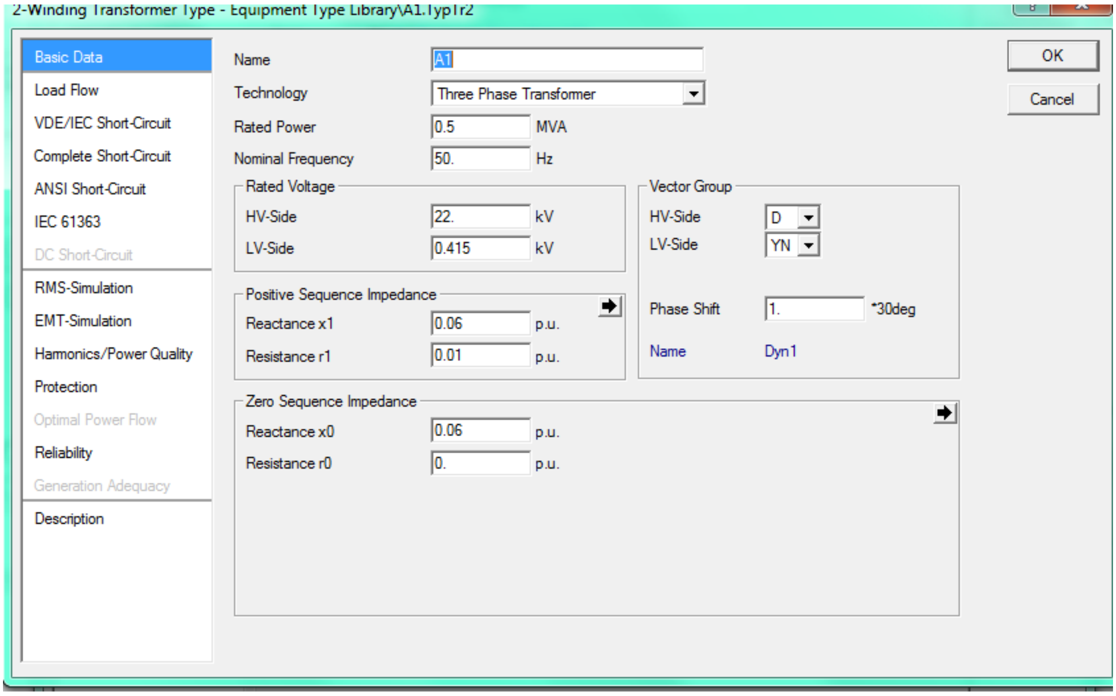
- LV cable

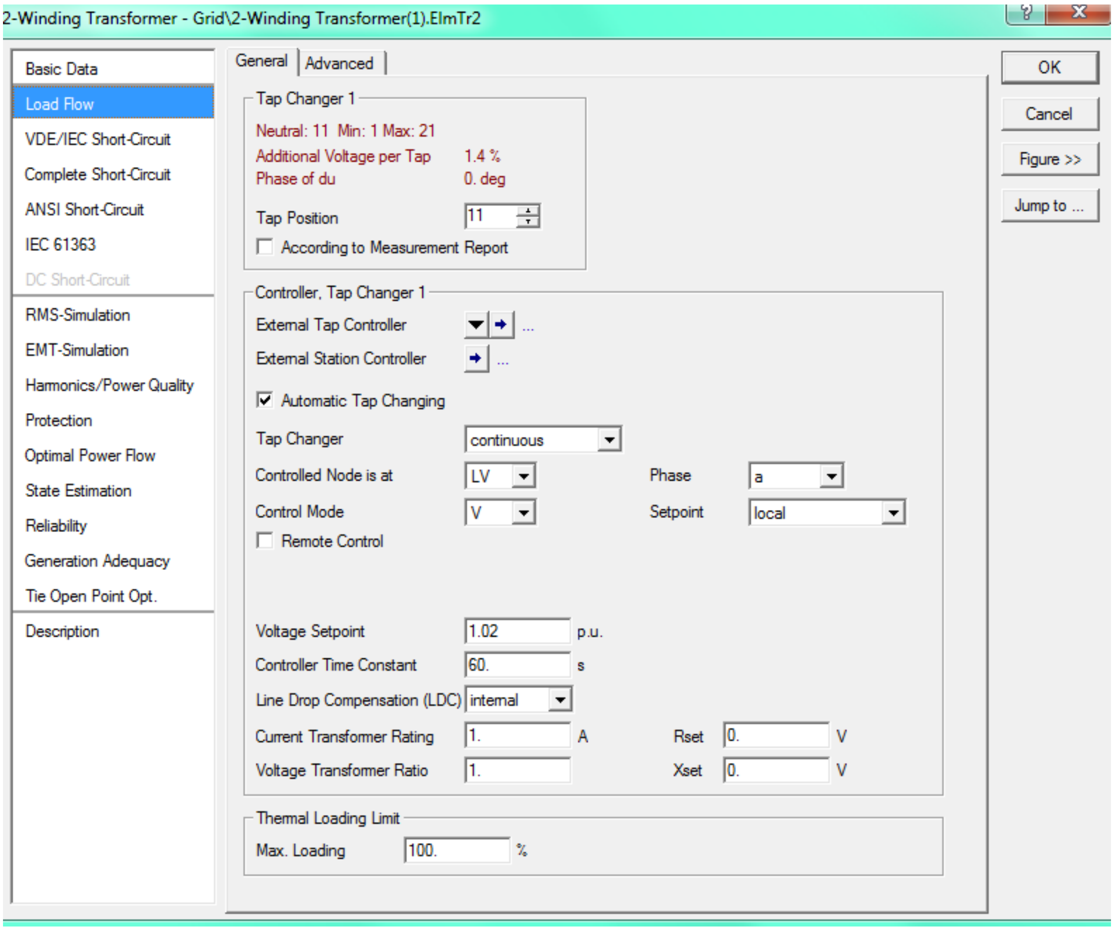
General table from database in PowerFactory:

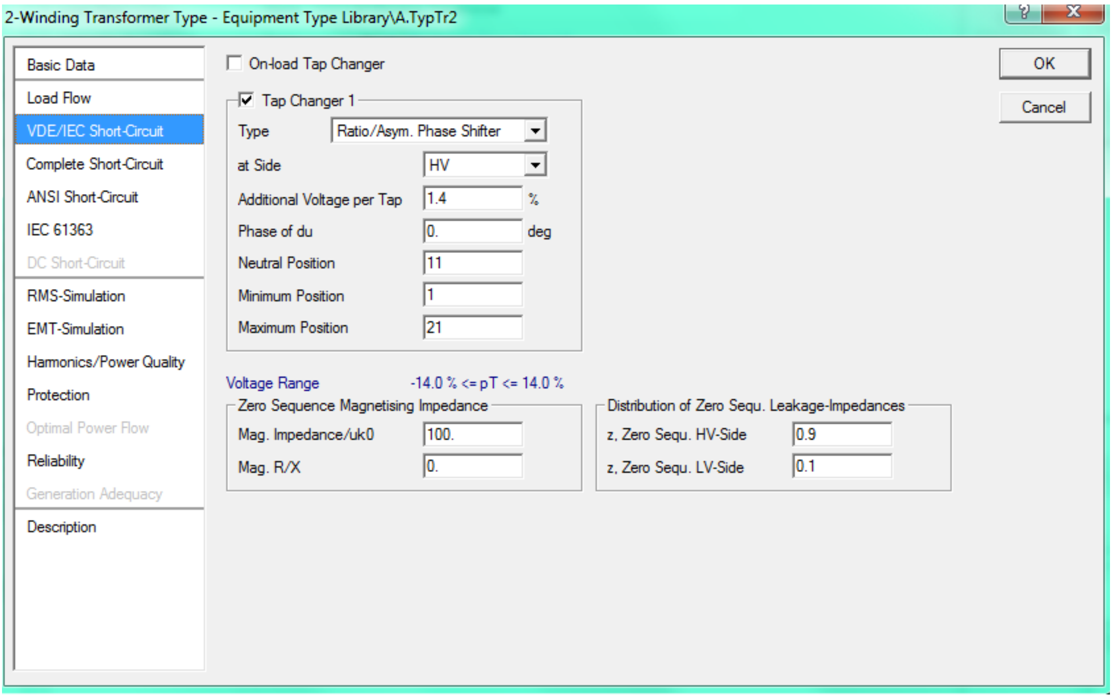


- MV transformer

General tables from database in PowerFactory:

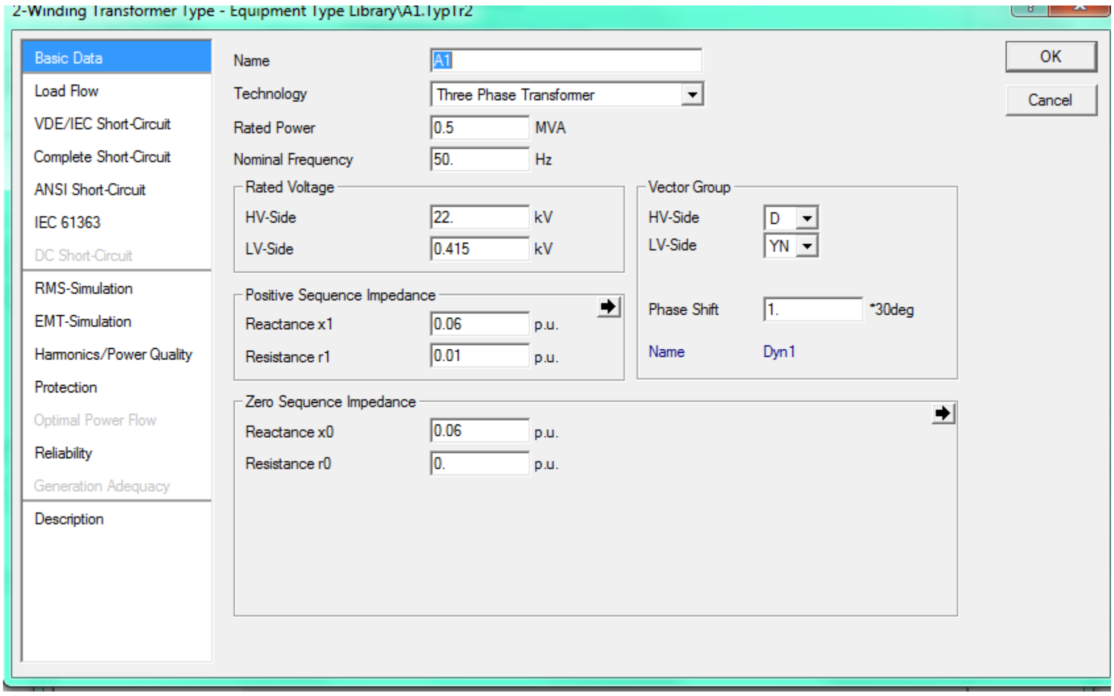


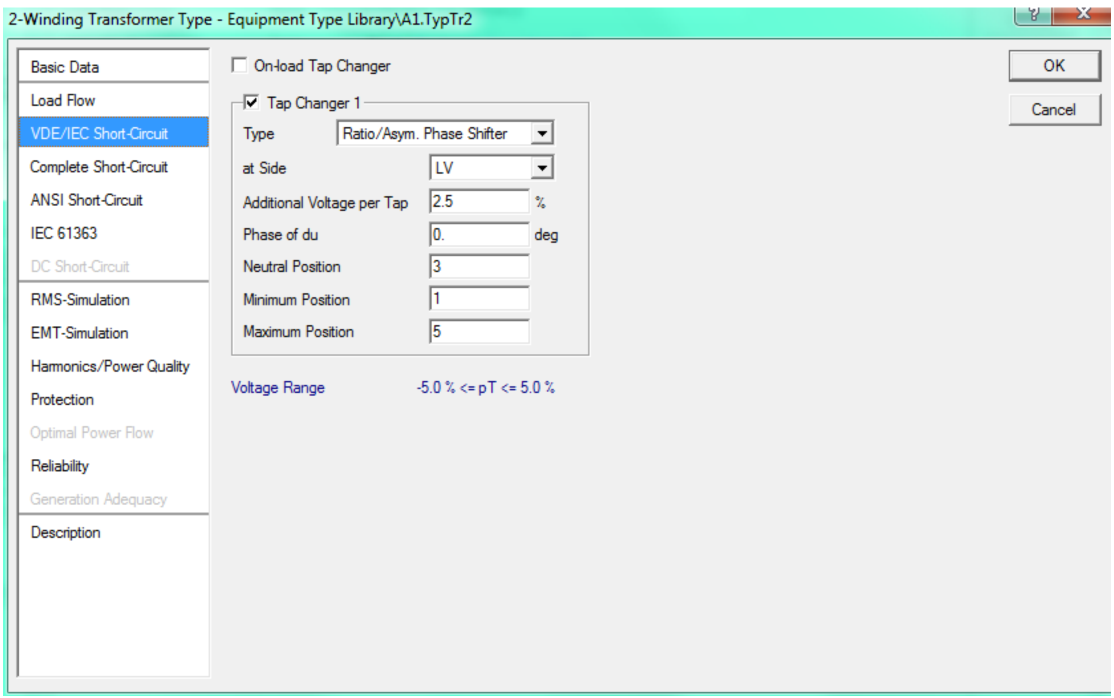

2-Winding Transformer - Grid\2-Winding Transformer(1).ElmTr2
Basic Data
Load Flow
VDE/IEC Short-Circuit
Complete Short-Circuit
ANSI Short-Circuit
IEC 61363
DC Short-Circuit
RMS-Simulation
EMT-Simulation
Harmonics/Power Quality
Protection
Optimal Power Flow
State Estimation
Reliability
Generation Adequacy
Tie Open Point Opt.
Description
General
Advanced
Tap Changer 1
Neutral: 11 Min: 1 Max: 21
Additional Voltage per Tap 1.4 %
Phase of du 0. deg
Tap Position 11
According to Measurement Report
Controller, Tap Changer 1
External Tap Controller
External Station Controller
Automatic Tap Changing
Tap Changer continuous
Controlled Node is at LV
Phase a
Control Mode V
Setpoint local
Remote Control
Voltage Setpoint 1.02 p.u.
Controller Time Constant 60. s
Line Drop Compensation (LDC) internal
Current Transformer Rating 1. A
Rset 0. V
Voltage Transformer Ratio 1.
Xset 0. V
Thermal Loading Limit
Max. Loading 100. %
OK
Cancel
Figure >>
Jump to ...


2-Winding Transformer Type - Equipment Type Library\A.TypTr2
Basic Data
Load Flow
VDE/IEC Short-Circuit
Complete Short-Circuit
ANSI Short-Circuit
IEC 61363
DC Short-Circuit
RMS-Simulation
EMT-Simulation
Harmonics/Power Quality
Protection
Optimal Power Flow
Reliability
Generation Adequacy
Description
On-load Tap Changer
Tap Changer 1
Type
Ratio/Asym. Phase Shifter
at Side
HV
Additional Voltage per Tap
1.4
%
Phase of du
0.
deg
Neutral Position
11
Minimum Position
1
Maximum Position
21
Voltage Range
-14.0 % <= pT <= 14.0 %
Zero Sequence Magnetising Impedance
Mag. Impedance/uk0
100.
Mag. R/X
0.
Distribution of Zero Sequ. Leakage-Impedances
z, Zero Sequ. HV-Side
0.9
z, Zero Sequ. LV-Side
0.1
OK
Cancel

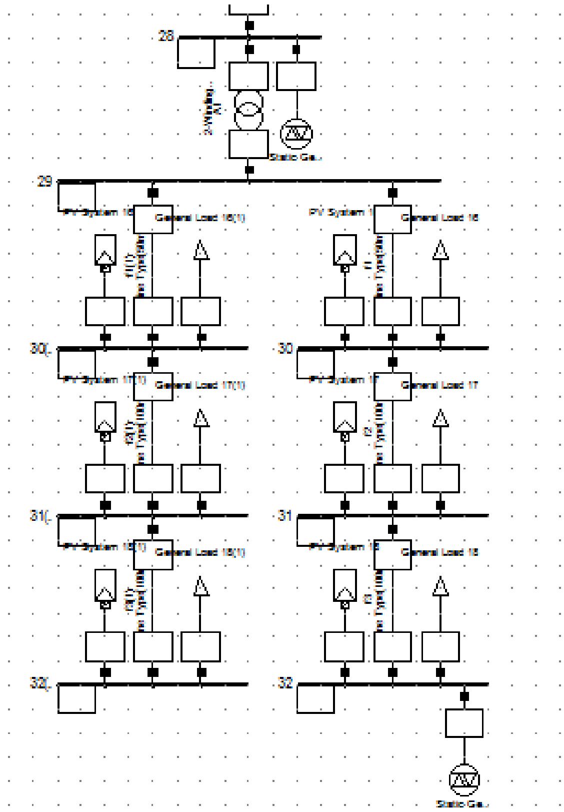
- LV transformer

General tables from database in PowerFactory:



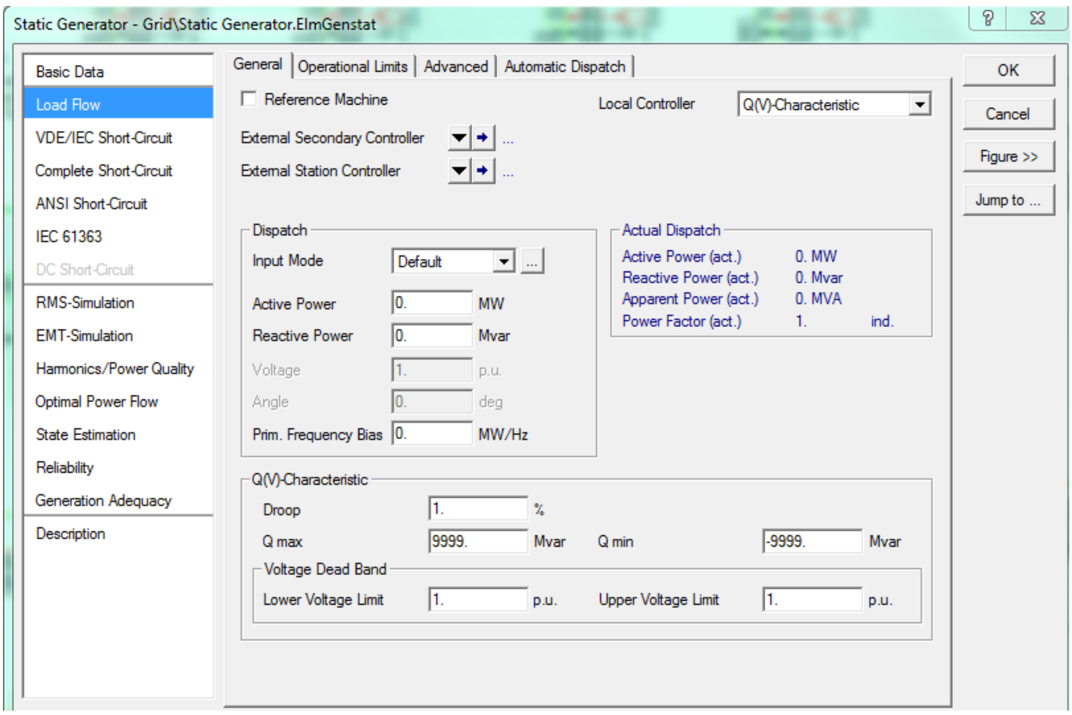


- STATCOM network diagram



- STATCOM transformer

General table from database in PowerFactory:



12.3 Appendix C: 12.7/22kV Three Core Ind. Screened & PVC Sheathed Aluminium conductors [12]

Electrical Characteristics

Nominal conductor area mm²	Maximum Conductor DC resistance at 20°C Ohm/km	Conductor AC resistance at 50Hz and 90°C Ohm/km	Inductive reactance at 50Hz Ohm/km	Insulation resistance at 20°C MegOhm.km	Conductor to screen capacitance µF/km	Charging current per phase A/km	Dielectric loss per phase W/km	Maximum dielectric stress kV/mm	DC resistance of screens at 20°C Ohm/km	Zero sequence resistance at 20°C Ohm/km	Zero seq. react. at 50Hz Ohm/km
35	0.868	1.11	0.140	15000	0.157	0.626	31.8	3.62	0.759	3.15	0.0919
50	0.641	0.821	0.134	14000	0.172	0.685	34.8	3.47	0.560	2.32	0.0855
70	0.443	0.568	0.124	13000	0.192	0.768	39.0	3.30	0.393	1.62	0.0757
95	0.320	0.410	0.117	11000	0.214	0.855	43.4	3.17	0.294	1.20	0.0697
120	0.253	0.325	0.113	10000	0.232	0.926	47.0	3.08	0.265	1.05	0.0657
150	0.206	0.265	0.110	9700	0.250	0.997	50.7	3.01	0.266	1.00	0.0622
185	0.164	0.211	0.106	9000	0.269	1.07	54.5	2.95	0.265	0.961	0.0591
240	0.125	0.161	0.102	8100	0.298	1.19	60.4	2.87	0.265	0.920	0.0550
300	0.100	0.130	0.0996	7400	0.327	1.30	66.3	2.81	0.265	0.896	0.0527
400	0.0778	0.102	0.0951	6700	0.363	1.45	73.5	2.75	0.266	0.876	0.0484
500	0.0617	0.0819	0.0915	5900	0.407	1.62	82.4	2.69	0.265	0.858	0.0450

12.4 Appendix D: LV cable data [15]

a.c. RESISTANCE (R_c) AT 50 Hz

CABLE TYPE: MULTICORE WITH SHAPED CONDUCTORS

1	2	3	4	5	6	7	8	9
Conductor size	a.c. resistance (R_c) at 50 Hz, Ω/km							
	Copper*				Aluminium			
	Conductor temperature, °C				Conductor temperature, °C			
mm^2	45	60	75	90	45	60	75	90
16	1.26	1.33	1.40	1.47	2.10	2.22	2.33	2.45
25	0.799	0.842	0.884	0.927	1.32	1.39	1.47	1.54
35	0.576	0.607	0.638	0.669	0.956	1.01	1.06	1.11
50	0.426	0.448	0.471	0.494	0.706	0.745	0.783	0.822
70	0.295	0.311	0.327	0.342	0.488	0.515	0.542	0.568
95	0.213	0.224	0.236	0.247	0.353	0.372	0.392	0.411
120	0.170	0.179	0.187	0.196	0.279	0.295	0.310	0.325
150	0.138	0.145	0.153	0.160	0.228	0.240	0.253	0.265
185	0.111	0.117	0.123	0.128	0.182	0.192	0.202	0.211
240	0.0859	0.0902	0.0945	0.0988	0.139	0.147	0.154	0.162
300	0.0698	0.0732	0.0766	0.0800	0.112	0.118	0.124	0.130
400	0.0563	0.0589	0.0615	0.0641	0.0886	0.0932	0.0978	0.102
500	0.0466	0.0486	0.0506	0.0526	0.0716	0.0752	0.0788	0.0824

* For the a.c. resistance of tinned copper conductor, multiply copper value by 1.01.

REACTANCE (X_c) AT 50 Hz

CABLE TYPE: **ALL CABLES EXCLUDING FLEXIBLE CORDS, FLEXIBLE CABLES, MIMS CABLES AND AERIAL CABLES**

1	2	3	4	5	6	7	8	9	10	11	12
Conductor size	Reactance (X_c) at 50 Hz, Ω/km										
	Single-core						Multicore				
	Trefoil (or single phase)			Flat touching*			Circular conductors			Shaped conductors	
mm²	Elastomer	PVC	XLPE	Elastomer	PVC	XLPE	Elastomer	PVC	XLPE	PVC	XLPE
1	0.179	0.168	0.166	0.194	0.184	0.181	0.139	0.119	0.114	—	—
1.5	0.167	0.157	0.155	0.183	0.172	0.170	0.129	0.111	0.107	—	—
2.5	0.153	0.143	0.141	0.168	0.159	0.156	0.118	0.102	0.0988	—	—
4	0.142	0.137	0.131	0.157	0.152	0.146	0.110	0.102	0.0930	—	—
6	0.133	0.128	0.123	0.148	0.143	0.138	0.104	0.0967	0.0887	—	—
10	0.123	0.118	0.114	0.138	0.134	0.129	0.0967	0.0906	0.0840	—	—
16	0.114	0.111	0.106	0.130	0.126	0.122	0.0913	0.0861	0.0805	0.0794	0.0742
25	0.109	0.106	0.102	0.125	0.121	0.118	0.0895	0.0853	0.0808	0.0786	0.0744
35	0.104	0.101	0.0982	0.120	0.117	0.113	0.0863	0.0826	0.0786	0.0761	0.0725
50	0.0988	0.0962	0.0924	0.114	0.111	0.108	0.0829	0.0797	0.0751	0.0734	0.0692
70	0.0941	0.0917	0.0893	0.109	0.107	0.104	0.0798	0.0770	0.0741	0.0710	0.0683
95	0.0924	0.0904	0.0868	0.108	0.106	0.102	0.0790	0.0766	0.0725	0.0706	0.0668
120	0.0889	0.0870	0.0844	0.104	0.102	0.0996	0.0765	0.0743	0.0713	0.0685	0.0657
150	0.0885	0.0868	0.0844	0.104	0.102	0.0996	0.0765	0.0745	0.0718	0.0687	0.0662
185	0.0878	0.0862	0.0835	0.103	0.101	0.0988	0.0762	0.0744	0.0720	0.0686	0.0663
240	0.0861	0.0847	0.0818	0.101	0.0999	0.0970	0.0751	0.0735	0.0709	0.0678	0.0653
300	0.0852	0.0839	0.0809	0.100	0.0991	0.0961	0.0746	0.0732	0.0704	0.0675	0.0649
400	0.0841	0.0829	0.0802	0.0993	0.0982	0.0955	0.0740	0.0728	0.0702	0.0671	0.0647
500	0.0830	0.0820	0.0796	0.0983	0.0973	0.0948	0.0734	0.0723	0.0700	0.0666	0.0645
630	0.0809	0.0800	0.0787	0.0961	0.0952	0.0940	—	—	—	—	—

* These reactance values may also be used as a conservative estimate for cables that are not strictly arranged 'flat touching', e.g. where cables are installed in a wiring enclosure.