Title: **Advanced Planning of PV-Rich Distribution Networks - Deliverable 1: HV-LV modelling of selected HV feeders**

Synopsis: This document first presents the process adopted by The University of Melbourne in collaboration with AusNet Services to select the HV feeders that will be modelled and used throughout the project. Then, the selected HV feeders are fully modelled along with their corresponding LV networks using the software OpenDSS.

Document ID: UoM-AusNet-2018ARP135-Deliverable1_v01

Date: 10th June 2019

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Executive Summary

This report corresponds to Deliverable 1 “HV-LV modelling of selected HV feeders” part of the project Advanced Planning of PV-Rich Distribution Networks funded by the Australian Renewable Energy Agency (ARENA) and led by the University of Melbourne in collaboration with AusNet Services. The project is established to develop analytical techniques to assess residential solar PV hosting capacity of electricity distribution networks by leveraging existing network and customer data. Additionally, planning recommendations will be produced to increase the hosting capacity using non-traditional solutions that exploit the capabilities of PV inverters, voltage regulation devices, and battery energy storage systems.

This document first presents the process adopted to select the HV feeders going to be used in the project. Chapter 3 details the procedure adopted to extract and process all feeder data to develop the corresponding digital feeder models considering different aspects and assumptions. Chapter 4 presents the topology and general characteristics of all fully modelled feeders along with a case study that considers a peak demand day time-series power flow analysis using the software OpenDSS. The corresponding analyses, which consider realistic demand data, help understanding the level of the detailed modelling performed while demonstrating the expected behaviour of each of the feeders.

The following key points summarising this report are listed below.

HV Feeder Selection

- **Four (4) significantly different HV (22kV) Feeders are selected** from the total number of feeders operated by Ausnet services. These correspond to two (2) Rural and two (2) Urban and described below:
    - **R1.** A long feeder with relatively high number of customers, medium maximum loading and high PV penetration level.
    - **R2.** A short feeder with relatively high number of customers, high maximum loading and high PV penetration level.
    - **U1.** A long feeder with medium number of customers, medium maximum loading and high PV penetration level.
    - **U2.** A medium length feeder with high number of customers, high maximum loading and high PV penetration level.
- **The selection considered several different feeder characteristics** (rural, urban, length, number of customers, number of PV system installations etc.) to capture different feeder types.
- **The selection considered the trade-off between the quality and availability of data** (network, smart meter, GIS, etc.), existing PV system installations (critical for validation of the analytical techniques), as well as the corresponding data extraction complexity.

HV Feeder Modelling

Using detailed anonymised feeder data, integrated high-voltage (HV, 22kV) and low-voltage (LV, 400V) three-phase network models were developed for the selected feeders.

- **The data provided for the selected HV feeders were successfully processed.** These included topologies, impedances, phase connections, tap ranges, elements connected (i.e., SWER transformers, capacitors, voltage regulators) and number of customers for several distribution transformers. The resulting models are believed to be highly accurate and representative of the HV feeder.
- **LV Networks**. Given the fact that LV network models are not readily available from AusNet Services, a methodology to realistically model LV networks is proposed based on Australian

electrical distribution substation standards and design manuals. This will allow quantifying –to some extent– the impacts closer to LV customers.

Modelled HV Feeders

The topology and general characteristics of the four modelled HV feeders were presented along with a time-series power flow analysis using OpenDSS. This initial analysis helps understanding the level of the detailed modelling performed while demonstrating the expected behaviour of each of the feeders.

- **General characteristics of modelled HV Feeders.**
  - Rural Feeders
    1. Total conductor length of R1 and R2 amounts to 470 and 280km, respectively.
    2. Both R1 and R2 supply 700+ residential LV substations (4500+ households) out of which 219 and 161 are made through SWER connections, respectively.
    3. R1 and R2 supply 61 and 24 non-residential LV substations.
    4. R1 and R2 have 10 and 7 SWER transformers, respectively.
    5. Both R1 and R2 have 2 900kVar HV capacitors.
    6. Both R1 and R2 have 2 in-line voltage regulators.
    7. R1 and R2 are approximately 16 times larger than the two Urban feeders.
  - Urban Feeders
    1. Total conductor length of U1 and U2 amounts to 12 and 30km, respectively.
    2. U1 and U2 supply 44 and 79 residential LV substations (3000+ households).
    3. U1 supplies 1 non-residential LV substation.
    4. U1 and U2 have no SWER transformers.
    5. U1 and U2 have no HV capacitors.
    6. U1 and U2 have no in-line voltage regulators.
- **Demand Profiles for Business-as-Usual Analyses.** Smart Meter data are not yet available for each of the selected feeders, demand profiles, hence demand profiles used in a previous project "*AusNet Mini Grid Clusters*" were considered in this report to demonstrate the behaviour of the feeders.
  - While their behaviour is demonstrated using realistic demand data, it is important to highlight that these do not correspond or represent the real-life demand in of the modelled feeders; their behaviour might under or over-estimated. As such, the analyses performed and presented in this report are used only for demonstration purposes.
- **Business-as-Usual Analyses.** The operation of the HV feeders was demonstrated through time-series analysis, considering a peak demand day. All values (voltages and currents) were found to be within the acceptable operating limits except some line segments in R1 and R2 which experienced congestion issues. This is believed due to the usage of load demand profiles that do not correspond to the corresponding geographical area; hence overestimating the loading conditions.
  - The level of voltage drops in R1 and R2, compared to the U1 and U2, is significantly larger given that Rural feeders are considerably larger and supply remote areas through SWER connections.
  - In all feeders, a higher utilisation of assets was observed during peak demand (late evening and night hours) compared to the low demand during morning hours.

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1 Introduction

According to the Australian PV Institute, the aggregated installed capacity of solar PV in Australia is currently exceeding 6.5 GW, with many these installations being residential. The percentage of dwellings with solar PV varies from 12% in the Northern Territory to 30% in Queensland. This, combined with a growing number of commercial customers adopting the technology, will soon pose significant technical challenges on the very infrastructure they are connected to: the low voltage (LV) and high voltage (HV) distribution networks.

Due to the rapid uptake of the technology, many Distribution Network Service Providers (DNSPs) across the country have adopted the use of PV penetration limits based on the capacity of the distribution transformers feeding LV customers. Once this limit is reached, complex and time-consuming network analyses are often required to determine the need for any mitigating action due to asset congestion or voltage rise issues (e.g., network augmentation, use of off-load tap changers).

Whilst, in principle, the use of a PV penetration limit is a sensible approach to swiftly deal with many connection requests, the lack of advanced planning approaches has led DNSPs to adopt values that might under or over-estimate their actual hosting capacity, particularly due to voltage issues in LV networks and aggregated congestion issues in HV networks. Similarly, assessing the effectiveness of non-traditional solutions, such as actively controlling smart PV inverters or deploying distribution transformers fitted with on-load tap changers, becomes a task beyond typical planning studies carried out by DNSPs. All this, in turn, becomes a barrier for the widespread adoption of solar PV as it can create delays, increase cost, and could undermine the consumer attractiveness of the technology.

To help remove the aforementioned barriers and accelerate the adoption of solar PV in Distribution Networks, this project is established to develop analytical techniques to rapidly assess residential solar PV hosting capacity of electricity distribution networks by leveraging existing network and customer data. Additionally, planning recommendations will be produced to increase the hosting capacity using non-traditional solutions that exploit the capabilities of PV inverters, voltage regulation devices, and battery energy storage systems.

The report at hand is structured as follows: Chapter 2 presents the process adopted by The University of Melbourne in collaboration with AusNet Services to select the HV feeders that will be used for the project purposes. Chapter 3 details the procedure adopted to extract and process all feeder data in order to develop the corresponding digital feeder models considering different aspects and assumptions. Chapter 4 presents the topology and general characteristics of all fully modelled feeders along with a case study that considers a peak demand day time-series power flow analysis using the software OpenDSS. The corresponding analyses, which consider realistic demand data, help understanding the detailed modelling while demonstrating the expected behaviour of each of the feeders. Finally, conclusions and next steps are presented in Chapter 5 and 6, respectively.

2 HV Feeder Selection

For the successful completion of the project, full network models will be used from which analytical techniques can then be defined. Thus, and as defined in the project, the first Task will produce integrated high-voltage (HV, 22kV) and low-voltage (LV, 400V) three-phase network models. For this, using AusNet Service's expertise, four (4) significantly different HV feeders (operated by AusNet Services) were identified and selected considering several characteristics (rural, urban, length, number of customers, number of PV system installations etc.) so as to capture different feeder types. It is important to highlight that the feeder selection was also performed considering the trade-off between the quality and availability of data (network, smart meter, GIS, etc.), existing PV system installations (critical for validation of the analytical techniques), as well as the corresponding data extraction complexity and associated time restrictions. The selected feeders will allow demonstrating that the proposed techniques can be applied, to the extent that is possible, across the wide spectrum of HV feeders in the AusNet Services area and other DNSP areas across Australia.

This chapter presents the process adopted by The University of Melbourne in collaboration with the expert views and knowledge of AusNet Services to select the HV Feeders that will be modelled and used for the project purposes.

2.1 Characteristics of HV Feeders

HV feeders can be described using several characteristics. For this project, the focus is on those characteristics that are key with respect to the effects from PV system installations. For instance, the number of customers will relate to the future number of PV installations. Larger distances will produce larger impedances and, therefore, a higher voltage rise due to reverse power flows. Furthermore, given the smart meter data requirements of this project, its availability is also critical.

The following are considered as key characteristics for this project. It should be highlighted that some of these characteristics might not be readily available or difficult/time-consuming to extract from AusNet Service's databases.

- **Geography/Type.** The feeder type in terms of location and structure (e.g., rural, urban).
- **Length.** The total conductor length in the feeder. If available, this can be divided into underground, overhead and total conductor lengths.
- **Maximum or Average loading**. The maximum or average loading (i.e., MVA, MVAr, MW) of the feeder. This characteristic can be considered as a good indicator to identify feeders that are more likely to face technical issues (i.e., voltage, asset congestion).
- **Number of customers**. The number of customers connected and supplied by the feeder.
- **Number of PV system installations.** This corresponds to the number of PV systems connected to the feeder. It can be provided in the form of an exact number or as a percentage of customers with a PV system installation (i.e., penetration level). Given the nature of the project which aims at providing solutions and recommendations of PV-rich Distribution Networks, this characteristic allows identifying those feeders with high number of PV system installations hence compare and validate the solutions.
- **Operating voltage**. The rated voltage at which the feeder is operated (e.g., 22kV, 11kV)
- **Availability/Quality of Smart Meter Data.** Although this is not a direct characteristic, it allows identifying those feeders that have good availability of recorded smart meter data, hence enabling a detailed modelling for the corresponding analyses as well as validating and comparing the proposed analytical techniques and solutions.

2.2 HV Feeder Information Across the AusNet Services Area

Given the time restrictions and the time-demanding process in extracting the information listed above (as well as the availability of data), a simplified database of the total HV feeders operated by AusNet Services was facilitated to the University of Melbourne. This database contains anonymized data that correspond to a total of 351 HV feeders located in Victoria. Given the complexity of Smart Meter data availability and quality, this information remained within AusNet Services. Therefore, for each feeder, six (6) key characteristics are recorded and these correspond to the following:

- **Type.** The type of the feeder (i.e., Rural, Urban)
- **Length.** The total conductor length that the feeder is comprised from.
- **Maximum loading.** The recorded maximum loading of the feeder as a percentage of its rating.
- **Number of customers.** The total number of connected customers.
- **PV Penetration Level.** The percentage of customers with a PV system.
- **Operating voltage.** All of them 22kV.

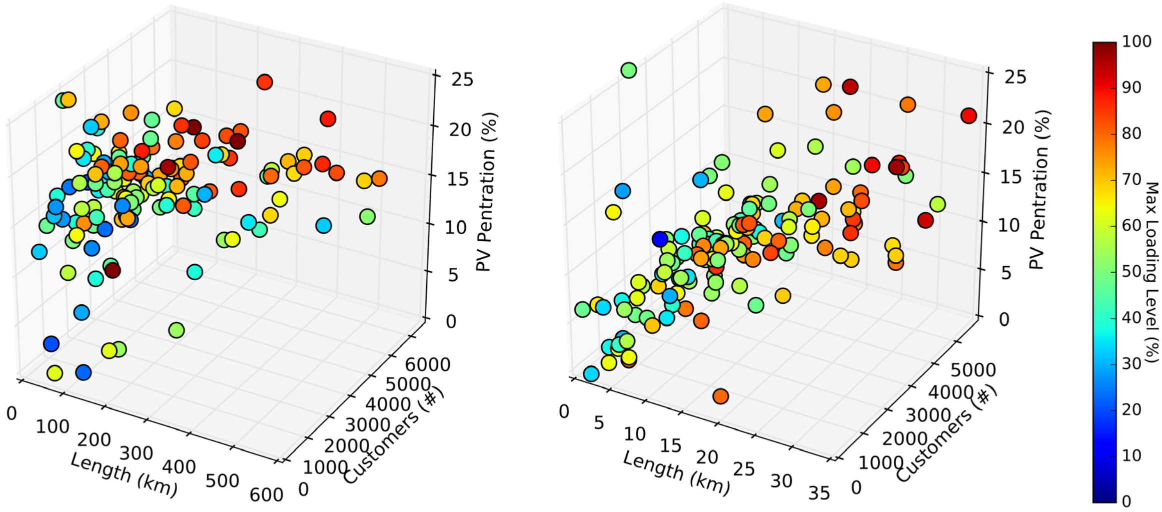
Given the data sourced by different databases, several feeders missing information were identified and discarded through a data-cleaning process. The final (cleaned) database, which includes approximately 300 HV feeders, was then split into two distinct sets (categories) based on the Type of each feeder; **Urban**[1] and **Rural**[2]. While rural feeders, based on the Distribution Code, can further be categorised into short and long, the selection process in this report does not consider this subcategorization.

For each type (i.e., rural and urban), feeders were then mapped based on their **Length**, **Number of Customers**, **PV Penetration Level** and **Maximum Loading** as shown in Figure 1. To help with the visualization of the mapping, each feeder is colour-mapped according to its maximum loading; the higher the loading, the closer to the red colour. Based on the close correlation of existing load and potential impacts from PV systems, the feeder loading level can be considered as a good indicator of those feeders that are expected to face technical issues (i.e., voltage, asset congestion) with future PV system installations.

As observed in Figure 1, the length of rural feeders ranges from a couple of kilometres to hundreds (up to 600km) where urban feeders are considerably shorter (up to 30km). Despite the significant length difference between the two Types, both present a similar trend where the higher the number of customers, the higher the feeder loading. As previously mentioned, feeders featuring high number of customers (hence higher loading conditions) are more likely to face technical issues, given that larger numbers of PV systems are expected to be installed in a feeder with higher number of customers. Crucially, such feeders should be included in the selected set of feeders for this project as this will allow compare and validate the analytical techniques and solutions that will be developed in this project.

[1] According to the Distribution Code produced by the Essential Services Commission a feeder is categorized as Urban if (1) it is not in a central business district (CBD) and (2) its load density is greater than 0.3MVA/km.

[2] According to the Distribution Code produced by the Essential Services Commission a feeder is categorized as Rural if (1) it is not in a central business district (CBD) and (2) not categorized as Urban. A Rural feeder is further categorized as into a Short (less than 200km) and Long Rural (greater than 200km).



(a) Rural Feeders **(b) Urban Feeders**

Figure 1 HV Feeders Operated by AusNet Services (Mapping)

Following the mapping of each type of feeders, a statistical analysis was performed for each type to identify the maximum, median and minimum values for each characteristic (i.e., length, maximum loading, customers, PV penetration). The statistical analysis for each characteristic is demonstrated using a boxplot representation which includes the maximum, median and minimum values recorded in the database for all rural (Figure 2) and urban feeders (Figure 3).

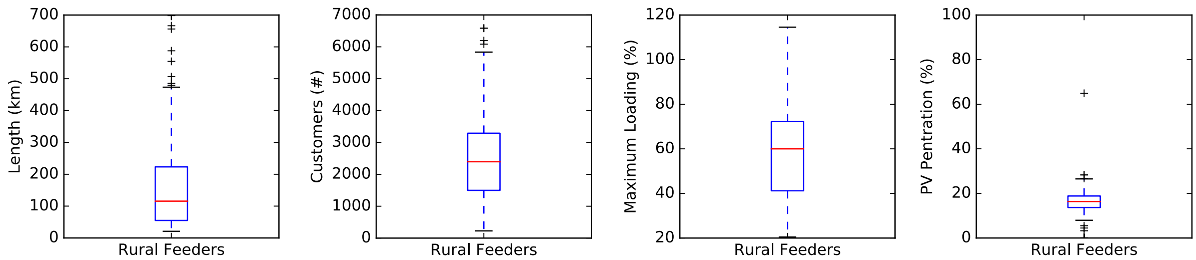


Figure 2 Statistical Analysis: Rural Feeders

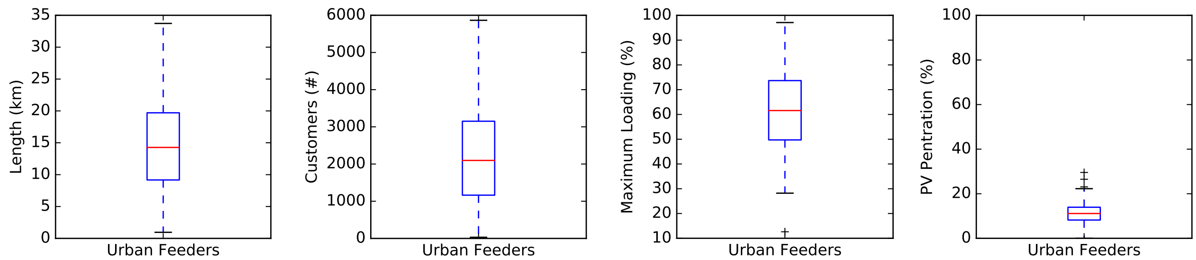


Figure 3 Statistical Analysis: Urban Feeders

The above analyses can help selecting feeders that are significantly different, so as to cover, to the extent that is possible, the wide spectrum of HV feeders in the AusNet Services area. In an ideal scenario, feeders featuring characteristics with values close to the extremes. However, such feeders (e.g., maximum length with maximum loading with maximum number of customers) might not exist in reality. Furthermore, from the perspective of their digital model and quality of data (including Smart Meter data), the modelling of certain HV feeders might not be feasible. Hence, a trade-off between the quality and availability of data (i.e., digital feeder models, smart meter data) as well as the corresponding time restrictions should be considered.

More importantly and given the first objective of the project (development of analytical techniques to assess the solar PV hosting capacity of electricity distribution networks), it is crucial to select feeders that already show (relatively) high penetrations of PV systems. Such feeders, where PV generation and demand data from smart meters will be available, will allow comparing and validating the developed analytical techniques.

Considering the aforementioned and given the fact that data availability and quality information remained within AusNet Services, the University of Melbourne requested at least two Rural and two Urban feeders. For each type, the characteristics of the feeders should, where possible, have values aligned with at least two of the following descriptors (which are related to the values presented in Figure 1 to Figure 3):

(a) Long Feeder, High Number of Customers, High Maximum Loading, High PV Penetration, Good quality of Digital Model, Good quality of Smart Meter Data
(b) Medium Length Feeder, Medium Number of Customers, Medium Maximum Loading, High PV Penetration, Good quality of Digital Model, Good quality of Smart Meter Data
(c) Short Feeder, Low Number of Customers, Low Maximum Loading, High PV Penetration, Good quality of Digital Model, Good quality of Smart Meter Data

2.3 Selected Feeders and Data Provided

The mapping and statistical analysis of feeders along with the descriptors of the Rural and Urban feeders were passed on to AusNet Services to provide their expert views on the feeder identification and selection process. After multiple discussions with AusNet Services and based on the know-how from their engineers, the quality of available digital feeder models, the availability of smart meter data and the different required characteristics, the feeders presented in Table 1 were selected:

Table 1 Selected Feeders

Name	Type	Length (km)	Max Loading (%)	Customers (#)	PV Penetration (%)	Digital Feeder Model Quality	Smart Meter Data Quality
R1	RURAL	485	60	3223	21	Good	Good
R2	RURAL	277	85	3977	18	Good	Good
U1	URBAN	34	50	3125	20	Good	Good
U2	URBAN	20	94	5161	22	Good	Good

Considering the Rural feeders, the selected feature the following:

- **R1.** A long feeder with relatively high number of customers, medium maximum loading and high PV penetration level.
- **R2.** A short feeder with relatively high number of customers, high maximum loading and high PV penetration level.

Considering the Urban feeders, the selected feature the following:

- **U1.** A long feeder with medium number of customers, medium maximum loading and high PV penetration level.

- **U2.** A medium length feeder with high number of customers, high maximum loading and high PV penetration level.

The selected feeders feature values that are close to the specified descriptors and more importantly have a high penetration level of PV systems. The selected feeders (for each type) present different enough characteristics in terms of distance, loading and number of customers, hence allowing to investigate and demonstrate the techniques to be developed in this project. Finally, given the good availability and quality of both digital feeder models and smart meter data, the adequate modelling of these HV feeders is expected to be achievable. Based on these aspects, the University of Melbourne and AusNet Services consider the selected four HV feeders are an adequate compromise as they feature significant differences between them.

The full anonymised model data of the selected feeders were facilitated to the University of Melbourne along with useful documentation to enable the corresponding modelling of the selected HV feeders. The received data and documentation are listed below:

1. **PSS Sincal Model for each selected HV Feeder.** These models correspond to the databases (.mdb format) used by the software PSS Sincal and contain all the details for each feeder (i.e., conductor details, connections, capacitors, regulators, transformers etc.)
2. **Distribution Substations Information**. These files (.xlsx format) correspond to the details of the distribution substations (i.e., Substation ID, Substation Name, Substation Number, Transformer Size and Connected Phases, number of customers, number of customers with solar PV) connected in each HV feeder. Given that this information is not included in the PSS Sincal models it will help realistically model the LV networks.
3. **AMS – Electricity Distribution Network: Subtransmission Line and Station Data for Planning Purposes** (Number AMS 20-24).
4. **AMS – Distribution Network Planning Standards and Guidelines** (Number AMS 20-16).
5. **Specification for Polemounting Distribution Transformers** (ENA DOC 007-2016).

The processing of these data files and the corresponding modelling aspects is explained in Chapter 3.

3 HV Feeder Modelling

This section provides an overview of the procedure and parameters used to model the selected HV feeders the corresponding LV networks. These were modelled using the software OpenDSS (developed by the Electric Power Research Institute - EPRI, USA). Noting that LV network models are not readily available from AusNet Services (and, in general, from DNSPs), LV networks can be modelled based on the estimated number of customers per distribution transformer and design principles (e.g., length, conductor, distribution of customers, etc.). Modelling the LV networks, even if not exactly as in reality, it will possible to have a better quantification of the impacts closer to LV customers, in particular, voltages at the customer connection points.

3.1 HV Feeder Modelling

This section provides the relevant information on how the network model was extracted from the PSS Sincal files. It is important to notice that the procedure might vary slightly depending on the network and destination format (in this case, OpenDSS files), but overall it can be automated if the input format remains identical. For the conversion of files, there is no need of using PSS Sincal, as all the relevant information is within the “database.mdb” file that comes along with the PSS Sincal file.

3.1.1 Cables and Overhead Lines

For the extraction of cables and overhead lines, two tables from the database are used: “QueryTopologyTwoPort” and “Line”.

Within the “QueryTopologyTwoPort” lie the connection points (nodes) of each line in the network. Three fields are of interest: “Element_ID”, “Node_1.Node_ID” and “Node_2.Node_ID”. “Element_ID” is a unique numerical identifier for all elements in the network. “Node_1.Node_ID” and “Node_2.Node_ID” are the numerical identifications of the two connection points of each line (buses). Please note that all these numbers are internally generated identification numbers, and do not represent the real element IDs (anonymized data).

The “Line” table on the other hand contains the physical characteristics of each line (impedances, length and conductor type). Eight fields are of interest in this table: “Element_ID”, “LineTyp”, “l”, “r”, ”x”, ”c”, ”r0”, ”x0”, “c0” and “Ith”. “Element_ID” is the same as previously defined and it’s what combines the two tables together. “LineTyp” is the type of the conductor, “l” is the length of each segment in kilometres, while “r”, ”x”, ”c”, ”r0”, ”x0” and “c0” are the positive and zero sequence, resistances, reactances and capacitances per kilometre respectively. “Ith” is the ampacity (maximum current rating) of the cable, per phase.

To extract the required information, a Python script was run that iterated through all of the elements in the two tables, identifying each unique line segment, allocating a start bus and end bus to each, along with the physical characteristics of it (length and impedances). While PSS Sincal data extraction process can be automated, it is important to highlight that manual verification of the extracted data is required given the complexity of the corresponding HV feeder (e.g., SWER lines, node connection phasing etc.).

3.1.1.1 Identification of single and three-phase connections

The feeder model facilitated by AusNet Services (database.mdb) does not provide any information about which nodes and lines (connections between nodes) are single or three-phase. Given the numerous SWER connections (i.e., single-phase lines) in the models, this information (i.e., phases) is essential to produce as accurate as possible model in OpenDSS.

To identify each phase connection, every line segment in the circuit was traced from the head of the feeder to each one of the secondary distribution substations. If within the path an isolation transformer (SWER) is identified, the path downstream the isolation transformer is characterised as single-phase line connections. With the purpose of determining the connected components, the Breadth First Search Algorithm (BFSA) has been adopted (details of BFSA are given in Appendix A).

3.1.2 Primary Substation

While the physical characteristics of the primary substation are defined in the received item 3 (AMS 20-24), it is required that the connection point of the primary transformer within our model if defined. For this, the "QueryTopologySinglePort" table (in database.mdb) is used. The primary transformer is identified by the field "ElementType". The row containing the information required is the one identified as "Infeeder". What is needed to identify the connection point is in the field "Node_ID".

Although the nominal transformation ratio of the transformer at the head of each HV Feeder is 66kV/22kV, these are modelled with a modified transformation ratio so as to mimic the voltage target as shown in Figure 4 and defined in item 3 (*AMS – Electricity Distribution Network: Subtransmission Line and Station Data for Planning Purposes*).

Site	#of Tx	Installed Capacity (MVA)	Station N Rating				Station N-1 Rating				Remarks for N-1 Ratings	Bus Target Voltage (kV)	Station Cap bank (MVar)	Station Cap bank Step Size
			SCR		WCR		SCR		WCR					
			MVA	A	MVA	A	MVA	A	MVA	A				
BN	3	40.5	48.8	1230	56.5	1424	32.5	819	37.5	945	Loss of T1 or T2	22.9	6	2x3 Mvar
							35.6	898	41.2	1039	Loss of T3	22.9		
BRT	2	40	55.8	1464	60.0	1575	27.9	732	30.0	787	Loss of T1 or T2	22.0	0	
CF	3	15	17.9	453	20.6	522	11.8	299	15.5	392	Loss of T3	22.8	0	
							12.3	311	14.2	360	Loss of T1 or T2	22.8		
CLPS	2	26									Flat Load			
MBY	2	10	13.7	345	15.0	378	6.9	174	7.5	189	Loss of T1 or T2	22.9	0	
MJG	1	20	28.9	729	27.6	696	0.0	0	0.0	0	N rating only	22.9	0	

Figure 4 Head of HV Transformer

3.1.3 In-line Transformers

Similar to the modelling of the cables and overhead lines, the distribution transformers modelling has two parts too: identifying the connection points and the physical characteristics of each in-line transformer. For the identification of the connection points, the table named "QueryTopologySinglePort" is used. Within this table, there are three fields of interest. "ElementName", "ElementType" and "Node_ID". What is important here is identifying the "ElementType" rows that are "TwoWindingTransformer". After these have been identified, the connection point of each transformer is found in the "Node_ID" field. Please note that the "Node_ID" field here matches the buses that were declared when the cables and overhead lines were extracted.

While all transformers in the provided databases are defined as "TwoWindingTransformer", based on discussions with AusNet Services, two types of transformers exist in their networks: (a) Single wire earth return (SWER) Isolating Transformers and (b) OLTC-enabled in-line voltage regulators. To identify the exact type of each transformer, the property "ElementName" is processed in the automated script and the type is defined as SWER or Regulator if the word ISO or REG is found, respectively.

3.1.3.1 Single wire earth return (SWER) transformers

All SWER system used to supply electricity to rural and remote areas are modelled according to the provided document (4) AMS 20-16 *"Distribution Network Planning Standards and Guidelines"*. Figure 5, shows the network configuration adopted in this report to model the corresponding SWER networks. As shown, a SWER connected load is supplied using a SWER Isolating transformer (ISO) through a single wire that is used to supply the load with earth acting as the return path conductor.

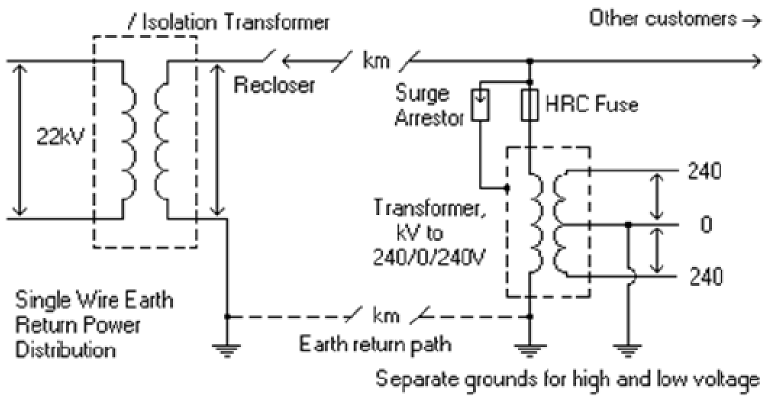


Figure 5 SWER Configuration[3]

All single-phase SWER connected transformers are modelled assuming a nominal transformation ratio of 12.7/0.240kV and with an off-load tap capability ranging from -5% (position 1) to +7.5% (position 5) with a step of 2.5% and position 3 as nominal. With a no-load voltage at the primary side of the transformer of 12.7kV, the busbar line-to-neutral voltages corresponding to the different off-load tap positions are given in Table 2.

Table 2 SWER transformer off-load tap capability

Tap position	HV L-N (kV)	LV L-N (V)	Vbase = 0.23kV Vpu
1	12.7	228	1.028
2	12.7	234	1.055
3	12.7	240	1.083
4	12.7	246	1.110
5	12.7	252	1.137

3.1.3.2 OLTC-Enabled In-line Voltage Regulation Transformers

All three-phase OLTC-enabled in-line voltage regulator transformers are modelled considering the specifications in item 4 (AMS 20-16 *"Distribution Network Planning Standards and Guidelines"*). The modelling assumes a nominal transformation ratio of 22/22kV and with an on-load tap capability ranging from -5% (position 1) to +33% (position 17) with a step of 1.94% and position 4 as nominal. With a no-load voltage at the primary side of the transformer of 22kV, the busbar line-to-neutral voltages corresponding to the different on-load tap positions are given in Table 3.

[3] AMS 20-16 *"Distribution Network Planning Standards and Guidelines"*

Table 3 In-line voltage regulator transformer on-load tap capability

Tap position	Primary Side L-L (V)	Secondary Side L-L (V)	Vbase = 22kV Vpu
1	22000	20796	0.95
2	22000	21182	0.96
3	22000	21583	0.98
4	22000	22000	1.00
5	22000	22433	1.02
6	22000	22883	1.04
7	22000	23352	1.06
8	22000	23840	1.08
9	22000	24350	1.11
10	22000	24881	1.13
11	22000	25436	1.16
12	22000	26017	1.18
13	22000	26625	1.21
14	22000	27261	1.24
15	22000	27929	1.27
16	22000	28631	1.30
17	22000	29369	1.33

3.1.4 Distribution Substations

Following the same process with the cables and overhead lines, the distribution substarion modelling has also two parts too: identifying the connection points and the physical characteristics of each transformer. For the identification of the connection points, the table named “QueryTopologySinglePort” is used. Within this table, there are three fields of interest. “ElementName”, “ElementType” and “Node_ID”. What is important here is identifying the “ElementType” rows that are Loads. After these have been identified, the connection point of each transformer is found in the “Node_ID” field. Please note that the “Node_ID” field here matches the buses that were declared when the cables and overhead lines were extracted. Furthermore, it is required that the name of each load is saved as this will be required when declaring the physical characteristics of each transformer.

Defining the physical characteristics of each distribution transformer requires information that is not contained in the PSS Sincal model. Using the names of each transformer as identified from the “ElementName” field, items (2) can be used to identify the size, type and phase connection of each transformer. Furthermore, the tap range of the distribution transformers can be identified using (5) and the nominal impedances of the transformers adopting the process in [1] .

A table with the impedances of transformers was created based on their size, and a Python script iterated through all the required spreadsheets to create the required distribution transformer model. This process can also be automated, however due to how different spreadsheets are used, outside of the scope of PSS Sincal, this is more prone to errors and it is recommended that the results are checked manually.

3.1.4.1 Tap Capabilities

The secondary distribution transformers for the given HV feeder are modelled considering the following nominal transformation ratios and tap capabilities also specified in the previous project *“HV-LV Analysis of Mini Grids Clusters”* [1]. It is also important to mention that because the Business As Usual (current state) off-load tap positions are not known, these were adjusted based on a peak loading scenario so that all network voltages are within their corresponding limits as specified by the standard AS 61000.3.100.

1. All three-phase transformers are modelled assuming a nominal transformation ratio of 22/0.433kV and with an off-load tap capability ranging from -5% (position 1) to +7.5% (position 5) with a step of 2.5% and position 3 as nominal. With a no-load voltage at the primary side of the transformer of 22kV, the busbar line-to-line voltages corresponding to the different off-load tap positions are given in Table 4.

Table 4 Three-phase transformer off-load tap capability

Tap position	HV L-L (kV)	LV L-L (V)	Vbase = 0.4kV Vpu
1	22	411	1.028
2	22	422	1.055
3	22	433	1.083
4	22	444	1.110
5	22	455	1.137

2. All single-phase transformers are modelled assuming a nominal transformation ratio of 22/0.250kV and with an off-load tap capability ranging from -5% (position 1) to +7.5% (position 5) with a step of 2.5% and position 3 as nominal. With a no-load voltage at the primary side of the transformer of 22kV, the busbar line-to-line voltages corresponding to the different off-load tap positions are given in Table 5.

Table 5 Single-phase transformer off-load tap capability

Tap position	HV L-L (kV)	LV L-L (V)	Vbase = 0.23kV Vpu
1	22	237	1.028
2	22	244	1.055
3	22	250	1.083
4	22	256	1.110
5	22	262	1.137

3.1.5 Capacitors

Similar to the modelling of the cables and overhead lines, the HV capacitors modelling has two parts: identifying the connection points and the physical characteristics of each capacitor. For the identification of the connection points, the table named “QueryTopologySinglePort” is used. Within this table, there are three fields of interest. “ElementName”, “ElementType” and “Node_ID”. What is important here is identifying the “ElementType” rows that are “ShuntCondensator”. After these have been identified, the connection point of each capacitor is found in the “Node_ID” field. Please note that the “Node_ID” field here matches the buses that were declared when the cables and overhead lines were extracted.

3.1.6 Coordinates

Within the PSS Sincal database, each of the nodes of the network has a set of coordinates. This set of coordinates does not represent actual geolocational coordinates, but rather are a set of internally generated coordinates that are used for the purposes of visually displaying the network. These can be extracted using the “GraphicElement” table. The fields of interest are the “GraphicElement_ID”, “SymCentreX” and “SymCentreY”. For each of the elements in the network, this information is extracted and stored.

While this set of coordinates is sufficient for distribution transformers and the primary transformer, for lines an end-point needs to be declared. To do so, a script is run which sets the end point of each line to the start point of every line that is connected to. After this is run, the modified information is stored, can be used to be plotted either in a coordinate plotting software or even in Python. For the purposes of this project, this set of coordinates is used to visually represent the network, as is can be useful in identifying the network's "weak spots".

3.2 LV Networks

Given that LV network models are not readily available from AusNet Services, LV networks are modelled based on the number of customers (i.e., either provided or estimated) per distribution transformer and LV design principles, as specified by the industry [2-6]. This allows quantifying –to some extent– the impacts closer to LV customers. The steps followed to model the LV networks are described in this section.

3.2.1 Number of customers in the LV network

If the number of connected customers for each distribution substation is not provided in the item (2), the total number of customers is estimated based on the customer's After Diversity Maximum Demand (ADMD) [2, 3] using (1).

$$\boldsymbol{C^{TX}} = \left\lfloor \frac{TX^{kVA}}{C^{ADMD}} \right\rfloor \tag{1}$$

where $\boldsymbol{C^{TX}}$ is the total number of customer the secondary distribution transformer is supplying, TX^{kVA} is the transformer's rated capacity and C^{ADMD} is the assumed ADMD for a single customer (i.e., Villa, Townhouse, Apartment). The brackets, $\lfloor \ \rfloor$, denote that the number is rounded down to the nearest integer.

The ADMD value to be considered in the analyses throughout this project is 4kW (unity power factor, i.e., 4kVA).

3.2.2 Number of LV Feeders and Connected Customers

Depending on the conductor going to be used, the maximum number of customers allowed to be connected on each feeder can be calculated using the conductor's ampacity using (2). This allows defining the total number of feeders to be connected at the secondary distribution substation.

$$\boldsymbol{C^{F}} = \left\lfloor \frac{I_{AMP} \times 3 \times V_{L-N}}{C^{ADMD}} \right\rfloor \tag{2}$$

Where $\boldsymbol{C^{F}}$ the total number of feeders, I_{AMP} is the rated ampacity of the cable used and V_{L-N} is the line-to-neutral voltage.

Then, using $\boldsymbol{C^{F}}$, the number of feeders connected to the TX can be defined using (3).

$$\boldsymbol{F} = \left\lceil \frac{\boldsymbol{C^{TX}}}{\boldsymbol{C^{F}}} \right\rceil \tag{3}$$

where $\boldsymbol{F}$ is the total number of feeders connected to the TX and the brackets, $\lceil \ \rceil$, denote that the number is rounded up to the nearest integer.

The LV feeder conductor to be considered in the analyses throughout this project is a 240mm^2 with the following details:

R1	X1	B1	R0	X0	B0	I_{AMP}
0.127	0.0272	0.0001	0.342	0.089	0.0001	280

3.2.3 Length of LV Feeder and Distribution of Customers

To calculate the length of each feeder, design specifications adopted by Horizon Power [5, 6] are used. These design specifications define the maximum length of an LV feeder based on a maximum equivalent length defined by a 95mm^2 cable which is also based on the transformer's size and feeder's LV fuse size as shown in Figure 6.

Once the maximum equivalent length is defined, using (4) it is converted to the actual maximum length of the feeder going to be modelled by reversing the procedure shown in Figure 7 and defined in [5].

$$F^{l}_{max\_act} = F^{l}_{max\_eq} \times sf \qquad (4)$$

where $F^{l}_{max\_act}$ is the feeder actual maximum length in meters, $F^{l}_{max\_eq}$ is the feeder equivalent maximum length in meters and sf is the equivalent length conductor scaling factor which is based on the conductor's size.

Maximum Equivalent Lengths

The maximum "equivalent length" for a given LV fuse/transformer combination can be calculated, as shown in Table 7-2.

These lengths of 95 mm^2 LV ABC are equivalent to the actual feeder length, at the end of which, the phase-to-neutral fault current will be at least three times the fuse rating.

Table 7-2: Maximum Equivalent Lengths of 95 mm^2 LV ABC

Transformer Size (kVA)	Maximum Equivalent Length (m) (of 95 mm2 LV ABC)		
	LV Fuse Size		
	315 A	160 A	100 A
1000	310	610	980
630	310	610	980
315	305	610	975
160	290	595	965
63	240	565	940

Figure 6 Equivalent Maximum Lengths [5]

Once the feeders' actual maximum length ($F^{l}_{max\_act}$) is defined, the actual length of each feeder is calculated as a proportional to the number of houses connected to it. For example, considering that the maximum number of customers a feeder can supply is $\boldsymbol{C^F}$ then this means that for this number the length of feeder will be equal to the maximum length i.e., $F^{l}_{max\_act}$. Considering this, the length of each feeder will be calculated using (5).

$$F^{l}_{i} = F^{l}_{max\_act} \times \left(\frac{C^{F}_{i}}{\boldsymbol{C^F}}\right) \qquad (5)$$

where F^{l}_{i} is the length of feeder i.

Once the length of each feeder is calculated, houses (i.e., loads) are evenly distributed across the whole feeder. Each house is connected through a 10m service cable.

Feeder Equivalent Length Calculation

To calculate the "equivalent length" for a LV feeder constructed using several different conductors, simply divide the individual conductor length in the particular section with the appropriate "scaling factor" appropriate for the type of conductor, and add up the resulting lengths.

The appropriate "scaling factors" are shown in Table 7-1.

Table 7-1 LV Feeder Equivalent Length Scaling Factors

CONDUCTOR CLASS / TYPE		EQUIVALENT LENGTH CONDUCTOR SCALING FACTOR
UNDERGROUND CABLES	240 mm^2 ALUM	2.57
	185 mm^2 ALUM	2.08
	120 mm^2 ALUM	1.45
	25 mm^2 COPPER	0.52
LOW VOLTAGE ABC	95 mm^2 LV ABC	1.00

Example

Suppose a LV feeder was constructed as follows:

1) 80 m of 185 mm^2 AL U/G cable,

2) 300 m of 120 mm^2 AL U/G cable, and

Then, the "equivalent length" (of 95 mm" LV ABC) of the feeder is:

E.Length = (80 ÷ 2.08) + (300 ÷ 1.45) = 245 m

Figure 7 Feeder Equivalent Length Calculation [5]

The lengths of the LV feeders in the analyses throughout this project will be defined considering a 95mm^2 maximum equivalent length based on [38]. The LV service cable to be considered in the analyses throughout this project is a 16mm^2 and has the following characteristics:

R1	X1	B1	R0	X0	B0	I_{AMP}
1.149	0.08	0.0001	4.26	0.092	0.0001	100

4 Modelled HV Feeders

This chapter presents the topology and general characteristics of the four modelled HV feeders. To illustrate how these models are going to be used for distribution network analyses, this chapter also demonstrates the behaviour of the feeders using realistic demand data (no PV generation).

Given that Smart Meter data are not yet available for each of the selected feeders, demand profiles, used in a previous project "*AusNet Mini Grid Clusters*" [1] are also used in this report to assess the corresponding modelling and also demonstrate the behaviour of the feeders. While their behaviour is demonstrated using realistic demand data, it is important to highlight that these do not correspond or represent the real-life demand in of the modelled feeders; their behaviour might under or over-estimated. As such, the analyses performed and presented in this report are used only for demonstration purposes.

4.1 Residential and Non-Residential Demand Data

For the initial modelling and analyses a pool of 30-min resolution, year-long (i.e., 17,520 points), anonymized smart meter demand data, collected from 342 individual residential customers in the year of 2014 is used. These data where facilitated to the University of Melbourne for the purposes of a previous project "*AusNet Mini Grid Clusters*" [1]. Using this pool, the yearly demand profiles were broken down in daily profiles, resulting in a pool of ~30,000 daily demand profiles. For demonstration purposes sample residential demand profiles are presented in Figure 8.

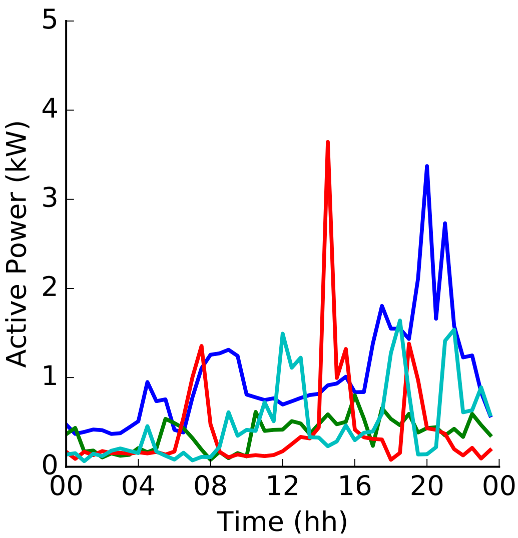


Figure 8 Sample Residential Demand Profiles

Given the fact that no information is provided in terms of the type of customers (i.e., residential or non-residential) supplied by the secondary distribution substations, the type is assumed based on the substation name (as provided in the feeder's database), size and number of customers connected to it. Considering this information, a secondary distribution substation in the analyses is considered to supply a non-residential customer if:

1. The substation name is clearly stating a non-residential customer and its corresponding customer type (e.g., hospital, prison, sewerage etc.); or
2. The substation rating is ≥100kVA and the number of customers supplied is ≤10. This is assumed to be an Office/Shop load.

In an effort to provide a more realistic modelling of non-residential customers', real-world commercial and industrial load profiles, provided by CSIRO[4] are used to create daily load profiles for the 5 most common non-residential customers found in the selected feeders (i.e., Hospital, Prison, Sewerage, Water Treatment, Office/Shop). The procedure followed to create these load profiles is described below.

1. Based on the load profiles provided by CSIRO 30-min resolution load profiles are created for a whole year (365 daily profiles) and for the 5 most common non-residential customers found in the feeders (i.e., Hospital, Prison, Sewerage, Water Treatment, Office/Shop). For demonstration purposes Figure 9, shows the yearly daily load profiles for a hospital.
2. Using all daily profiles, the average profile for the year is created. This is shown with a black thick line in Figure 9.
3. The average profile for each of the 5 common non-residential customers found in the feeders (i.e., Hospital, Prison, Sewerage, Water Treatment, Office/Shop) is then normalised. Figure 10 shows the normalised average daily load profiles for all 5 non-residential customers considered in this study.

All non-residential customers are then modelled using the corresponding normalised load profiles shown in Figure 10 multiplied with 70% of the transformer's capacity, except the case where load is assumed to be an office/shop and is multiplied with the 50% of the transformer's capacity.

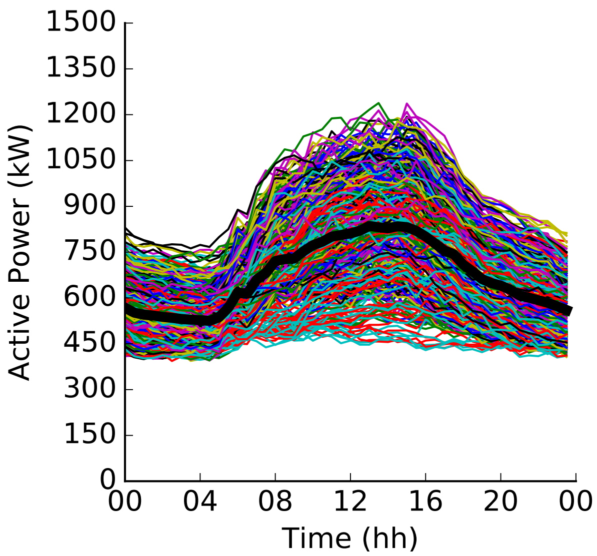


Figure 9 Daily load profiles for a hospital during 2014-2015

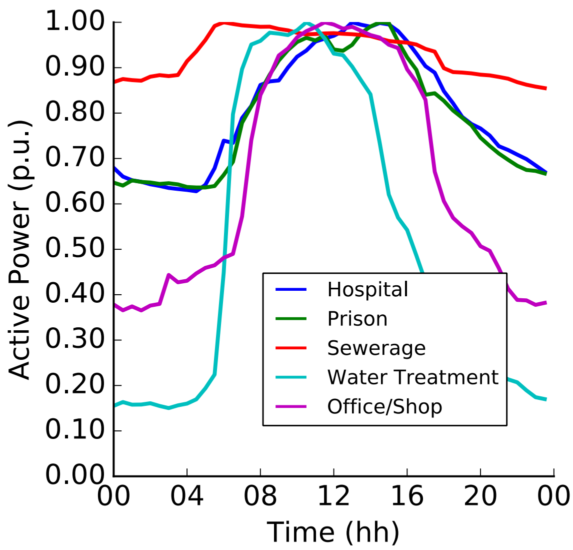


Figure 10 Normalised load profiles for non-residential customers

4.1.1 Operation of the HV Capacitors

Based on information provided by AusNet Services, the HV capacitors located in the HV feeders are switched on during peak demand conditions and switched off during low demand conditions. Considering this information, the capacitors are switched on between from 10am to 11pm, to boost the voltage during the peak demand period of non-residential customers (i.e., midday) and residential customers (i.e., night).

[4] Representative Australian Electricity Feeders with load and solar generation profiles, Australia: CSIRO. [Online]. Available: https://doi.org/10.4225/08/5631B1DF6F1A0. Accessed on April 2018.

4.2 Operation of Voltage Regulators

Based on information provided by AusNet Services, the voltage regulators located in the HV feeders are operating with a fixed voltage target. However, given that the exact voltage target is not readily available, all voltage regulators in the analyses performed in this report are assumed to monitor the voltage at the secondary side of the transformer and have a fixed voltage target of 1.0p.u.

4.3 Business-As-Usual Analysis Methodology

This section presents the methodology adopted in this report to investigate the behaviour of the modelled HV Feeders in a business-as-usual load-only scenario.

The main steps are described below.

1. For each customer, a random daily load profile is selected from the pool of daily load profiles (see section 4.1) corresponding to a specific day of the year.
2. Unbalanced, 30-min resolution, time-series, three-phase four-wire power flows over a 24-hour period are carried out with OpenDSS.
3. Simulation results are collected (voltage, current, power, etc.) for post data analysis.

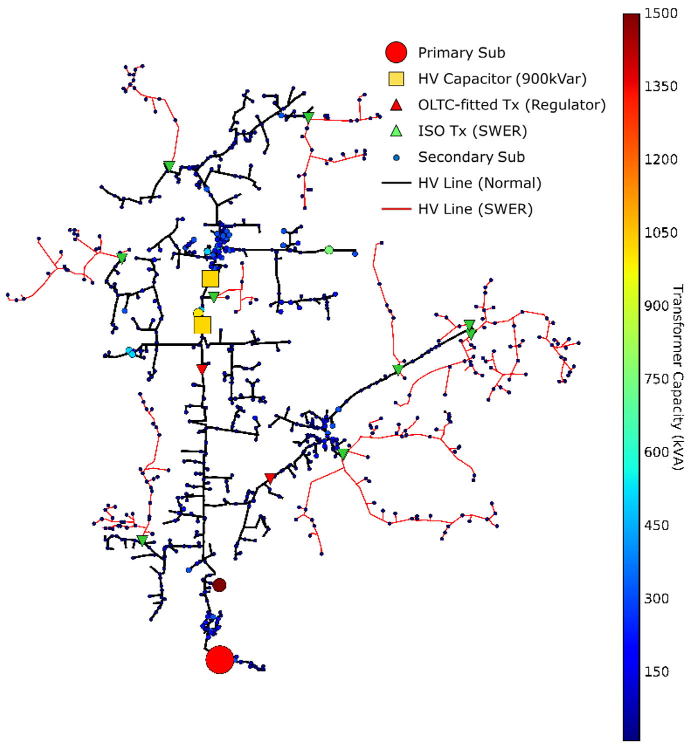
4.4 Feeder R1 (SMR8)

This section presents the topology and general characteristics of the Feeder R1. Furthermore, for demonstration purposes, this section presents a time-series power flow analysis of the HV Feeder R1 considering a peak demand day. These analyses are presented to understand the time-series behaviour of the HV feeder.

4.4.1 Topology and General Characteristics

Figure 11 shows the topology of the Feeder R1, along with its general characteristics. The feeder is assumed to be connected at a primary substation (large red circle) and supplied by a 2x33MVA, 66kV/22kV primary substation (large red circle). For simplicity, the voltage at the head of the HV feeder is considered to be constant at 22.9kV (1.04pu) which corresponds to the voltage target setting used by the OLTC at the substation.

This feeder is assumed to supply 704 residential and 61 non-residential LV networks. Each LV network and depending on its type and phase connection (i.e., single-phase, three-phase, SWER) is supplied by either a 22kV/0.433kV, a 22kV/0.25kV or a 12.7kV/0.24kV distribution transformer with off-load tap capabilities as described in section 3.1.4. Distribution transformers are shown as circles in the Figure 11 and their rated capacities can be identified using the colour map. The total number of residential customers (single-phase) in the HV feeder is assumed to be 3,608 and the total number of non-residential customers (three-phase) is assumed to be 61. The total conductor length of the integrated HV feeder amounts to 486km out of which 194km corresponds to single-phase lines. Additionally, given the large distances that exist between the primary substation and some secondary distribution substations (i.e., 52km the farthest), the HV feeder has also two in-line voltage regulators (red triangles) as well as two 900kVar capacitors (yellow square) to compensate for voltage drop issues.



# of LV Residential Substations:	704
# of LV Residential Customers:	3608
# of LV Non-Residential Substations:	61
# of LV Non-Residential Customers:	61
Distance of Farthest Transformer (km):	52
# of HV Capacitors (900kVar each):	2
# of SWER Transformers:	10
# of REGULATOR Transformers:	2
Total HV Conductors (km):	486
Total HV SWER Conductors (km)	194

Figure 11 Feeder R1 – Topology and General Characteristics

4.4.2 Business-as-Usual Analysis

Load profiles for each customer are randomly selected and allocated based on the procedure described in section 4.1.1 for the day 15 January 2014 (considered to be the highest demand day in the pool of smart meter data).

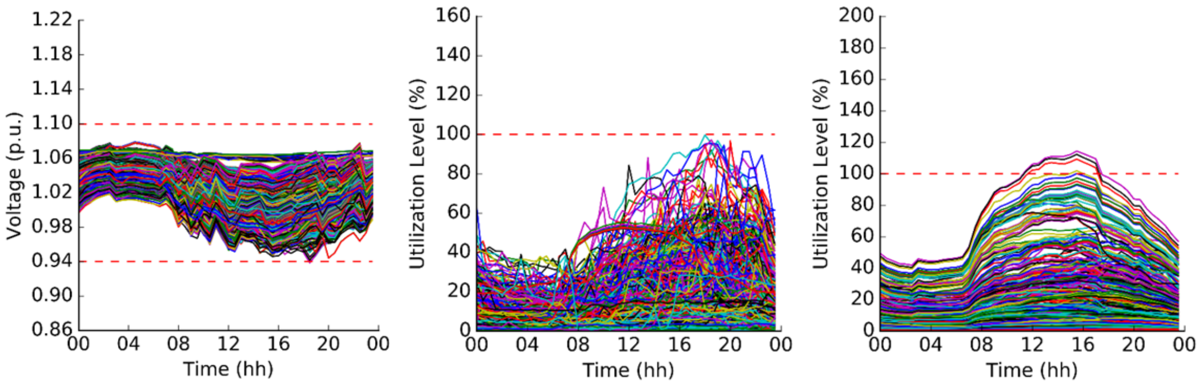
Figure 12 (a) shows the daily 30-min voltage profiles of all residential customers in R1. All profiles lie within the statutory voltage limits (i.e., 1.10 - 0.94p.u.). In this network, the level of voltage drop, compared to the U1 and U2 (see section 4.7), is significantly larger given the fact that this feeder is considerably larger (i.e., almost 16 times as large) and supplies 219 remote areas through SWER connections (i.e., single high impedance lines). To provide more understanding, it is also important to mention that the farthest distribution substation in this feeder is located 52km downstream the head of the HV feeder, whereas for the U1 and U2, the farthest substation is located approximately 10km away. In other words, R1, can be considered more prone to voltage drop and rise issues (i.e., longer lines, hence higher impedance).

Figure 12 (a) shows that voltages during low demand (morning hours) are within the range of 1.00p.u. and 1.07p.u., where at around 8am voltages start reducing due to the increase of residential and non-residential demand. At 10am, it can be observed that voltages are boosted up by the HV capacitor (switched on) to help keep all voltages within the limits. During peak demand (late evening and night hours), when customers return home from work (and demand increases further), voltages reduce down to ~0.94p.u. This specific case (peak demand) allows quantifying the maximum level of voltage drop that can be faced in this network and hence understand the available tap position footroom for each distribution transformer (i.e., ability to reduce off-load tap position without resulting to violation of the lower voltage limit). As observed for this feeder, no footroom exists.

Taking into account the utilisation level of the assets (i.e., distribution transformers and HV lines), shown in Figure 12 (b) and (c), a similar behaviour to the voltage profiles is also noticed. A higher utilisation is observed during peak demand (late evening and night hours) compared to the low demand during morning hours. Considering the transformers supplying residential customers, the peak utilisation is around ~99% and is observed during night hours. The peak utilisation of transformers supplying non-residential customers, is around 50% and is observed during midday (working hours). In terms of the HV lines, a higher utilisation is be noticed during night, reaching ~110%.

It should be highlighted that the corresponding behaviour is observed due to the fact that the demand profiles used correspond to the peak demand day, hence the utilisation level of the assets is expected to be high as well as the voltage profiles low. However, it should also be highlighted that the load profiles used, correspond to customers located in different geographical area than the studied network. Hence the use of these load profiles (residential and non-residential) might be overestimating the behaviour.

To provide more understanding of the loading conditions of this case study, the monitored kVA power at the primary substation is shown in Figure 13 and the peak utilization level of the HV lines is demonstrated in Figure 14 considering a topology heatmap.



(a) (b) (c)

Figure 12 Feeder R1 BaU: (a) Voltage profiles, (b) LV Transformers and (c) HV lines utilisation

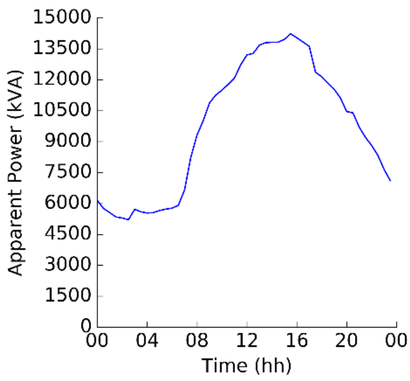


Figure 13 Feeder R1 BaU: Primary Substation Monitored Power (kVA)

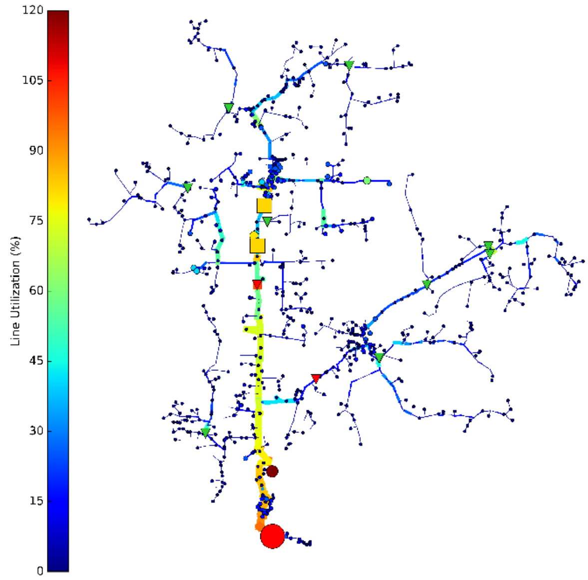


Figure 14 Feeder R1 BaU: Line Utilization Level Heatmap

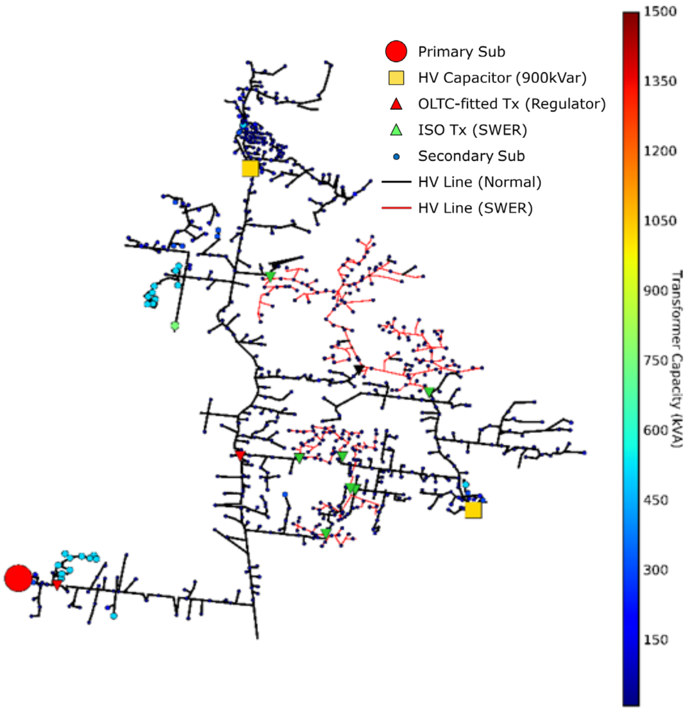
4.5 Feeder R2 (KLO14)

This section presents the topology and general characteristics of the Feeder R2. Given the significantly complex particularities associated with the corresponding Feeder (isolation transformers, SWER connections, capacitor, regulator transformer, multi-voltage level feeder paths, single-phase and three-phase transformers etc.) the modelling of the feeder, is still in progress. Hence, a BaU analysis is not performed for this feeder.

4.5.1 Topology and General Characteristics

Figure 15 shows the topology of the Feeder R2, along with its general characteristics. The feeder is assumed to be connected at a primary substation (large red circle) and supplied by a 2x33MVA, 66kV/22kV primary substation (large red circle). For simplicity, the voltage at the head of the HV feeder is considered to be constant at 22.9kV (1.04pu) which corresponds to the voltage target setting used by the OLTC at the substation.

This feeder is assumed to supply 700 residential and 24 non-residential LV networks. Each LV network and depending on its type and phase connection (i.e., single-phase, three-phase, SWER) is supplied by either a 22kV/0.433kV, a 22kV/0.25kV or a 12.7kV/0.24kV distribution transformer with off-load tap capabilities as described in section 3.1.4. Distribution transformers are shown as circles in the Figure 15 and their rated capacities can be identified using the colour map. The total number of residential customers (single-phase) in the HV feeder is assumed to be 4691 and the total number of non-residential customers (three-phase) is assumed to be 24. The total conductor length of the integrated HV feeder amounts to 275km out of which 54km corresponds to single-phase lines. Additionally, given the large distances that exist between the primary substation and some secondary distribution substations (i.e., 36km the farthest), the HV feeder has also two in-line voltage regulators (red triangles) as well as two 900kVar capacitors (yellow square) to compensate for voltage drop issues.



# of LV Residential Substations:	700
# of LV Residential Customers:	4691
# of LV Non-Residential Substations:	24
# of LV Non-Residential Customers:	24
Distance of Farthest Transformer (km):	36
# of HV Capacitors (900kVar each):	2
# of SWER Transformers:	7
# of REGULATOR Transformers:	2
Total HV Conductors (km):	275
Total HV SWER Conductors (km)	54

Figure 15 Feeder R2 – Topology and General Characteristics

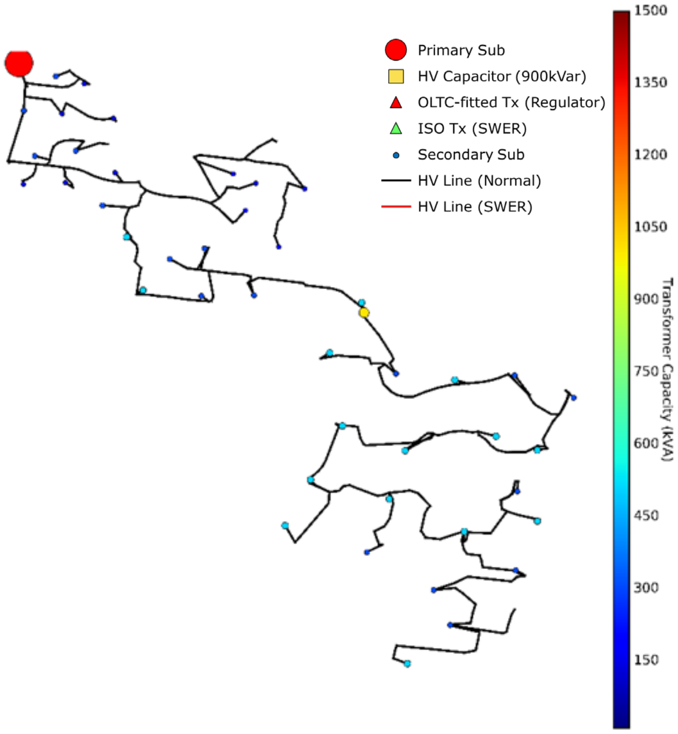
4.6 Feeder U1 (HPK11)

This section presents the topology and general characteristics of the Feeder U1. Furthermore, for demonstration purposes, this section presents a time-series power flow analysis of the HV Feeder U1 considering a peak demand day. These analyses are presented to understand the time-series behaviour of the HV feeder.

4.6.1 Topology and General Characteristics

Figure 16 shows the topology of the Feeder U1, along with its general characteristics. The feeder is assumed to be connected at a primary substation (large red circle) and supplied by a 2x33MVA, 66kV/22kV primary substation (large red circle). For simplicity, the voltage at the head of the HV feeder is considered to be constant at 22.7kV (1.03pu) which corresponds to the voltage target setting used by the OLTC at the substation.

This feeder is assumed to supply 44 residential and 1 non-residential LV networks. Each LV network and depending on its type and phase connection (i.e., single-phase, three-phase) is supplied by either a 22kV/0.433kV or a 22kV/0.25kV distribution transformer with off-load tap capabilities as described in section 3.1.4. Distribution transformers are shown as circles in the Figure 16 and their rated capacities can be identified using the colour map. The total number of residential customers (single-phase) in the HV feeder is assumed to be 5274 and the total number of non-residential customers (three-phase) is assumed to be 1. The total conductor length of the integrated HV feeder amounts to 70km (no single-phase lines). The distance between the primary substation and the farthest secondary distribution substation in this feeder is 12km, and the feeder does not have any capacitor or in-line voltage regulator.



# of LV Residential Substations:	44
# of LV Residential Customers:	5274
# of LV Non-Residential Substations:	1
# of LV Non-Residential Customers:	1
Distance of Farthest Transformer (km):	12
# of HV Capacitors (900kVar each):	0
# of SWER Transformers:	0
# of REGULATOR Transformers:	0
Total HV Conductors (km):	70
Total HV SWER Conductors (km)	0

Figure 16 Feeder U1 – Topology and General Characteristics

4.6.2 Business-as-Usual Analysis

Load profiles for each customer are randomly selected and allocated based on the procedure described in section 4.1.1 for the day 15 January 2014 (considered to be the highest demand day in the pool of smart meter data).

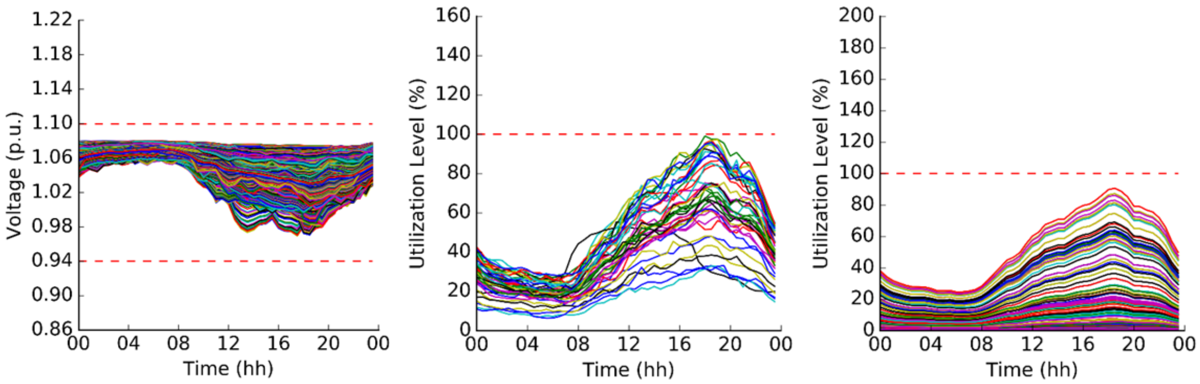
Figure 17 (a) shows the daily 30-min voltage profiles of all customers in U1. All profiles lie within the statutory voltage limits (i.e., 1.10 - 0.94p.u.). Given that the off-load tap position of all secondary distribution transformers is assumed to be at the nominal position (i.e., position 3), voltages during low demand (morning hours) are close to ~1.08p.u. However, during peak demand (late evening and night hours), when customers return home from work (and demand increases), voltages reduce to ~0.97p.u.

It is also important to highlight that this specific case (peak demand) allows quantifying the maximum level of voltage drop that can be faced in this network and hence understand the available tap position footroom for each distribution transformer (i.e., ability to reduce off-load tap position without resulting in violation of the lower voltage limit). For this HV feeder, a footroom of approximately 0.03p.u. exists which can be translated into 1 off-load taps positions (2.5% per step).

Taking into account the utilisation level of the assets (i.e., distribution transformers and HV lines), shown in Figure 17 (b) and (c), a similar behaviour to the voltage profiles is also noticed. A higher utilisation is observed during peak demand (late evening and night hours) compared to the low demand during morning hours. All transformers and lines operate within their limits and the peak transformer and line utilisations are around ~100 and ~90%, respectively.

It should be highlighted that the corresponding behaviour is observed due to the fact that the demand profiles used correspond to the peak demand day, hence the utilisation level of the assets is expected to be high as well as the voltage profiles low. However, it should also be highlighted that the load profiles used, correspond to customers located in different geographical area than the studied network. Hence the use of these load profiles (residential and non-residential) might be overestimating the behaviour.

To provide more understanding of the loading conditions of this case study, the monitored kVA power at the primary substation is shown in Figure 18 and the peak utilization level of the HV lines is demonstrated in Figure 19 considering a topology heatmap.



(a) **(b)** **(c)**

Figure 17 Feeder U1 BaU: (a) Voltage profiles, (b) LV Transformers and (c) HV lines utilisation

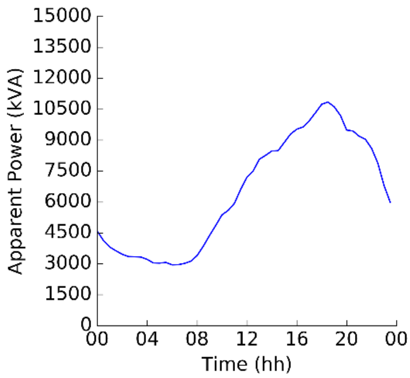


Figure 18 Feeder U1 BaU: Primary Substation Monitored Power (kVA)

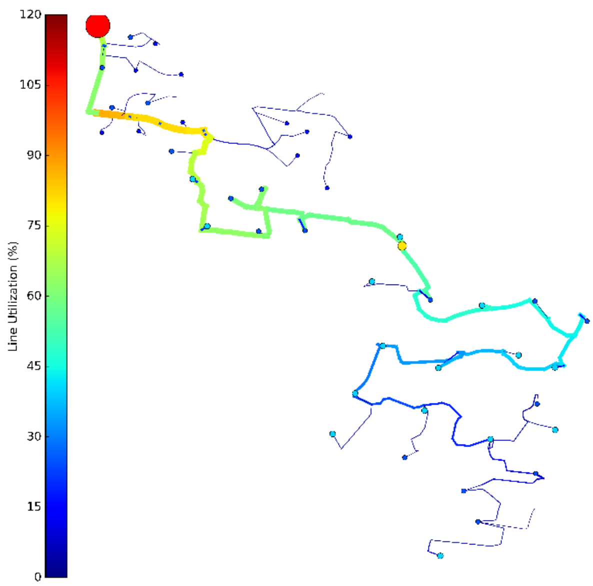


Figure 19 Feeder U1 BaU: Line Utilization Level Heatmap

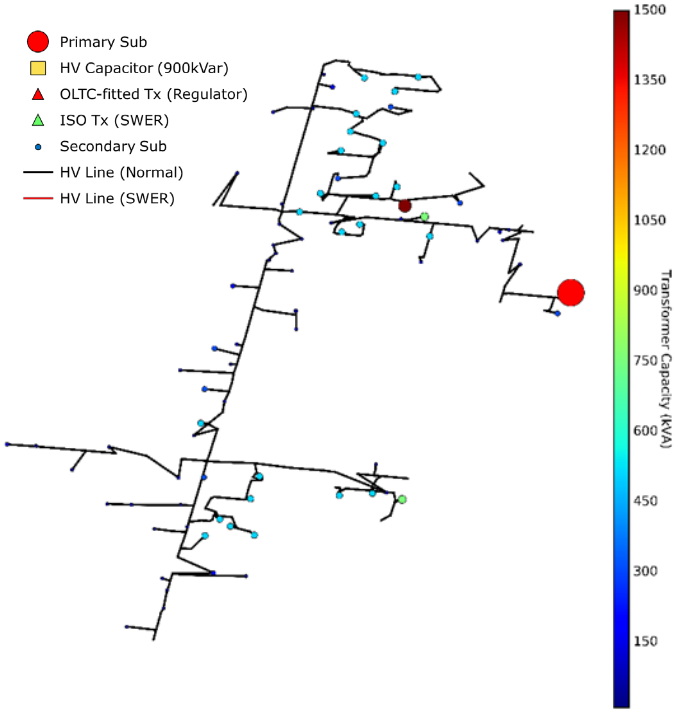
4.7 Feeder U2 (CRE21)

This section presents the topology and general characteristics of the Feeder U2. Furthermore, for demonstration purposes, this section presents a time-series power flow analysis of the HV Feeder U2 considering a peak demand day. These analyses are presented to understand the time-series behaviour of the HV feeder.

4.7.1 Topology and General Characteristics

Figure 20 shows the topology of the Feeder U2, along with its general characteristics. The feeder is assumed to be connected at a primary substation (large red circle) and supplied by a 2x33MVA, 66kV/22kV primary substation (large red circle). For simplicity, the voltage at the head of the HV feeder is considered to be constant at 22kV (1.0pu) which corresponds to the voltage target setting used by the OLTC at the substation.

This feeder is assumed to supply 79 residential LV networks. Each LV network and depending on its type and phase connection (i.e., single-phase, three-phase) is supplied by either a 22kV/0.433kV or a 22kV/0.25kV distribution transformer with off-load tap capabilities as described in section 3.1.4. Distribution transformers are shown as circles in the Figure 20 and their rated capacities can be identified using the colour map. The total number of residential customers (single-phase) in the HV feeder is assumed to be 4626. The total conductor length of the integrated HV feeder amounts to 30km (no single-phase lines). The distance between the primary substation and the farthest secondary distribution substation in this feeder is 9km, and the feeder does not have any capacitor or in-line voltage regulator.



# of LV Residential Substations:	79
# of LV Residential Customers:	4626
# of LV Non-Residential Substations:	0
# of LV Non-Residential Customers:	0
Distance of Farthest Transformer (km):	9
# of HV Capacitors (900kVar each):	0
# of SWER Transformers:	0
# of REGULATOR Transformers:	0
Total HV Conductors (km):	30
Total HV SWER Conductors (km)	0

Figure 20 Feeder U2 – Topology and General Characteristics

4.7.2 Business-as-Usual Analysis

Load profiles for each customer are randomly selected and allocated based on the procedure described in section 4.1.1 for the day 15 January 2014 (considered to be the highest demand day in the pool of smart meter data).

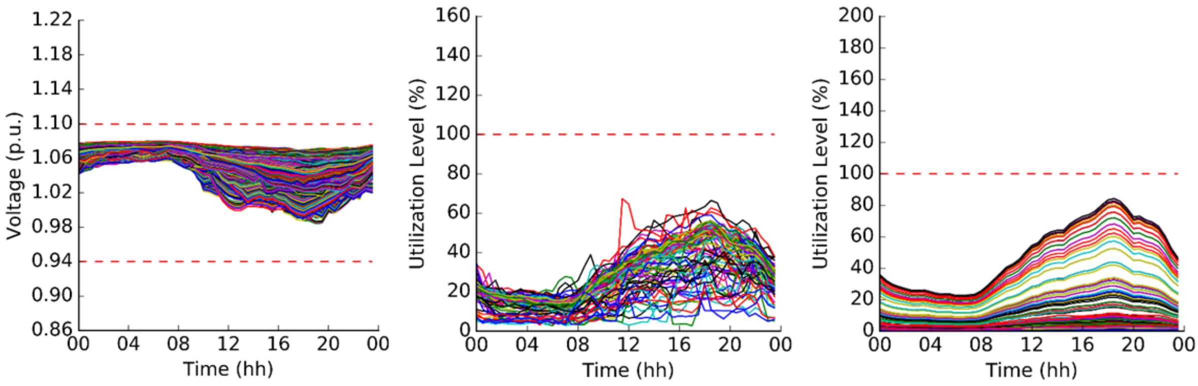
Figure 21 (a) shows the daily 30-min voltage profiles of all customers in U2. All profiles lie within the statutory voltage limits (i.e., 1.10 - 0.94p.u.). Given that the off-load tap position of all secondary distribution transformers is assumed to be at the nominal position (i.e., position 3), voltages during low demand (morning hours) are close to ~1.08p.u. However, during peak demand (late evening and night hours), when customers return home from work (and demand increases), voltages reduce to ~0.99p.u.

It is also important to highlight that this specific case (peak demand) allows quantifying the maximum level of voltage drop that can be faced in this network and hence understand the available tap position footroom for each distribution transformer (i.e., ability to reduce off-load tap position without resulting in violation of the lower voltage limit). For this HV feeder, a footroom of approximately 0.05p.u. exists which can be translated into 2 off-load taps positions (2.5% per step).

Taking into account the utilisation level of the assets (i.e., distribution transformers and HV lines), shown in Figure 21 (b) and (c), a similar behaviour to the voltage profiles is also noticed. A higher utilisation is observed during peak demand (late evening and night hours) compared to the low demand during morning hours. All transformers and lines operate within their limits and the peak transformer and line utilisations are around ~67 and ~80%, respectively.

It should be highlighted that the corresponding behaviour is observed due to the fact that the demand profiles used correspond to the peak demand day, hence the utilisation level of the assets is expected to be high as well as the voltage profiles low. However, it should also be highlighted that the load profiles used, correspond to customers located in different geographical area than the studied network. Hence the use of these load profiles (residential and non-residential) might be overestimating the behaviour.

To provide more understanding of the loading conditions of this case study, the monitored kVA power at the primary substation is shown in Figure 22 and the peak utilization level of the HV lines is demonstrated in Figure 23 considering a topology heatmap.



(a) (b) (c)

Figure 21 Feeder U1 BaU: (a) Voltage profiles, (b) LV Transformers and (c) HV lines utilisation

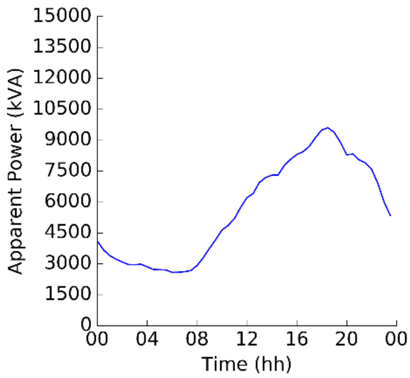


Figure 22 Feeder U2 BaU: Primary Substation Monitored Power (kVA)

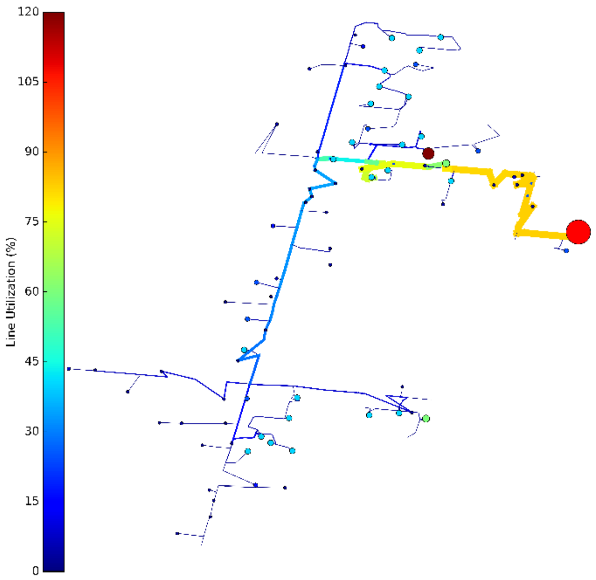


Figure 23 Feeder U2 BaU: Line Utilization Level Heatmap

5 Conclusions

This report corresponds to Deliverable 1 "HV-LV modelling of selected HV feeders" part of the project Advanced Planning of PV-Rich Distribution Networks funded by the Australian Renewable Energy Agency (ARENA) and led by the University of Melbourne in collaboration with AusNet Services.

This document first presented the process adopted by The University of Melbourne in collaboration with AusNet Services to select the HV feeders that will be used for the project purposes. Chapter 2 presented the process adopted by The University of Melbourne in collaboration with AusNet Services to select the HV feeders that will be used for the project purposes. Chapter 3 detailed the procedure adopted to extract and process all feeder data to develop the corresponding digital feeder models considering different aspects and assumptions. Chapter 4 presented the topology and general characteristics of all fully modelled feeders along with a case study that considers a peak demand day time-series power flow analysis using the software OpenDSS. The corresponding analyses, which consider realistic demand data, help understanding the level of the detailed modelling performed while demonstrating the expected behaviour of each of the feeders.

The following key points summarising this report are listed below.

HV Feeder Selection

The University of Melbourne in collaboration with the expert views and knowledge of AusNet Services selected the HV Feeders that will be modelled and used for the project purposes.

- **Four (4) significantly different HV (22kV) Feeders selected** from the total number of feeders operated by Ausnet services. These correspond to two (2) Rural and two (2) Urban feeders and listed below:
  - **R1.** A long feeder with relatively high number of customers, medium maximum loading and high PV penetration level.
  - **R2.** A short feeder with relatively high number of customers, high maximum loading and high PV penetration level.
  - **U1.** A long feeder with medium number of customers, medium maximum loading and high PV penetration level.
  - **U2.** A medium length feeder with high number of customers, high maximum loading and high PV penetration level.
- **The selection considered a number of different feeder characteristics** (rural, urban, length, number of customers, number of PV system installations etc.) to capture different feeder types.
- **The selection considered the trade-off between the quality and availability of data** (network, smart meter, GIS, etc.), existing PV system installations (critical for validation of the analytical techniques), as well as the corresponding data extraction complexity.
- The University of Melbourne considers the selected four HV feeders being an adequate compromise as they feature significant differences between them.

HV Feeder Modelling

The University of Melbourne using the data provided by Ausnet Services, developed the four (4) integrated high-voltage (HV, 22kV) and low-voltage (LV, 400V) three-phase network models of the selected feeders.

- **The data provided for the selected HV feeders were successfully processed.** These included topologies, impedances, phase connections, tap ranges, elements connected (i.e., SWER transformers, capacitors, voltage regulators) and number of customers for several distribution transformers. However, assumptions had to be taken for no-load and on-load losses for all distribution transformers as well as tap positions for some of them. The resulting models are believed to be highly accurate and representative of the HV feeder.

- **LV Networks**. Given the fact that LV network models are not readily available from AusNet Services, a methodology to realistically model LV networks is proposed based on Australian electrical distribution substation standards and design manuals. This will allow quantifying –to some extent– the impacts closer to LV customers.

Modelled HV Feeders

The topology and general characteristics of the four modelled HV feeders were presented along with a time-series power flow analysis using OpenDSS. This initial analysis helps understanding the level of the detailed modelling performed while demonstrating the expected behaviour of each of the feeders.

- **General characteristics of modelled HV Feeders.**
  - Rural Feeders
    1. Total conductor length of R1 and R2 amounts to 470 and 280km, respectively.
    2. Both R1 and R2 supply 700+ residential LV substations (4500+ households) out of which 219 and 161 are made through SWER connections, respectively.
    3. R1 and R2 supply 61 and 24 non-residential LV substations.
    4. R1 and R2 have 10 and 7 SWER transformers, respectively.
    5. Both R1 and R2 have 2 900kVar HV capacitors.
    6. Both R1 and R2 have 2 in-line voltage regulators.
    7. R1 and R2 are approximately 16 times larger than the two Urban feeders.
  - Urban Feeders
    1. Total conductor length of U1 and U2 amounts to 12 and 30km, respectively.
    2. U1 and U2 supply 44 and 79 residential LV substations (3000+ households).
    3. U1 supplies 1 non-residential LV substation.
    4. U1 and U2 have no SWER transformers.
    5. U1 and U2 have no HV capacitors.
    6. U1 and U2 have no in-line voltage regulators.
- **Demand Profiles for Business-as-Usual Analyses.** Smart Meter data are not yet available for each of the selected feeders, demand profiles, hence demand profiles used in a previous project "*AusNet Mini Grid Clusters*" were considered in this report to demonstrate the behaviour of the feeders.
  - While their behaviour is demonstrated using realistic demand data, it is important to highlight that these do not correspond or represent the real-life demand in of the modelled feeders; their behaviour might under or over-estimated. As such, the analyses performed and presented in this report are used only for demonstration purposes.
- **Business-as-Usual Analyses.** The operation of the HV feeders was demonstrated through time-series analysis, considering a peak demand day. All values (voltages and currents) were found to be within the acceptable operating limits except some line segments in R1 and R2 which experienced congestion issues. This is believed due to the usage of load demand profiles that do not correspond to the corresponding geographical area; hence overestimating the loading conditions.
  - The level of voltage drops in R1 and R2, compared to the U1 and U2, is significantly larger given that Rural feeders are considerably larger and supply remote areas through SWER connections.
  - In all feeders, a higher utilisation of assets was observed during peak demand (late evening and night hours) compared to the low demand during morning hours.

6 Next Steps

The next steps to be carried out by The University of Melbourne for the "Advanced Planning of PV-Rich Distribution Networks" project include:

Task 2 Innovative Analytical Techniques

This task will define and validate different analytical techniques to assess PV hosting capacity for a given HV feeder. To achieve this, first stochastic HV-LV network studies will be carried out on selected HV feeders to capture impacts on network performance and customers resulting from different solar PV penetrations. More importantly, these studies will allow investigate and extract the correlations between customer data and PV penetrations to define those analytical techniques that can help assess the PV hosting capacity. The resulting analytical techniques will be validated using real smart meter data from the investigated HV feeders.

Deliverable 2: Innovative Analytical Techniques (Delivery Date: 10th October 2019)

Synopsis: A technical report presenting the developed analytical techniques and corresponding algorithms to estimate PV hosting capacity in Distribution networks.

Deliverable 3: Webinar presenting the key findings from Task 2 (Delivery Date: End October 2019)

7 References

[1] K. Petrou and L. F. Ochoa, *AusNet Mini Grid Clusters - Deliverable 1 "HV and LV Network Modelling"*, Melbourne: University of Melbourne and AusNet Services, 2017.

[2] A. Jehad, *Electrical Design Standard for Underground Distribution Cable Networks, Technical Standard - TS-100*, Australia: SA Power Networks, 2012. [Online]. Available: https://goo.gl/gqiKuY. Accessed on: January 2018.

[3] A. Seneviratne and J. Murphy, *Electrical Design Information for Distribution Networks: After Diversity Maximum Demand*, Australia: Horizon Power, 2013. [Online]. Available: https://goo.gl/HLWjwT. Accessed on: January 2018.

[4] J. Bridge, *Distribution Annual Planning Report 2017 -2021*: AusNet Services, 2017. [Online]. Available: https://goo.gl/RXtnEu. Accessed on: January 2018.

[5] A. Seneviratne and J. Murphy, *Distribution Design Manual – Underground Cable Distribution*: Horizon Power, 2014. [Online]. Available: https://goo.gl/KQB9go. Accessed on: January 2018.

[6] *Distribution Substation Manual (DSM) Section 1 - Customer Supply Arrangements*, Australia: Western Power, 2009. [Online]. Available: https://goo.gl/7qrdcn. Accessed on: January 2018.

Appendix A

The Breadth First Search (BFSA)[5,6] is a graph search algorithm that begins at the root node and explores all the neighbouring nodes. Then, for each of the latter nodes, it explores their (unexplored) neighbouring nodes, and so on, until it finds every node connected. The basic structure of the algorithm is as follows:

1. Enqueue the root node.
2. Dequeue a node and examine it.
3. If the element sought is found in this node, quit the search and return a result. Otherwise, enqueue any successors (the direct child nodes) that have not yet been discovered.
4. If the queue is empty, every node on the graph has been examined. Otherwise, repeat from Step 2.

An example of the application of this algorithm implemented in Python and applied using the feeder model information (converted from .mdb to .csv file) is shown in Figure 24.

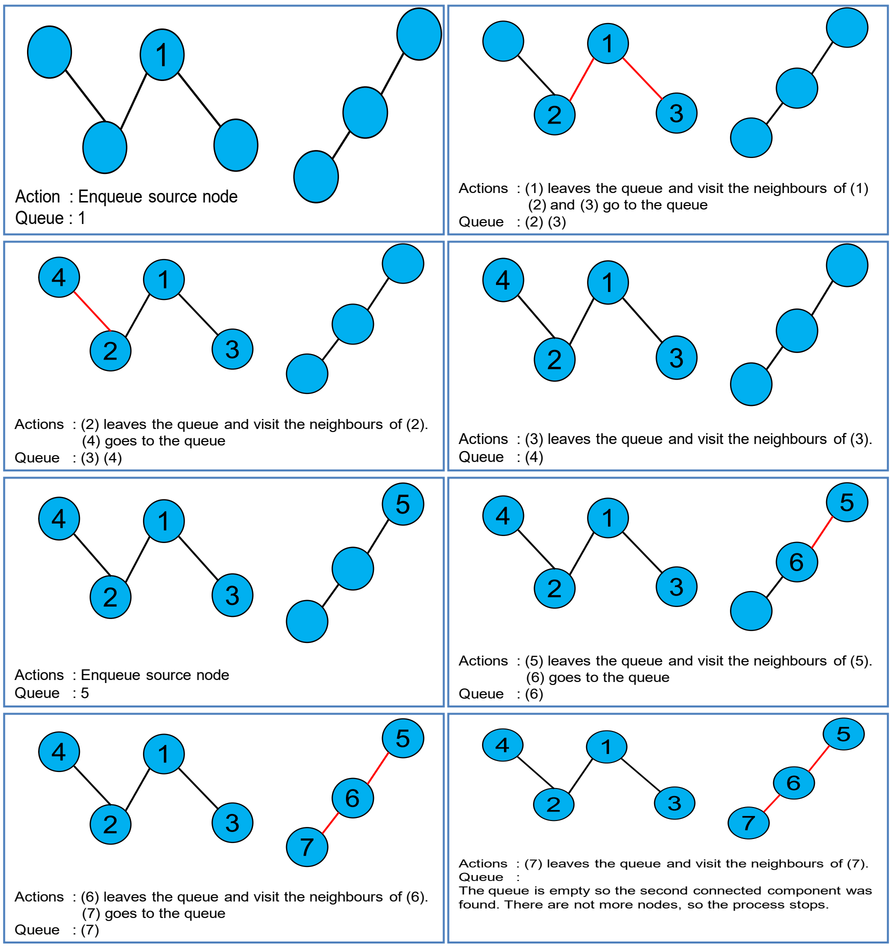


Figure 24: Example of Breadth First Search Implementation

[5] A. N. Espinosa, "Low Carbon Technologies in Low Voltage Distribution Networks: Probabilistic Assessment of Impacts and Solutions," Doctor of Philosophy, Electrical Energy and Power Systems Group, The University of Manchester, Manchester, 2015.

[6] G. T. Heineman, Algorithms In A Nutshell. Shroff Publishers & Distributors, 2008.