Jemena DER Hosting Capacity Project

Interim Knowledge Sharing Report

August 2020

Table of Contents

Acknowledgements 4
Executive Summary 5
1. Overview 7
  1.1 ARENA DER Hosting Capacity Project 7
  1.2 Project Partners 7
  1.3 Project scope 7
  1.4 Project Stages 8
  1.5 This Report 9
2. Network Modelling 11
  2.1 Low-voltage Distribution Network (LVDN) 11
  2.2 Impedance Calculation and Data Processing 11
  2.3 Power Flow Calculations in LVDN 13
  2.4 Placement and Control of PSDs in LVDN 16
  2.5 Conclusions 20
3. Appliance Testing 21
  3.1 Testing Objectives 21
  3.2 Introduction of Phase Switching Device 21
  3.3 Testing Implementation Process 22
  3.4 Challenges during Testing Implementation 24
  3.5 Testing Results 24
  3.6 Conclusions and Recommendations for Control Logic Design 26
4. Design, Installation & Commissioning of Phase Shifting Devices and Power Compensation Device 27
  4.1 Power Compensation Device (PCD) 27
  4.2 Phase Switching Device (PSD) & Central Controller 28
  4.3 Project Learnings so far 28
    4.3.1 New technologies and vendor 28
    4.3.2 Design & Installation 28
    4.3.3 Wood vs Concrete Poles 28
    4.3.4 Antennas 28
    4.3.5 Operations 29
  4.4 Trial Installations 29
  4.5 Commissioning 29
  4.6 Device Communications & Cybersecurity 31

4.7 Customer Experience 32
5. Design, Installation & Commissioning of Jemena's Battery Energy Storage System 33
5.1 Purpose of the Battery Energy Storage System (BESS) 33
5.2 BESS Sizing 33
5.3 BESS Location 33
5.4 BESS Design 34
5.5 BESS Anciliary Equipment 35
5.6 BESS Control Logics 36
5.7 Status of BESS 37
6. Approach to Implementation of Innovation Projects 38
6.1 New Network Technologies 38
6.2 Approach to Risk Assessment 38
6.3 Approach to Operational Procedures 38
6.4 Approach to Software Development 39
7. Conclusions 40
Appendices (Powerpoint Slides) 41

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Executive Summary

In Australia many roof-top residential photovoltaic (PV) generators have been connected to the Low Voltage (LV) grid, making Australia the top ranking country for residential solar installation on a per capita basis[1]. This trend has not slowed down, with the expectation that more PV systems will be connected in future.

Residential roof-top PV generators, a form of renewable distributed energy resource (DER), has made a significant contribution to Australia meeting its greenhouse gas abatement commitment.

As distribution networks are not traditionally designed to host DERs, the two-way flow of electricity created has impact on the ability of the distribution networks to deliver quality electricity supply to its customers.

The amount of DER that can be connected to a distribution network while the network remains within its technical limits is called its 'hosting capacity'.

Jemena and its project partners believe that hosting capacity can be increased by retrofitting novel, grid-based, dynamic and deployable power electronics technologies and control systems to the existing distribution networks, and set to demonstrate the technologies in this Jemena DER hosting capacity project.

The Jemena DER hosting capacity project started in January 2019. By the time of this report, network modelling and bench testing have been completed by University of New South Wales (UNSW), control schemes and hardware designs completed, equipment manufactured and delivered by the equipment supplier, and Jemena and AusNet Services have installed and commissioned all three technologies in their distribution networks. Experiences gained from these activities are documented in this interim knowledge sharing report.

Key findings of the Jemena DER hosting capacity project since project commencement (January 2019) include:

- Network modelling
    - Necessary data for network analysis has been generated based on physical parameters of the network and historical data.
    - Power flow algorithm for unbalanced three-phase LV Distribution Network (LVDN) has been developed and tested on both Jemena and AusNet networks.
    - An efficient method to place Phase Dhifting Devices (PSDs) in LVDN has been developed to provide optimal locations to install PSDs and static strategies to control PSDs under high PV generation levels.
- Appliance testing
    - The effect of phase shifting operation on commonly used electrical appliances has been quantified in the laboratory.
    - Most common household appliances work normally during the phase switching process.
    - Negative impacts of phase switching process on some appliance operation have been observed during negative sequence switching actions and the reasons can be explained with the help of transient waveforms. But no appliance damage is found.
    - Appliance testing results have been incorporated into the control logics of the PSD.

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[1] Solar Trend-Report for Solar Citizens, UNSW/Australian PV Institute, 2018

- Design, installation and commissioning of the PSD and Power Compensation Devices (PCD) have been successfully completed on both the Jemena and AusNet Services distribution networks
    - The PCD and PSDs are commercially available and have been deployed successfully on low voltage networks overseas. However, since both the vendor and the equipment are relatively new to the Australian market, this presented the project team with some significant challenges to overcome.
    - One such challenge was the team had to work closely with the vendor to design a simple control algorithm that built on existing equipment capabilities, with a view to grow complexity only after core functionality had been tested in the field.
- Design, installation and commissioning of the Battery Energy Storage System (BESS) has been successfully completed on the Jemena distribution network
    - The 100kW/200kWh BESS has been made as compact as possible, with a footprint of 2.5m by 3m.
    - With the support of the local council, Jemena secured the lease of a road reserve for the placement of the BESS.
    - While not considered mandatory, the BESS is fitted with a sophisticated fire detection and suppression system provided by an Australian vendor.
- Innovation approach
    - The project is implementing three new technologies that have not been used on either electricity network for the purpose of increasing DER hosting capacity. A summary is given for the the approach that Jemena and AusNet Services has each taken to implement the project, and learning where there are differences in approach.

The remaining project activities include the conduct of various use cases where the technologies are used, independently and in combination, to improve the DER hosting capacity of the distribution networks they are connected to. Data from these use cases will be collected, collated, analysed and evaluated. Findings from these project activities will be documented in the final knowledge sharing report in early 2021.

1. Overview

1.1 ARENA DER Hosting Capacity Project

The project, funded by ARENA's "Demonstration projects improving network hosting capacity of Distributed Energy Resources (**DER**)" Funding Announcement under the Advancing Renewables Program and is titled "Demonstration of three dynamic grid-side technologies for increasing distribution network DER hosting capacity". It aims to implement three novel, grid-based, dynamic and deployable power electronics technologies and intelligent control systems to demonstrate their ability to increase network DER hosting capacity, while also improving customer power supply quality and reduce the impacts caused by high penetration of roof-top PV systems. The project is known internally as the "Solar Friendly Neighbourhoods project", reflecting the project partners' aspiration to create an electricity network environment that allows solar systems to flourish.

1.2 Project Partners

Jemena is the lead partner for the project, ablely supported by project partners including AusNet Services, the Energy System Group of the UNSW, and State Grid International Development Ltd. The Hume City Council supports the project by sharing their local knowledge and leasing the land on which the Battery Energy Storage System (BESS) is installed.

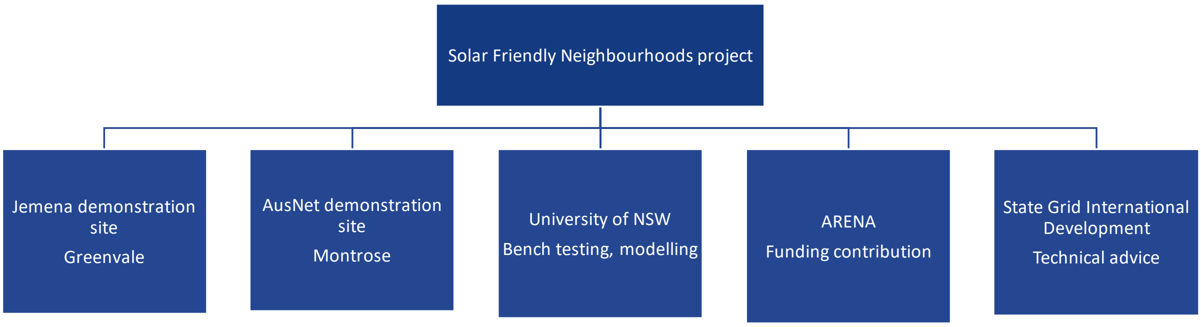


Figure 1.1. Project partners

1.3 Project scope

The three innovative technologies to be demonstrated in the Project include:

a) Dynamic phase switching of customer loads on low voltage feeders to help mitigate the localised over-voltage challenge caused by increasing DER;
b) Dynamic power compensation to adjust the output voltage and mitigate the load unbalance challenge at the source distribution transformer; and
c) Battery energy storage with Virtual Synchronous Generator (VSG) capability, to mitigate potential power quality and network stability challenges caused by very high penetration of DER. This includes potentially mitigating steady-state events of asset power overloads and

high reverse power flow affecting upstream voltage regulation, and transient events such as cloud passage impacts on PV output and upstream grid disturbance events.

Two LV network sites with different characteristics have been selected to demonstrate the technologies, one on Jemena's network and one on the AusNet Services network. Dynamic phase switching and dynamic power compensation will be installed in both sites while battery energy storage will be implemented at Jemena's site only.

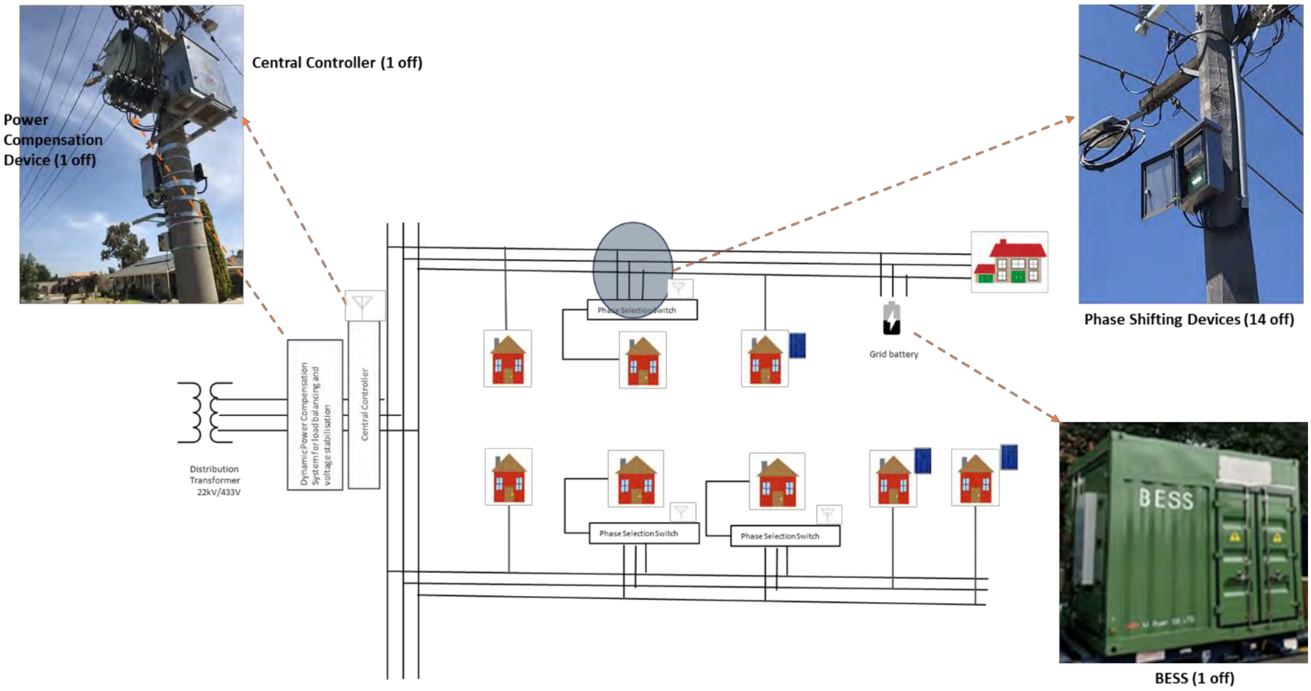


Figure 1.2. Illustration of the three technologies to be implemented in the LV sites (note BESS is only installed in the Jemena site)

1.4 Project Stages

The project is divided into four key stages as follows:

- **Stage 1 – Program Design & Procurement (circa January 2019 to May 2019)**

During this stage the project partners developed the detailed design for the project, including conducting the modelling and simulation to input into the design. As the design progressed, the key materials and services requirements were identified and detailed specifications were developed. Requests for tender were issued, evaluated and orders for equipment placed. The key items of equipment procured and installed for each technology include:

a) Dynamic phase switching technology: 28 customer phase switching devices (PSD), comprising 14 customer connection points at each LV site;
b) Dynamic power compensation technology: two (2) three-phase dynamic power compensation devices (PCD, one at each LV site);
c) Battery energy storage technology (with VSG capability) technology: One BESS with VSG capability (to be installed at the Jemena's LV site only), with a rating of 100kW/200kWh;
d) Two (2) central controllers (CC, one at each LV site).

Apart from procurement of equipment, two key activities carried out during this period include:

a) Established representative network models for the two trial networks. Developed load flow and optimisation algorithms to determine the optimal locations of the technologies and control parameters;
b) Bench test the effect of phase shifting operation on common household appliances, using a sample switch from the supplier. Learning from the bench testing is included in the formulation of the phase shifting control logic.

- **Stage 2 – Detailed design, off-site equipment testings and delivery (circa June 2019 to November 2019)**

Detailed design of the equipment panels and control logics was undertaken during this period. As the equipment was purchased from an overseas supplier, testing to relevant Australian and international standards, where appropriate, were carried out.

Upon completion of equipment manufacture and assembly, the supplier conducted Factory Acceptance Testing (FAT) at its factory to demonstrate that the equipment met the purchase specifications. FAT was witnessed by representatives from Jemena and AusNet Services. After the successful completion of FAT, the supplier shipped the equipment to Australia.

Jemena and AusNet Services carried out designs for the construction and installation of the equipment at their respective sites.

- **Stage 3 – Installation, commissioning and trial commencement (circa December 2019 to February 2020)**

This stage involved the installation, commissioning, and commencing operation of the equipment at the selected LV sites on the Jemena and AusNet Services networks.

- **Stage 4 – Trial operation, evaluation and final report (circa March 2020 to December 2020)**

After the installation, the project partners will monitor and refine the operation and performance of the equipment. Use cases will be developed and conducted to undertake the analysis in different conditions, and data collected. After an extensive period of performance monitoring, the project partners will collate the data and perform the analysis to underpin the evaluation of the trial. Specifically, the trial outcomes will provide findings including, but not limited to:

a) Quantifying the improvement in network DER hosting capacity.
b) Interpretation and modelling of how transferrable the results are likely to be for other network types.
c) Undertaking a cost-benefit analysis of the technologies, giving particular consideration to the network regulated expenditure process, to help inform the potential for subsequent deployment of the technologies.

1.5 This Report

This interim knowledge sharing report is written at the completion of stage 3, and covers the activities and learning in the first three stages of the project. It is organised in chronological order, beginning with the two key activities carried out in stage 1 by UNSW, that of network modelling and bench testing of dynamic phase switching technology on common household appliances. The chapters are then followed by the design, installation and commissioning experiences of the phase switching, power compensation and the battery energy storage technologies. Finally, as significant effort and cost are generally required to implement innovation projects such as this, the project partners feel it worthwhile to share our approaches and experiences in bringing this project to life.

A final knowledge sharing report will be issued at the completion of the project, with primary focus on stage 4 of the project.

2. Network Modelling

This chapter presents the network modelling of the project including the brief network introduction in "Low-voltage distribution network (LVDN)", parameters calculation in "Impedance calculation and data processing", modelling validation in "Power flow calculation in LVDN", "Placement and control of phase-switching devices (PSDs) in LVDN" and Conclusions.

2.1 Low-voltage Distribution Network (LVDN)

As the project is to investigate the benefits brought by the introduction of three technologies, i.e., PSD, PCD and BESS, to the low-voltage distribution network (LVDN), characteristics of LVDN and its differences from electric networks of other voltage levels should be identified.

A picture of the LVDN (only with several poles and the overhead lines) is presented in Fig. 2.1. A typical LVDN is a radial and asymmetric structure, and provides electricity directly to residential customers that are usually powered by single-phase (R, W or B) or three phases (RWB) at the voltage level of 230/400 V. Particularly, the LVDN is connected with its upstream medium-voltage distribution network (MVDN) via the distribution transformer.

Different from the transmission network or the MVDN, most parameters in the LVDN are not available and strong unbalance can be observed due to asymmetric PV or load distributions among three phases.

Figure 2.1. A picture of LVDN (only with several poles and the overhead lines)

2.2 Impedance Calculation and Data Processing

The first step in network modelling in LVDN is making sure all parameters are assessable and accurate. However, as network impedances, which are the most important parameter in network modelling and optimisation in later studies, are usually not available for LVDN as discussed previously, they are firstly calculated based on Carson's Equation with site physical parameters as illustrated by Fig. 2.2.

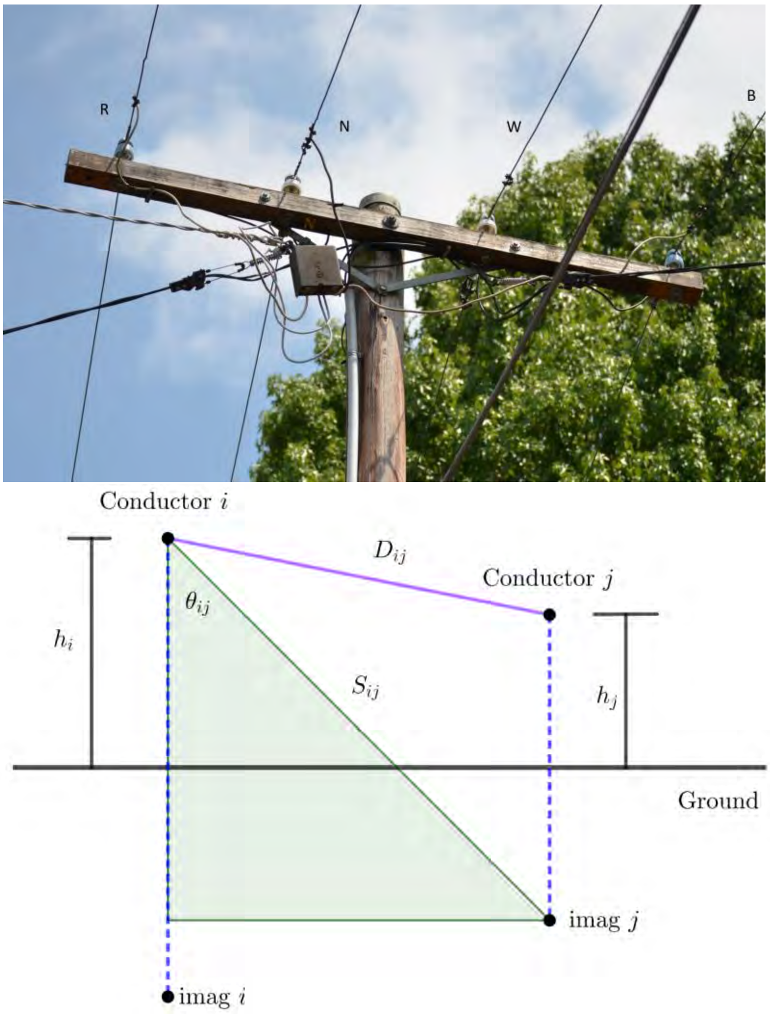


Figure 2.2. Site physical parameters and the geometrical illustration of three-phase four-wire conductors in the LVDN

Specifically, the self-impedance of any conductor and the mutual impedance of any two conductors based on the physical parameters are calculated first, and the commonly used 3*3 matrix is then obtained with Kron's Reduction technique. Moreover, topology information, and historical data, including voltage magnitudes and active/reactive powers of each residential customer, in the year 2018 from the two trial networks are processed to provide the basic data for modelling purposes in following sections.

2.3 Power Flow Calculations in LVDN

With calculated network impedances and other known parameters, power flow equations based on Kirchhoff's Current Law (KCL) and Ohm's Law (OL) can be formulated.

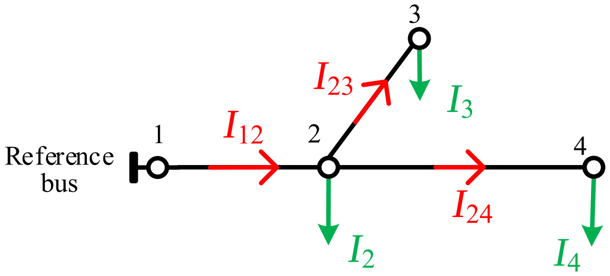


Figure 2.3. Illustration example of power flow calculations in LVDN

Taking the illustration example in Fig. 2.3 as an example, the power flow equations would be

$$\begin{bmatrix} I_{12} \\ I_{23} \\ I_{24} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix}, \begin{bmatrix} V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 \\ Z_{12} & Z_{23} & 0 \\ Z_{12} & 0 & Z_{24} \end{bmatrix} \begin{bmatrix} I_{12} \\ I_{23} \\ I_{24} \end{bmatrix}$$

where I_{ij}, I_k are the currents running through line ij and the demand current at bus k, respectively; V_k is the voltage at bus k, and Z_{ij} is the impedance of line ij.

The input information of power flow calculation would be the active/reactive powers at all nodes and the voltage at the reference bus. Output information would be the nodal voltages of all buses.

With the above equations, the sensitivity of demand current, i.e., I_k, at each bus to its nodal voltage, i.e., V_k, can be constructed. As demand current at each pole depends on both its active/reactive powers and terminal voltage, a widely used iteration-based algorithm is used in this project, where the terminal voltages of all nodes are successively updated until the algorithm is converged.

The algorithm is tested on two trial network and the results are compared with voltage measurements from historical data. For the trial network from AusNet, there are 27 nodes and 71 residential customers and the topology of the network is presented in Fig. 2.4. The voltages of three phases at node 15 from power flow calculation and historical measurements are also presented in Fig. 2.4.

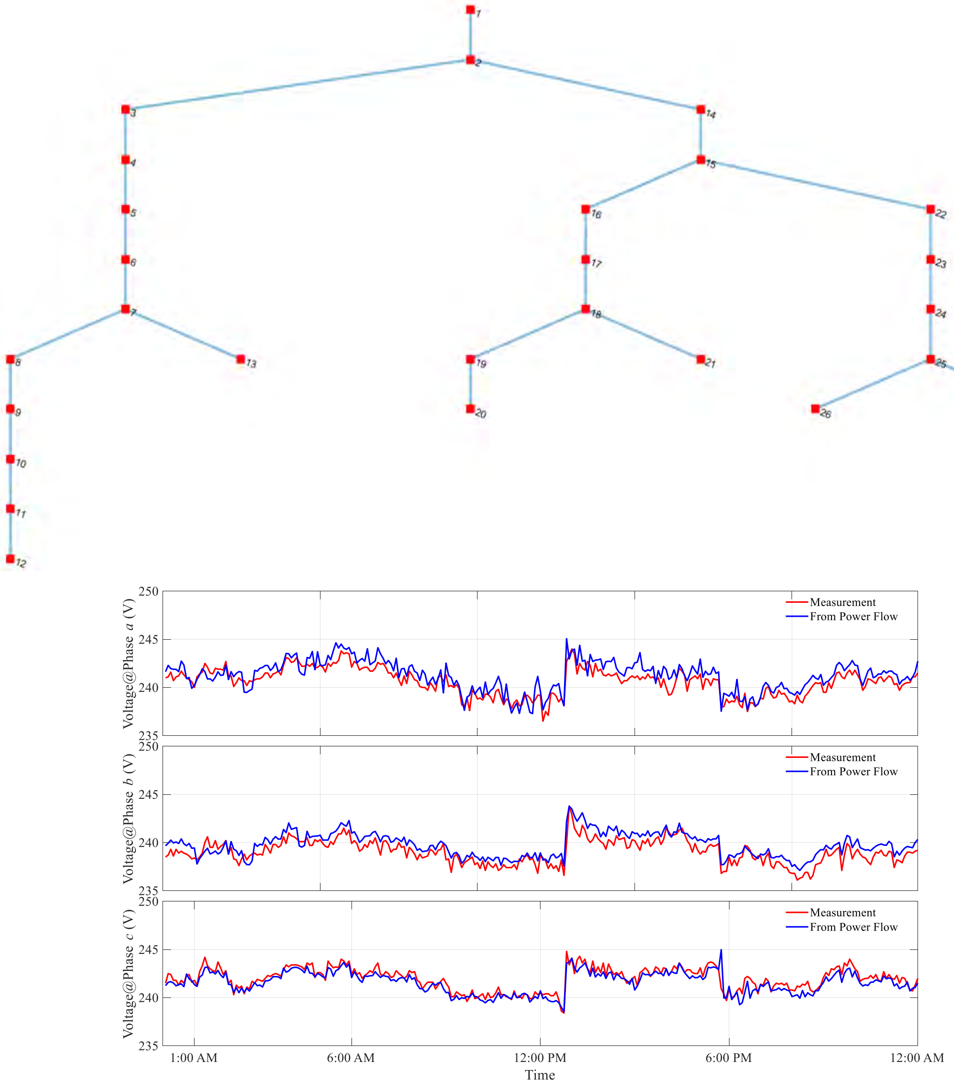


Figure 2.4. Topology and power flow calculation results at node 15 (AusNet).

For the trial network from Jemena, there are 36 nodes and 106 residential customers. The topology of the network and the voltages at node 3 are presented in Fig. 2.5.

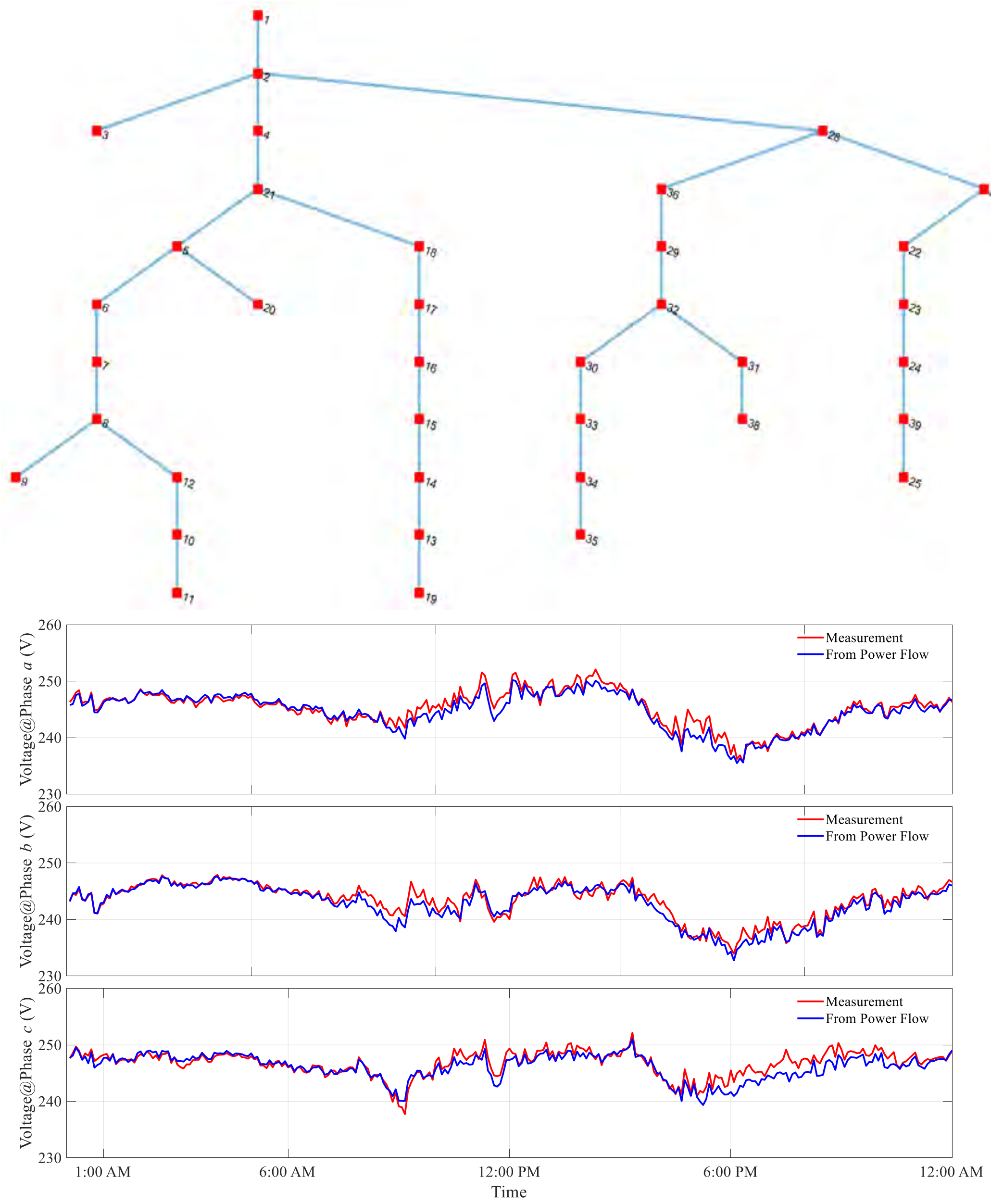


Figure 2.5. Topology and power flow calculation results at node 3 (Jemena).

Simulation results from Fig. 2.4 and Fig. 2.5 demonstrate that calculated parameters and the algorithm are accurate enough for further applications.

2.4 Placement and Control of PSDs in LVDN

With verified network modelling, the first question is where to place and control the PSDs to achieve the best operational performance improvement. Before addressing this issue, the control scheme of PSDs in LVDN is presented in Fig. 2.6.

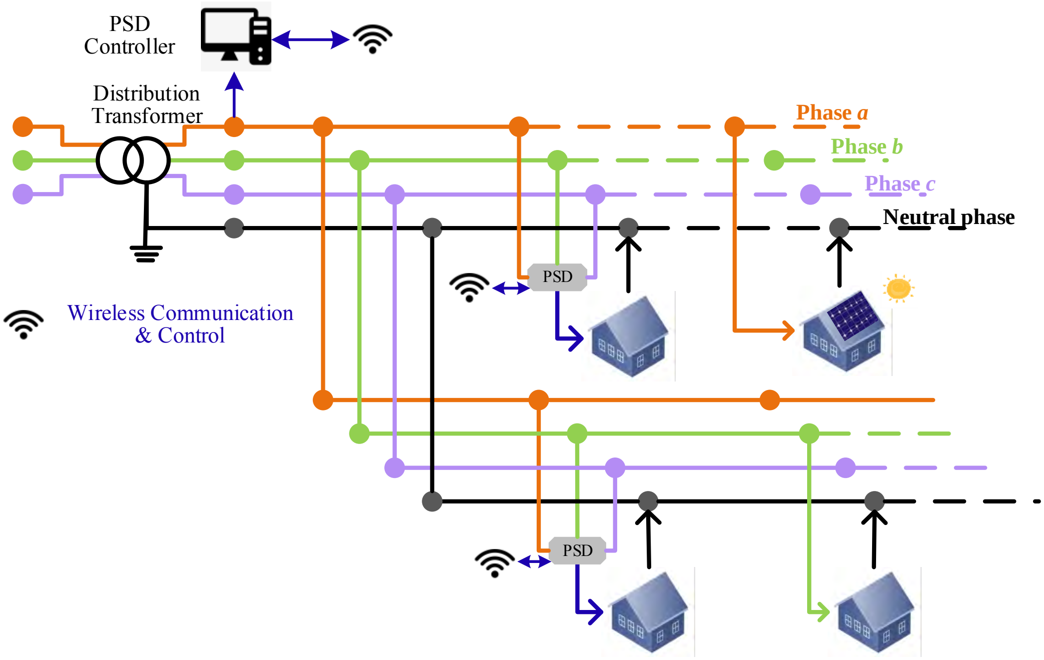


Figure 2.6. Control scheme of PSDs in LVDN.

The PSD controller (CC) installed at the secondary side of the distribution transformer can wirelessly communicate with PSDs to monitor the operational status of the network, and control PSDs to ameliorate the network's operational performance.

To give an overview of the whole placement and control of PSDs in the LVDN, the schematic illustration is presented in Fig. 2.7, where the connection between placement and control of PSDs are presented. After placing PSDs, their day-ahead strategies, which are activated at 2:00 AM every day to minimise the impacts on residential customers and reduce the number of switching operations in real-time control, can be obtained under various PV generation levels. As realised load/PV profiles may be different from roughly estimated values day-head, PSDs are further controlled in real-time when an operational violation occurs.

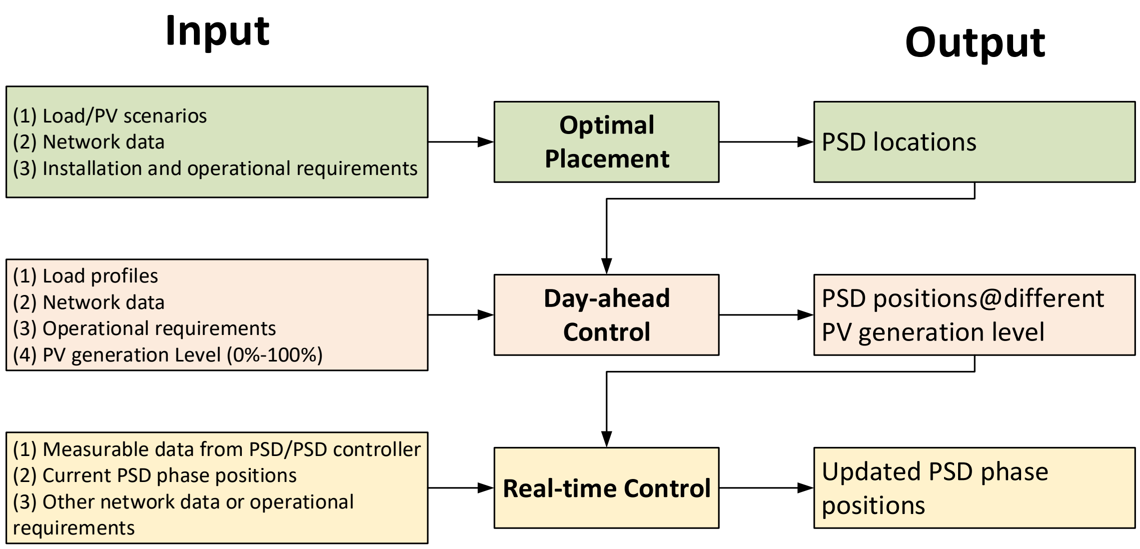


Figure 2.7. Schematic illustration of placing and controlling PSDs in LVDN.

Detailed explanations of the input data and mathematical formulation are given below.

- Input data
    - Network impedances calculated previously, the topology of the network
    - Typical demand scenarios, including the low demand+without PV (s=1), high demand+without PV (s=2), low demand with PV (s=3) and high demand with PV (s=4), based on historical data as shown in Fig. 2.8.

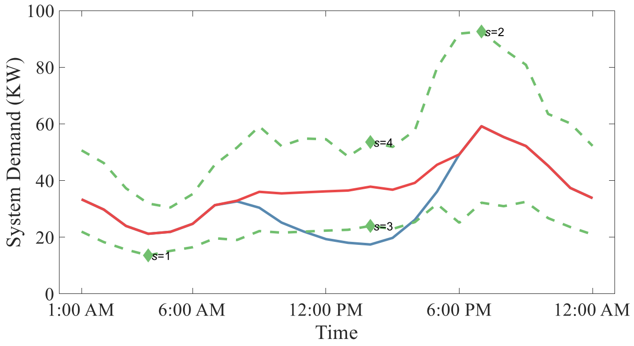


Figure 2.8. Selection of typical historical demand scenarios.

    - Typical PV generation scenarios, i.e., PVs generating at their capacity values for s=3 and s=4 to represent the extreme scenarios.
    - Operational requirements, e.g., voltage magnitudes/unbalance requirements, capacity limit of distribution transformer from network operators.
- Mathmatical Formulatoin
    - Objective: to minimise power unbalance among three phases in each circuit (two circuits for the trial network both in Jemena and AusNet).
    - Installation constraints: Maximum 2 PSDs at each pole (space limitation) and maximum 14 PSDs on 71/106 customers for the trial network both in Jemena/AusNet.
    - Operational constraints: typically include the KCL at each node, voltage magnitudes/unbalance constraints and capacity constraints for distribution

transformer, the power balance constraint for each customer and the phase connection constraints (each customer must be connected to one phase).

It is noteworthy that the formulation is flexible and can further take practical requirements into account in other application scenarios.

The simulation results, including the optimal locations to install PSDs and the optimal day-ahead PSD strategies, on one trial network are presented in Table 1, where the day-ahead strategies are quite different depending on the PV generation levels.

Table 1. Optimal PSD locations and day-ahead control strategies.

PSD Location (customer ID)	Initial PSD Position	PSD Phase Position@ PV Generation Level					
		100%	80%	60%	40%	20%	0%
1	1	1	3	2	3	2	2
9	1	3	3	3	3	3	3
13	1	3	3	3	2	3	2
19	1	1	1	1	2	3	3
27	2	2	2	2	2	2	2
28	3	2	2	2	2	2	2
30	3	2	2	2	2	2	2
38	1	2	2	2	2	2	2
43	1	2	2	2	2	2	2
45	1	2	2	2	2	2	2
52	3	1	1	1	1	2	2
56	3	2	2	2	2	1	2
63	2	3	3	3	3	3	3
64	1	2	2	2	3	2	3

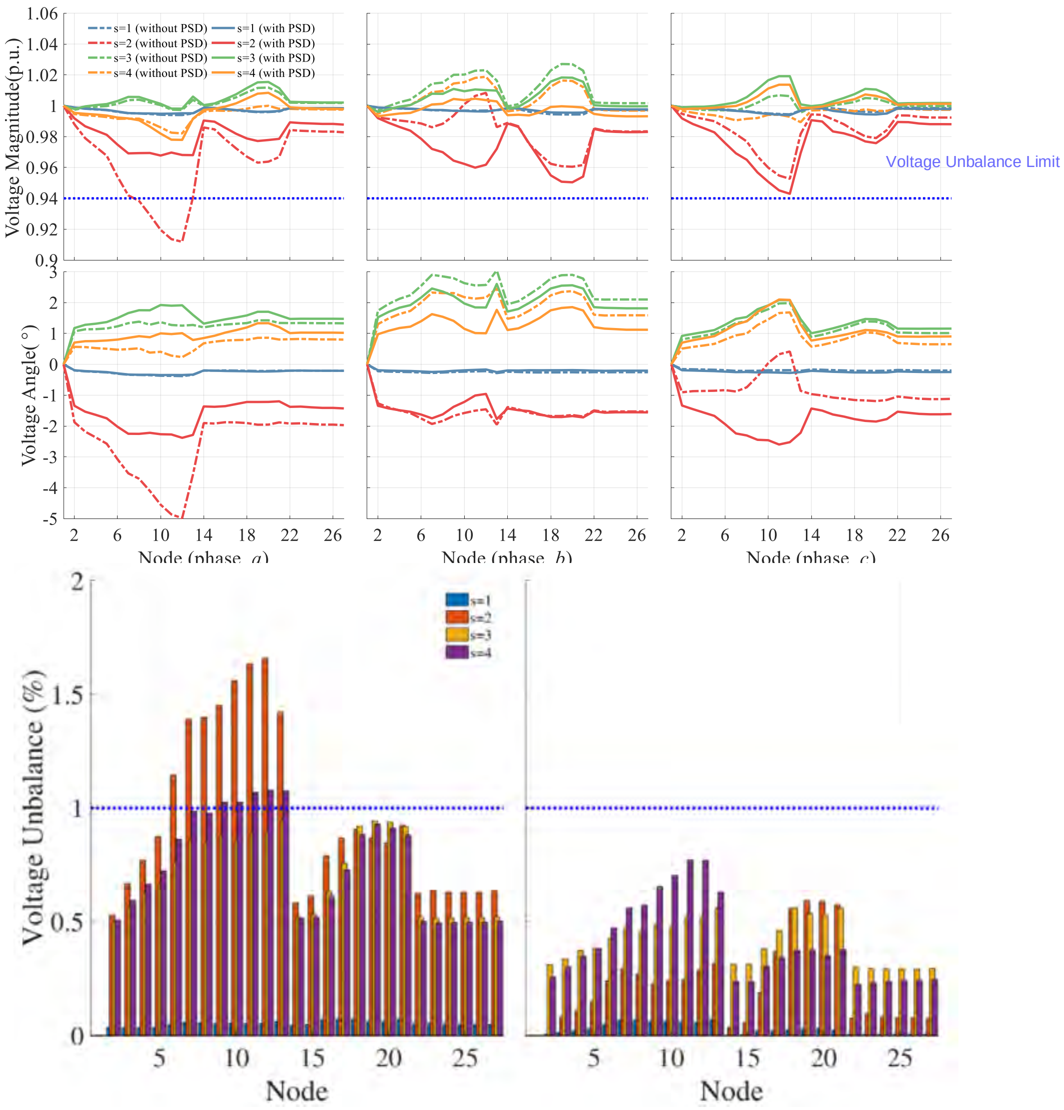


Figure 2.9. Voltage profiles of all nodes under four scenarios (Above) and voltage unbalance level of all nodes (Below).

The voltage profiles of all nodes are presented in Fig. 2.9 (Left), and it is easy to find that voltages are more balanced after switching some customers to optimised phases, which is further verified by voltage unbalance levels of all nodes as shown in the same figure (Right). Moreover, voltage violation issues under the extreme scenarios can be effectively addressed by optimal placing and controlling PSDs as shown in the two figures.

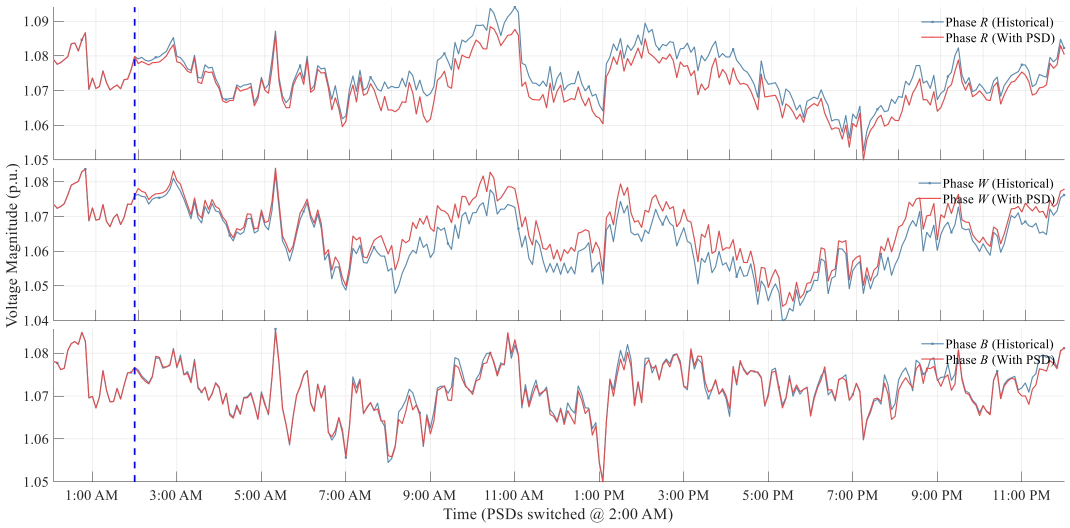


Figure 2.10. Impacts of controlling PSDs on improving voltage levels.

To clearly demonstrate the benefit of switching customers via PSDs, an illustrative example is presented in Fig. 2.10, where some customers are switched from phase W (most stressed phase) to phase R (least stressed phase) at 2:00 AM. Additionally, the voltage levels in the network can be ameliorated through the whole day, which may help accommodate more PV generations in Phase R due to a lowered voltage level.

2.5 Conclusions

Major conclusions of this chapter are given below.

- Necessary data for network analysis has been generated based on physical parameters of the network and historical data.
- Power flow algorithm for unbalanced three-phase LVDN has been developed and tested on both Jemena and AusNet networks.
- An efficient method to place PSDs in LVDN has been developed to provide optimal locations to install PSDs and static strategies to control PSDs under high PV generation levels.
- Other works finished/undergoing:
  - Optimisation model to control PSDs/PCD/BESS in real-time operation.
  - Analyse the hosting capacity improvement brought by introduced devices.

3. Appliance Testing

This chapter presents information of bench testing on the PSD and common household appliances, including objectives, device introduction, testing implementation, challenges during implementation, testing results, conclusions and recommendations for control logic design.

3.1 Testing Objectives

This bench testing aims to achieve the following objectives:

1. Testing the performance of the device, including the initialisation procedure, phase-switching and bypass power supply functions.
2. Investigating the interaction between the PSD and common customer appliances.

Based on the testing results, recommendations to minimise any negative impacts of phase-switching on the customer appliances will be provided for control logic design.

3.2 Introduction of Phase Switching Device

One sample PSD which is an early prototype version was purchased from the supplier for the bench testing. Figure 3.1 illustrates the inside components of the PSD. All the key components such as wire connection points, circuit breakers, control terminal and indicating lights are labelled on the photo. The upstream power supply and the downstream load are connected to the wire connection points, and the circuit breakers are closed to initialise the device. In addition, one of the circuit breakers is used for a bypass circuit. Moreover, the control terminal is used for manual control and the indicating lights shows the operating states.

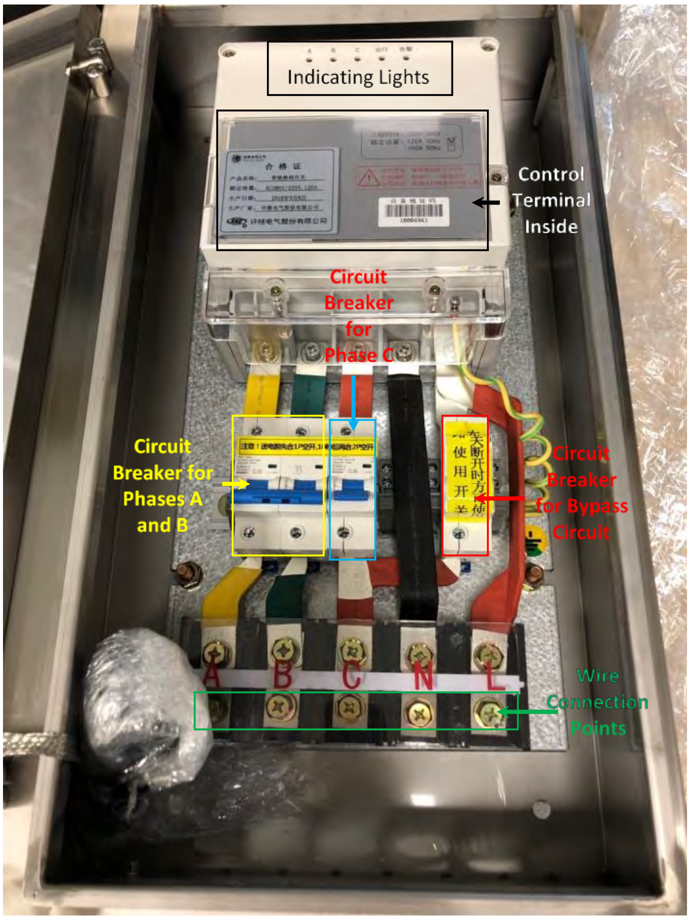


Figure 3.1. Demonstration of phase switching device (prototype)

3.3 Testing Implementation Process

The bench testing implementation process was designed and practiced.

Firstly, hardware and control logic are introduced. The UNSW team investigated the device dimension, the cable connection method, use of the control panel, and meaning of the indicating lights. More importantly, the zero-crossing switching logic is investigated and explained with help of Figure 3.2. The device keeps measuring the load current. The device cuts off the load when the load current is zero. Then, the device keeps measuring the load voltage and the voltage of the phase to be connected. Last, the device connects the load to the new power supply phase, when the load voltage is low and the voltage of the new phase is zero.

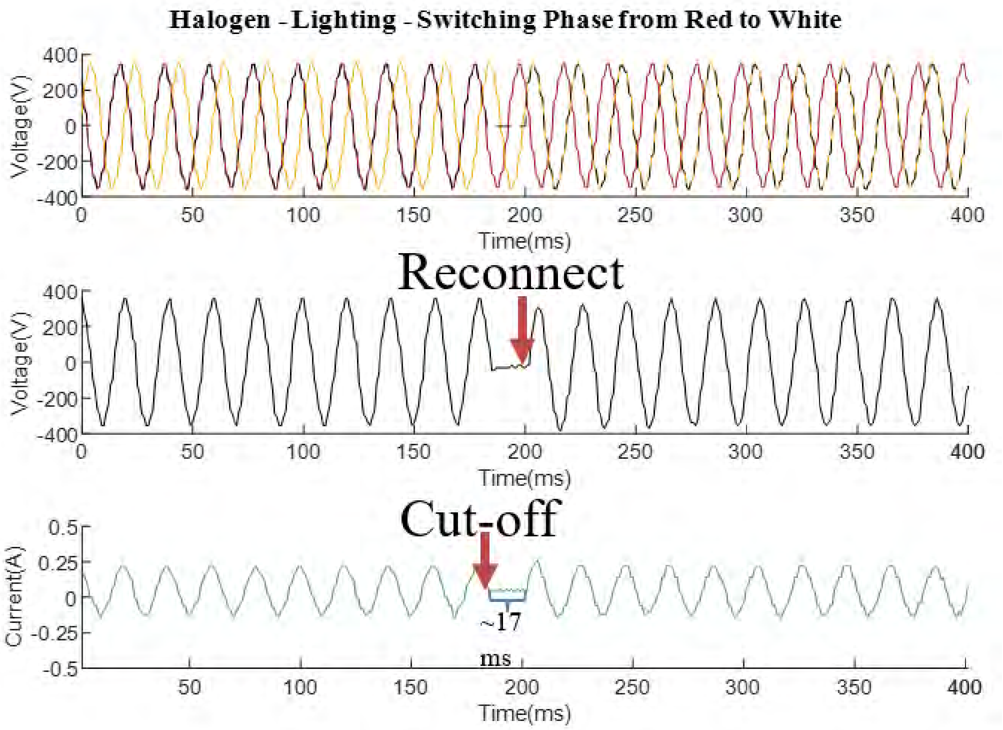


Figure 3.2. Zero-crossing switching logic

Secondly, the UNSW team designed a bench testing circuit as shown in Figure 3.3. This circuit connects the upstream three-phase power supply and the downstream appliance load via the PSD. With a 50-meter cable and a RCD, the practical residential household environment is simulated. Besides, oscilloscopes with voltage and current meters are used to capture transient waveforms during the phase switching process. Then, the device initialisation procedure where the circuit breakers and control knob are sequentially operated is introduced for practical use.

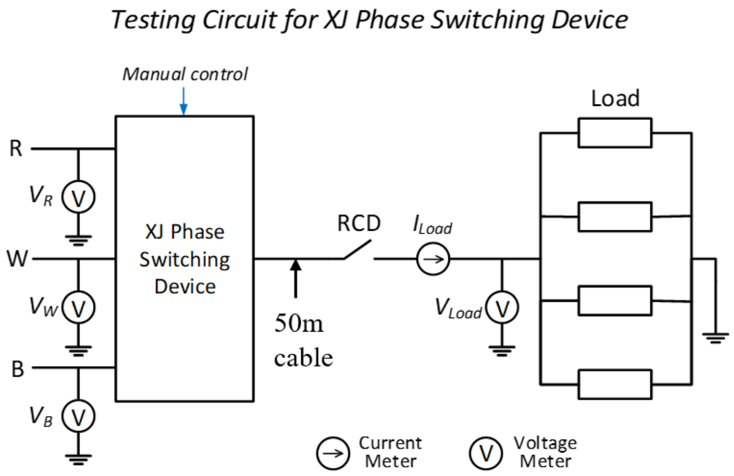


Figure 3.3. Bench Testing Circuit

Thirdly, the UNSW team set up the bench testing circuit in the lab as shown in Figure 3.4 and implemented the bench testing on common household appliances. The testing procedures of phase switching and bypass power supply functions include connecting different appliances, manual control on the PSD, applying positive and negative sequence switching actions, observations of appliance operation states and capturing transient voltage and current waveforms.

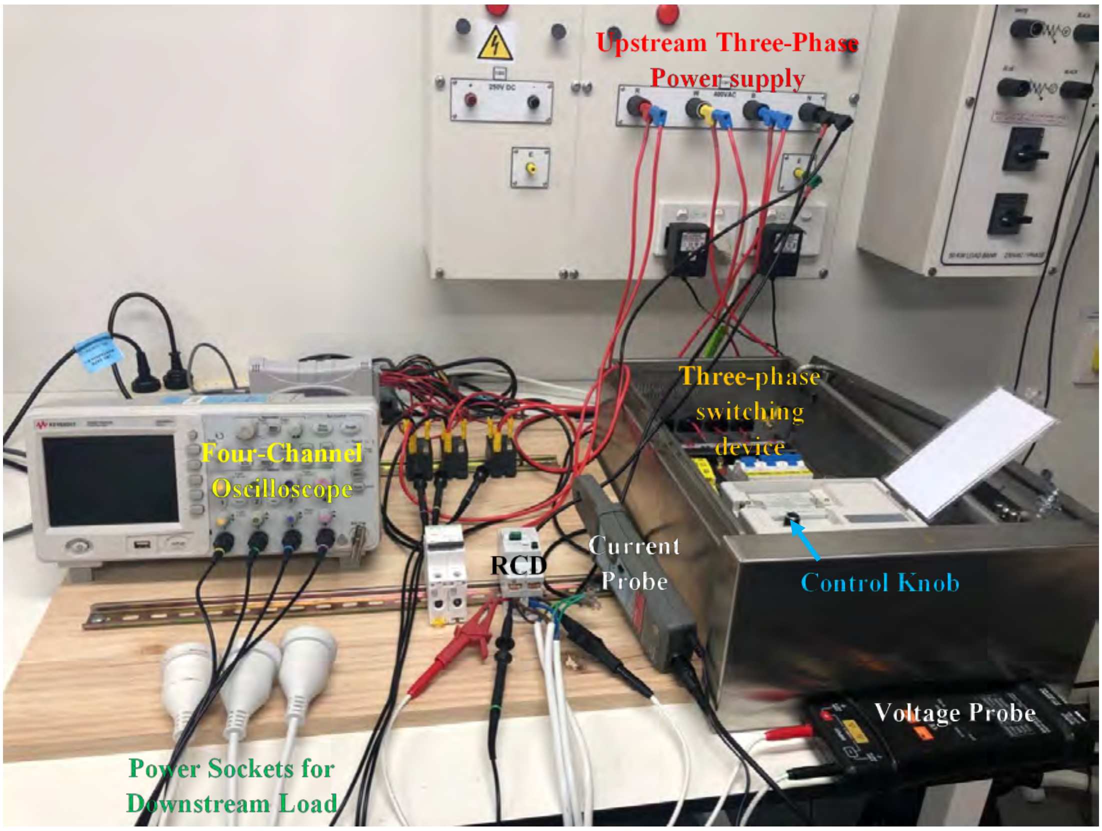


Figure 3.4. Bench testing implementation in the UNSW lab

In the bench testing, 30 appliances, 42 individual common operation states and 12 combined appliance operation states were applied. Particularly, air-conditioner and motor/compressor based appliances were tested with more attention. For example, the air-conditioner, fridge, freezer and pool pump were paid more attention and used for multiple combinations in the 12 combined appliance operation states.

3.4 Challenges during Testing Implementation

The UNSW team experienced some challenges during the bench testing implementation period. For example, as shown in Figure 3.5, challenges associated with the installation of air-conditioner, setup of water system and simulation of practical household environment were successfully addressed.

Installation of air conditioner

Set-up of water system

Addition of long cable and RCD

Figure 3.5. Solutions to challenges during the implementation

3.5 Testing Results

Finally, the UNSW team observed the appliance operation states during the phase switching process and captured transient voltage and current waveforms. Based on these, the UNSW team analysed the bench testing results.

Taking the pool pump running state test as an example, the positive sequence switching did not have much impact on the pool pump running operation. The pool pump might vibrate a little bit more than the normal operating condition. However, the negative sequence switching had significant impacts on the pool pump running operation, which led to heavy vibrations compared to its normal operating condition.

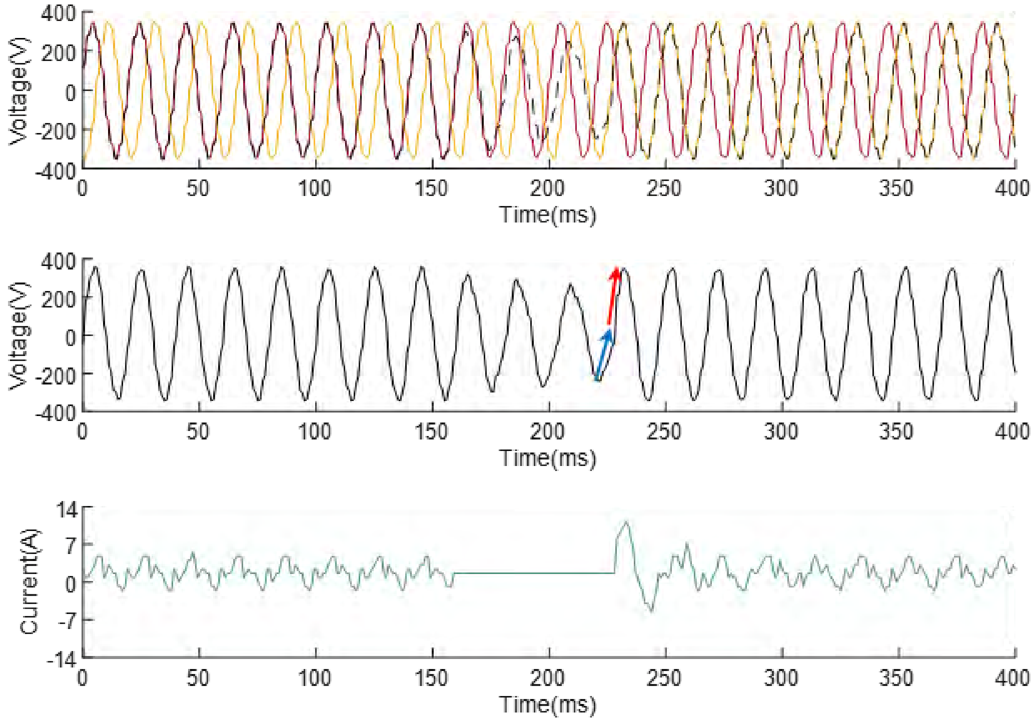
The reasons for the observations can be explained as the vibration degree depends on the load voltage changing tendency during the transient period. The captured transient waveforms are demonstrated in Figure 3.6.

For the positive sequence switching action, the PSD cut off the load from the original phase (Phase Red) as shown on the left. Due to the large motional inertia of the motor, the AC voltage of the load decreased slowly. In the middle sub-figure, the load voltage changing tendency after connecting to the new phase (red arrow) was the same as that before connecting (blue arrow). It meant that the motor kept running without much impact.

On the other hand, the transient waveforms for the negative sequence switching action are shown on the right. In the middle sub-figure, the load voltage changing tendency after connecting to the new phase (red arrow) and that before connecting (blue arrow) were in the opposite directions. It meant that the motor vibrated heavily once compared to its normal slight vibration level.

Therefore, the negative sequence switching action shuold be avoided as far as practicable.

Pool Pump - Running (No Load) - Switching Phase from Red to White



Pool Pump - Running (No Load) - Switching Phase from Red to Blue

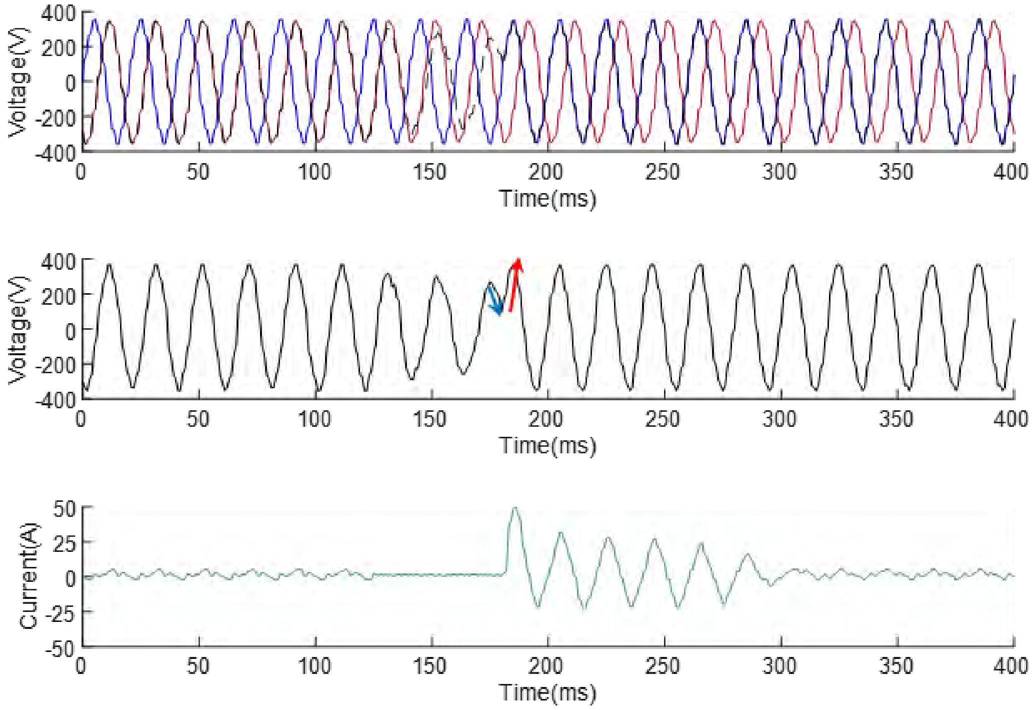


Figure 3.6. Waveforms of testing on pool pump (running – no load)

3.6 Conclusions and Recommendations for Control Logic Design

Based on the bench testing observations and waveform capture, the following conclusions can be drawn:

- Effectiveness of phase switching has been verified.
- Most common household appliances work normally during the phase switching process and they are not affected by the positive or negative sequence switching actions.
- Negative impacts of phase switching process on some appliance operation have been observed and the reasons can be explained with the help of transient waveforms. But no appliance damage is found.

Bencht testing results have provided input to control logic design. The recommendations are given as follows:

- It is suggested to apply consecutive positive sequence switching to replace the direct negative sequence switching (the device supplier has already modified the switching logic accordingly);
- It is suggested to select the periods when less appliances are in use to perform phase switching, for example during night time. This suggestion has been taken into account in the PSD control logics formulation, where a day-ahead switching at 2 am is used to prepare the network configuration to avoid over voltage occurrences during the next period of peak PV export, and a real-time switching in the event that voltage violation occurs due to incorrect forecast. Refer Section 2.4 for further details.
- It is also suggested to reduce the number of the phase switching actions during a day to minimise potential disturbance to customers.

4. Design, Installation & Commissioning of Phase Shifting Devices and Power Compensation Device

In December 2019, AusNet Services (AST) and Jemena installed and commissioned the equipment shown in Fig 4.1 at their respective trial sites in Montrose and Greenvale. Each trial site has a PCD and Central Controller (CC) located at the substation pole as well as fourteen PSD's connected to the customers' service poles. The PSD's were assigned to participant homes without solar PV to prevent any potential switching from directly impacting the operation of existing solar inverters.

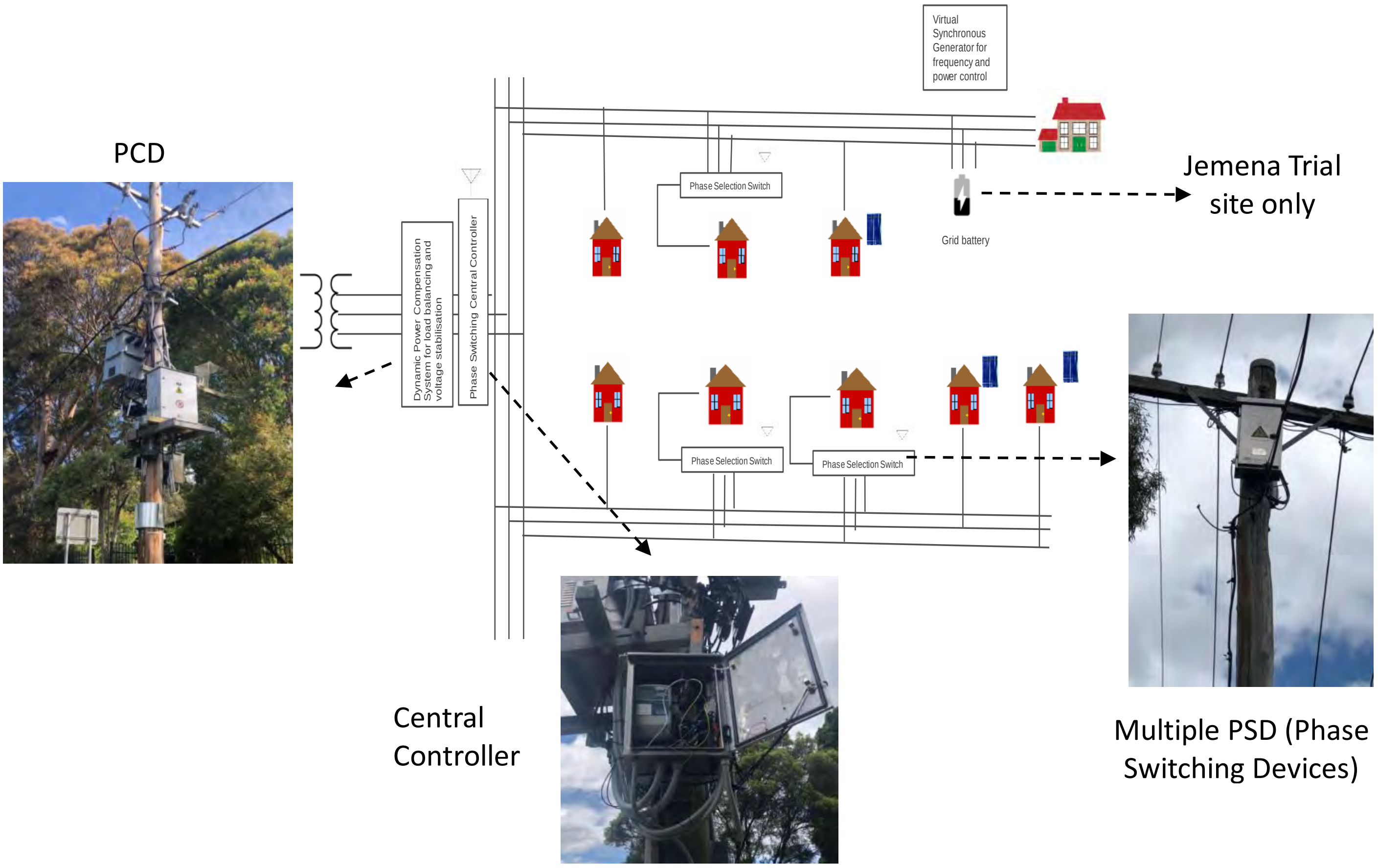


Figure 4.1. Scematic Representation

4.1 Power Compensation Device (PCD)

The PCD is a three phase smart inverter that has four operating modes. Its primary use in this project is to compensate for load unbalance such that the upstream transformer sees a balanced load. Modelling has shown this can have a significant impact on downstream voltages. Another capability is that it can inject reactive power (either capacitive or inductive).Therefore presenting near unity power factor to the transformer, which is also expected to impact the downstream individual phase voltages, and potentially increase the solar hosting capacity on the network.

4.2 Phase Switching Device (PSD) & Central Controller

The PSD is a very fast-acting switch that can dynamically transfer customer loads to any of the three supply phases in less than 10ms. The trial participants' service wires were disconnected from their original static connections and connected to the PSD to achieve dynamic switching, when commanded by the CC. Each phase switching device is connected to the Central Controller via a wireless communication system known as Long Range (LoRa) Communication.

The CC monitors local unbalance due to load and solar generation. If this discrepancy exceeds a set threshold, it commands the appropriate phase switching device to switch phases on a real-time basis.

4.3 Project Learnings so far

4.3.1 New technologies and vendor

The PCD and PSD's are commercially available and have been deployed successfully on low voltage networks overseas. However, since both the vendor and the equipment are relatively new to the Australian market, this presented the project team with some significant challenges to overcome. One such challenge was the team had to work closely with the vendor to design a simple control algorithm that built on existing equipment capabilities, with a view to grow complexity only after core functionality had been tested in the field. This was achieved by managing the language barriers and different working cultures throughout the design phase by ensuring face-to-face workshops and meetings at key milestones.

4.3.2 Design & Installation

Both Jemena and AST had to adopt several design changes to install the equipment in order to meet their own network standards and operational requirements. This resulted in some significant differences between Jemena and AST installations.

4.3.3 Wood vs Concrete Poles

It should be noted that the supplier predominantly had expertise with installing their equipment on concrete poles. Jemena's substation pole was concrete, however, AST pole was wood. Therefore, a local adaptation was made to the original design for the PCD and easily implemented at Montrose. Mounting the PSD's on both concrete and wooden poles was more straightforward and the connections to the overhead open wire and ABC conductors was also easily undertaken.

4.3.4 Antennas

Where applicable, standard antennas used in existing AST Remote Controlled installations were obtained and installed.

There was initial concern that the antennas provided by the supplier in the remote PSD's would not be adequate. They specified that these antennas are mounted internally (inside a closed steel box). Even though we acknowledged that distances involved were not excessive, we were not convinced the communications would be reliable. However, we have been pleasantly surprised and at the AST site all LoRa communication has been 100% reliable. Jemena, however, found that LoRa comms was not achievable in one PSD site and experienced intermittent drop out in a few other PSD locations. Improvement to LoRa comms reliability is in progress for Jemena.

4.3.5 Operations

Ongoing Operational requirements were a major factor in our design considerations and the following activities have been undertaken:

- The ability to easily disconnect individual components using standard Victorian Electrcity Supply Industry (VESI) equipment was accounted for.
- AST and Jemena have provided their Operating Authority and Field personnel written Work Instructions for the basic operating requirements.
- To facilitate on site investigations without having to deploy an authorised linesman, AST and Jemena have installed a secure communication port to the Central Controller at lower level. This will allow lesser authorised personnel to plug a laptop PC to interrogate the device as well as upload and download data as required.
- Detailed consultation was undertaken with Works Practices, Standards, Operational and Field groups to ensure everyone was satisfied the equipment would not unduly impact our customers.
    - If work was scheduled/required in that vicinity that would impact this new equipment what are the basic requirements to be undertaken to allow the necessary work to happen.
    - As the PSD may have a small impact on Customer Quality of supply a campaign of advice was undertaken in the form of newsletter drops.
- Our Faults Call Centre and other frontline interface personnel have been informed of this project and its purpose.
- Our Operations Management System has appropriate notes and warnings to advise all personnel of this new and unique equipment. LV Open points have signs attached on the respective poles so that field personnel are adequately advised.

4.4 Trial Installations

AST and Jemena are very much committed to minimising customer outages and always adhering to times stated in their outage notifications. To minimise the risk of potential delays, the project team decided to perform trial installations at their respective depots prior to the actual installation date. This allowed the field crew to familiarise themselves with the new equipment and the non-standard mounting requirements. As a result, the outage days went smoothly for both companies.

4.5 Commissioning

Due to the hard work invested in the lead up to commissioning, the days went relatively smoothly for both AusNet Services and Jemena. The testing confirmed the Master Station was able to successfully send commands and display real time information to and from the PCD and PSD’s (Fig 4.2). Some minor issues with communication delays were encountered when trying to switch the PSD’s manually, however, this didn’t result in any major technical difficulties. All modes of operation in the PCD are working as shown in Fig 4.3, as well as the auto and manual switching of the PSD’s.

Solar Friendly neighbourhoods Project-Equipment Overview

Va: 234.88V
Vb: 232.75V
Vc: 236.62V

Qa: -0.69 kVar
Qb: -1.44 kVar
Qc: -2.06 kVar

Pa: 25.25 kW
Pb: 20.81 kW
Pc: 21.81 kW

Qa: -0.69kVar
Qb: -0.69kVar
Qc: -0.69kVar

P: 28.20kW
Q: 1.24kVar

	Va	Vb	Vc		A	B	C
PSD#1-1	238.97V	238.49V	242.05V	🟩	🟢	🔴	🟢
PSD#1-2	237.73V	237.25V	240.52V	🟩	🟢	🟢	🔴
PSD#1-3	235.72V	237.73V	240.62V	🟩	🟢	🟢	🔴
PSD#1-4	233.69V	237.79V	238.85V	🟩	🟢	🟢	🔴
PSD#1-5	233.58V	237.58V	239.03V	🟩	🔴	🟢	🟢
PSD#1-6	233.12V	237.03V	238.61V	🟩	🟢	🔴	🟢
PSD#1-7	235.51V	237.73V	240.78V	🟩	🟢	🔴	🟢

P: 40.18kW
Q: -0.18kVar

	Va	Vb	Vc		A	B	C
PSD#2-8	237.01V	235.40V	243.72V	🟩	🟢	🔴	🟢
PSD#2-9	234.67V	234.64V	242.17V	🟩	🟢	🟢	🔴
PSD#2-10	234.85V	234.72V	242.78V	🟩	🟢	🔴	🟢
PSD#2-11	234.26V	233.78V	238.39V	🟩	🟢	🔴	🟢
PSD#2-12	238.58V	235.54V	237.74V	🟩	🟢	🟢	🔴
PSD#1-13	235.68V	231.95V	236.19V	🟩	🟢	🔴	🟢
PSD#2-14	237.99V	233.99V	237.55V	🟩	🟢	🟢	🔴

Unbalance of Branch1: 0.54
Unbalance of Branch2: 0.23

Equipment Status - PSD

Branch1 PSD	Branch1 current (A)	A	B	C	Branch PF	Unbalance Rate
		51.00	32.10	44.60	0.96	0.38

No.	Phase			PSD Control	Voltage (V)			Load Current (A)	Comm Status	PT disconn-ection(Ua)	PT disconn-ection(Ub)	PT disconn-ection(Uc)	PT disconn-ection(Ui)	Phase Error
	A	B	C		A	B	C							
1	🟢	🔴	🟢	🟩	238.77	238.28	242.05	5.19	🟢	🟢	🟢	🟢	🟢	🟢
2	🟢	🟢	🔴	🟩	237.73	237.25	240.73	2.00	🟢	🟢	🟢	🟢	🟢	🟢
3	🟢	🟢	🔴	🟩	235.92	236.71	239.80	2.64	🟢	🟢	🟢	🟢	🟢	🟢
4	🟢	🟢	🔴	🟩	235.33	236.13	237.61	10.13	🟢	🟢	🟢	🟢	🟢	🟢
5	🔴	🟢	🟢	🟩	235.23	236.34	237.37	0.75	🟢	🟢	🟢	🟢	🟢	🟢
6	🟢	🔴	🟢	🟩	235.00	235.78	236.75	1.75	🟢	🟢	🟢	🟢	🟢	🟢
7	🟢	🔴	🟢	🟩	236.13	236.30	239.34	2.07	🟢	🟢	🟢	🟢	🟢	🟢

Branch2 PSD	Branch2 current (A)	A	B	C	Branch PF	Unbalance Rate
		41.50	57.90	68.90	0.96	0.39

No.	Phase			PSD Control	Voltage (V)			Load Current (A)	Comm Status	PT disconn-ection(Ua)	PT disconn-ection(Ub)	PT disconn-ection(Uc)	PT disconn-ection(Ui)	Phase Error
	A	B	C		A	B	C							
1	🟢	🔴	🟢	🟩	238.27	236.03	242.45	3.54	🟢	🟢	🟢	🟢	🟢	🟢
2	🟢	🟢	🔴	🟩	236.12	235.26	241.76	1.33	🟢	🟢	🟢	🟢	🟢	🟢
3	🟢	🔴	🟢	🟩	236.09	236.17	242.36	12.40	🟢	🟢	🟢	🟢	🟢	🟢
4	🟢	🔴	🟢	🟩	235.09	234.19	236.74	2.63	🟢	🟢	🟢	🟢	🟢	🟢
5	🟢	🟢	🔴	🟩	237.54	235.33	237.33	15.39	🟢	🟢	🟢	🟢	🟢	🟢
6	🟢	🔴	🟢	🟩	236.93	231.52	235.15	1.22	🟢	🟢	🟢	🟢	🟢	🟢
7	🟢	🟢	🔴	🟩	238.61	233.58	236.94	9.39	🟢	🟢	🟢	🟢	🟢	🟢

Figure 4.2. AST Master Station User Interface

Figure 4.3. PCD Notch Test Results

4.6 Device Communications & Cybersecurity

Given the IoT nature of the devices, communications and cybersecurity teams in Jemena, AST and the vendor worked collaboratively to develop a communications approach that would provide reliable remote monitoring and control while mitigating cybersecurity risk as much as is practicable. Design decisions included restricting remote control functionality and choosing instead to leverage the field devices' autonomous control capabilities. In this aspect, Jemena and AST teams developed independent approaches for remote monitoring that were suitable for their respective business needs, with AST utilising the vendor-supplied remote monitoring system that is run independently from any existing systems (Fig 4.4), and Jemena integrating telemetry into their SCADA system. The approach taken by Jemena did result in significantly more effort to test the interoperability of the SCADA protocol (DNP3.0) with its master station.

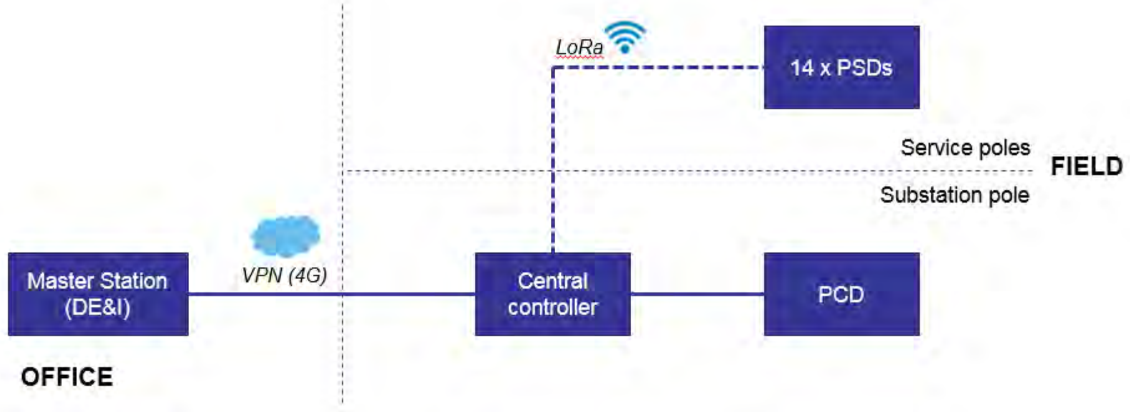


Figure 4.4. AusNet Service's Communications Diagram

4.7 Customer Experience

A key aspect of this trial is to understand the impacts as well as benefits of these new technologies on customers. Jemena and AST teams’ designed customer communications plans to ensure customers at the respective sites are aware of the new infrastructure being installed, any potential disturbances such as outages, and have clear communication channels should they have any enquiries or concerns.

To date, customer communications have included updated websites with detailed FAQs, project-specific letters provided to residents as the trial progresses, and drop-in visits to customers residing in closer proximity to installation works. Given the equipment is being deployed in a residential area, the AST project team also decided to conduct noise monitoring at the site to understand the potential for disruption. At this stage of the project there have been no concerns raised by the local community.

5. Design, Installation & Commissioning of Jemena's Battery Energy Storage System

5.1 Purpose of the Battery Energy Storage System (BESS)

The BESS is intended to absorb the excess solar generation during the day (BESS charging operation) and in so doing, reduce the impact of excess solar generation on the power quality of the LV network. An example of an application is to reduce the amount of reverse power flow through the distributon transformer. The stored energy can be used to maintain the stability of the electricity network against steady-state and transient events (BESS discharging operation). An example of a steady-state application is to reduce the peak load carried by the distribution transformer in a peak shaving operation.

5.2 BESS Sizing

The distribution substation has a transformer rating of 200kVA. Mild overload has been experienced in summer 17/18 (223kW). Aggregate capacity of PV customers supplied from the substation is 101kVA. Reverse power flow up to 40kW, through the distribution substation transformer, has been observed on a sunny day in 17/18 summer.

Jemena has opted for a BESS size of 100kW/200kWh. This is probably bigger that what is required to store the existing aggregate PV excess output. However, a bigger BESS capacity allows more meaningful response to transient network events. We'll make some assessment of the optimal BESS sizing in the project final report, after running the BESS through a number of test cases planned in the next few months.

5.3 BESS Location

UNSW conducted an optimal planning study of the BESS which includes two possible BESS locations. As the BESS is in a ground-mounted enclosure measuring 2.5m by 3m (and 2.9m high), its location cannot be arbitrarily selected but is based on the availability of suitable open parkland/road reserve that has minimal effect on neighbouring residents. In further discussion with the Hume Council (which has been a firm supporter of the project from the beginning), a third location, a road reserve, was ultimately decided upon. The third location is relatively close to one of the locations used in the BESS planning study so the planning study results can still be applied.

Figure 5.1. Views of the BESS enclosure

5.4 BESS Design

Figure 5.2 shows the layout of the BESS enclosure. There are two compartments: one housing the battery modules and one the Power Conversion System (PCS) & anciliary equipment. While the two compartments are linked via power and control cablings, they are effectively sealed from one another. This is important as it allows air-conditioning and a gaseous fire suppression system to be installed in the battery compartment.

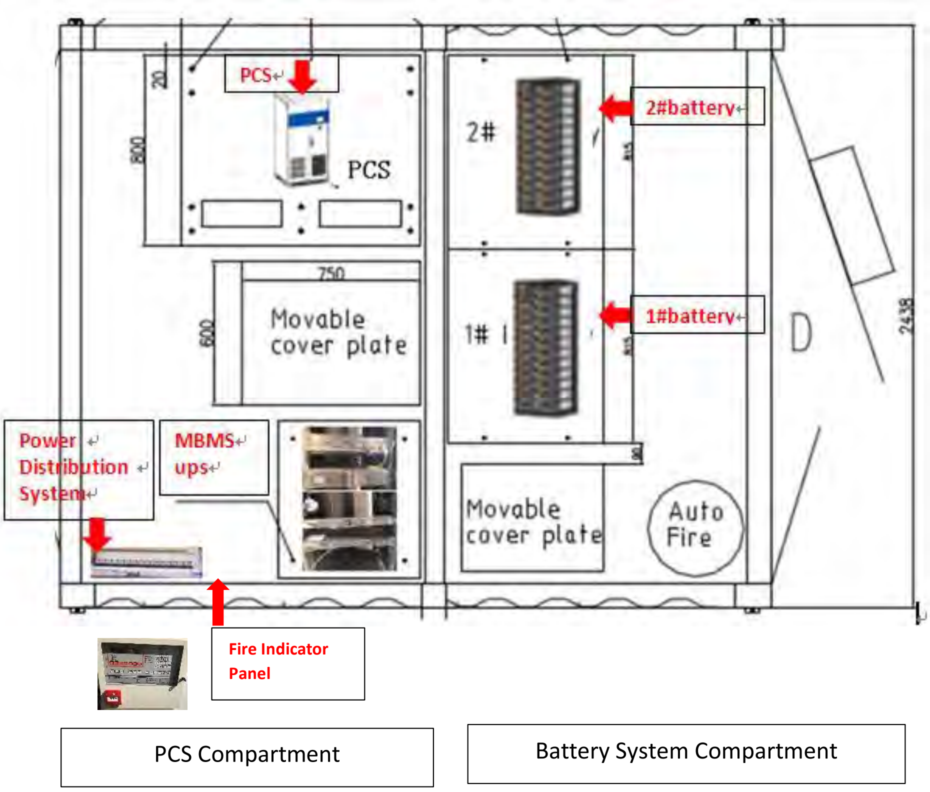


Figure 5.2. BESS enclosure

The battery system is made up of 2 parallel battery strings, each string consists of 21 battery modules connected in series. Each battery module has an output DC voltage of 32V and a capacity of 4.736 kWh. Apart from DC connections, the battery module also contains communication ports for connection to a Battery Management System (BMS), one BMS per battery string. The two BMS's are in turn connected to a Master Battery Management System (MBMS). The BMS's performs extensive monitoring of the health of the battery modules and initiate shutdown of the BESS (via communication to the PCS) when a fault is detected. The battery modules are based on Lithium-Ion Phosphate chemistry.

The PCS performs power conversion between the AC grid and the DC battery system. In the battery charging mode, the PCS converts the AC power from the grid into DC power to charge the battery system. In the battery discharging mode, the PCS converts the DC power from the battery system into AC and feeds the AC power into the grid. The bi-directional converter incorporates advanced islanding detection that meets the anti-islanding requirements of AS4777.2 i.e. the PCS will be disconnected from the grid when the grid connection is lost. The PCS is rated at 250kW but is set to a maximum output of 100kW for the Jemena application. The PCS also incorporates an isolation transformer (delta/star, star winding on the grid side) to match the rectified voltage to the grid voltage, and to prevent any DC voltage from appearing on the grid connection point.

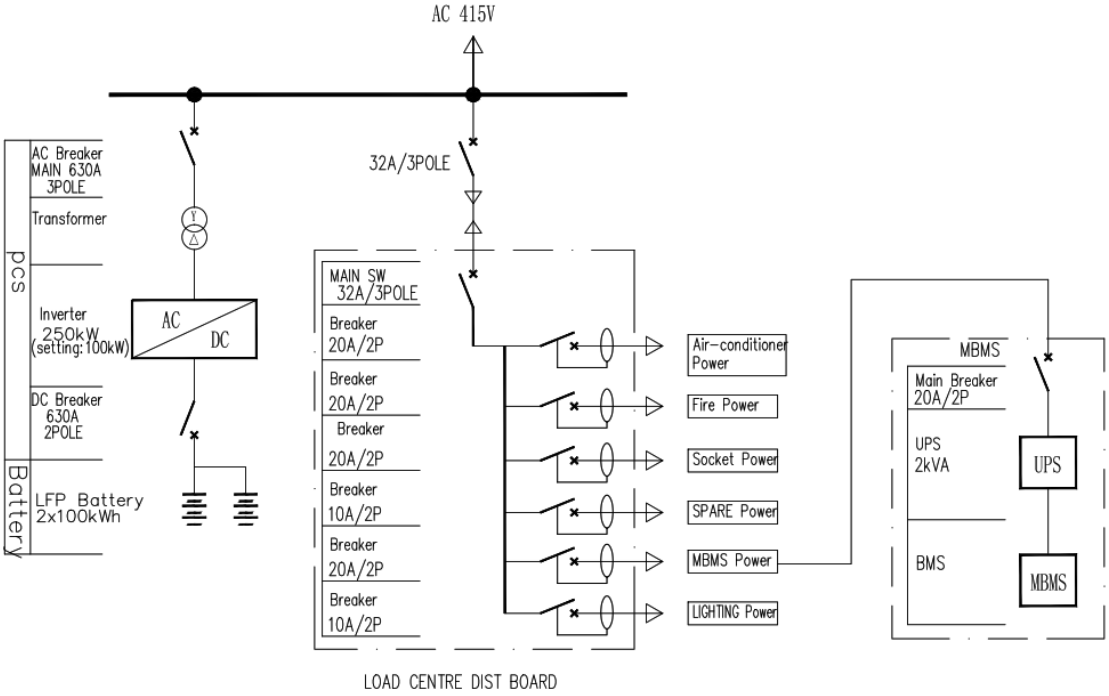


Figure 5.3. BESS single-line diagram

5.5 BESS Anciliary Equipment

A 2kVA Uninterruptible Power Supply (UPS) supplies auxiliary DC supply for the battery management systems (BMS, MBMS) as well as the LoRa communication module (for the wireless communication between BESS and the Central Controller). This setup provides clean power and allows the control system to function for a short duration even when the AC mains input is temporarily lost.

Wormald supplies and installs the fire detection and suppression system, primarily targeted for the battery system compartment, in the very unlikely event that a fire occurs on the battery module(s) when it fails to be shut down in time by the BMS. The detection system consists of a smoke detector and a Very Early Smoke Detection Apparatus (VESDA) system. When both are in alarm mode the fire suppression system is triggered after a 30-second delay. The fire suppression agent is INERGEN, an inert gaseous fire suppressant consisting of natural gases (nitrogen, argon, carbon dioxide) and extinguishes fire without causing harm to people, property or the environment. Auxiliary power supply for the fire detection and suppression system comes from the AC distribution board. Battery backup is provided in the even the AC supply is lost.

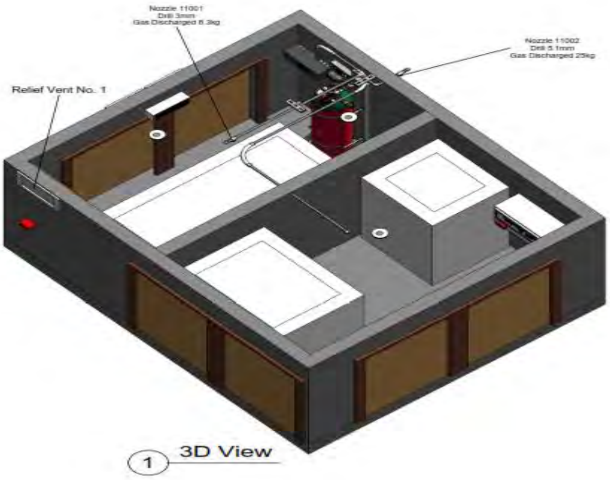


Figure 5.4. 3D view of the fire detection and suppression system

5.6 BESS Control Logics

A local control panel is installed on the PCS cubicle for setting operating parameters and for local operation of the BESS. The normal operation of the BESS is controlled remotely by the CC installed on the substation pole (Langton-Greenvale), via the LoRa wireless communication system.

The CC will exert coordinated control on the PCD and BESS, depending on the control scheme selected:

- Bus over voltage control strategy
- Bus under voltage control strategy
- Battery State-of-Charge (SOC) maintenance control strategy
- Transformer overload control strategy
- Transformer reverse power flow control strategy

The project will trial the effectiveness of the various control schemes. In addition, the project will trial the effectiveness of the BESS during transient network disturbances, primarily through simulation.

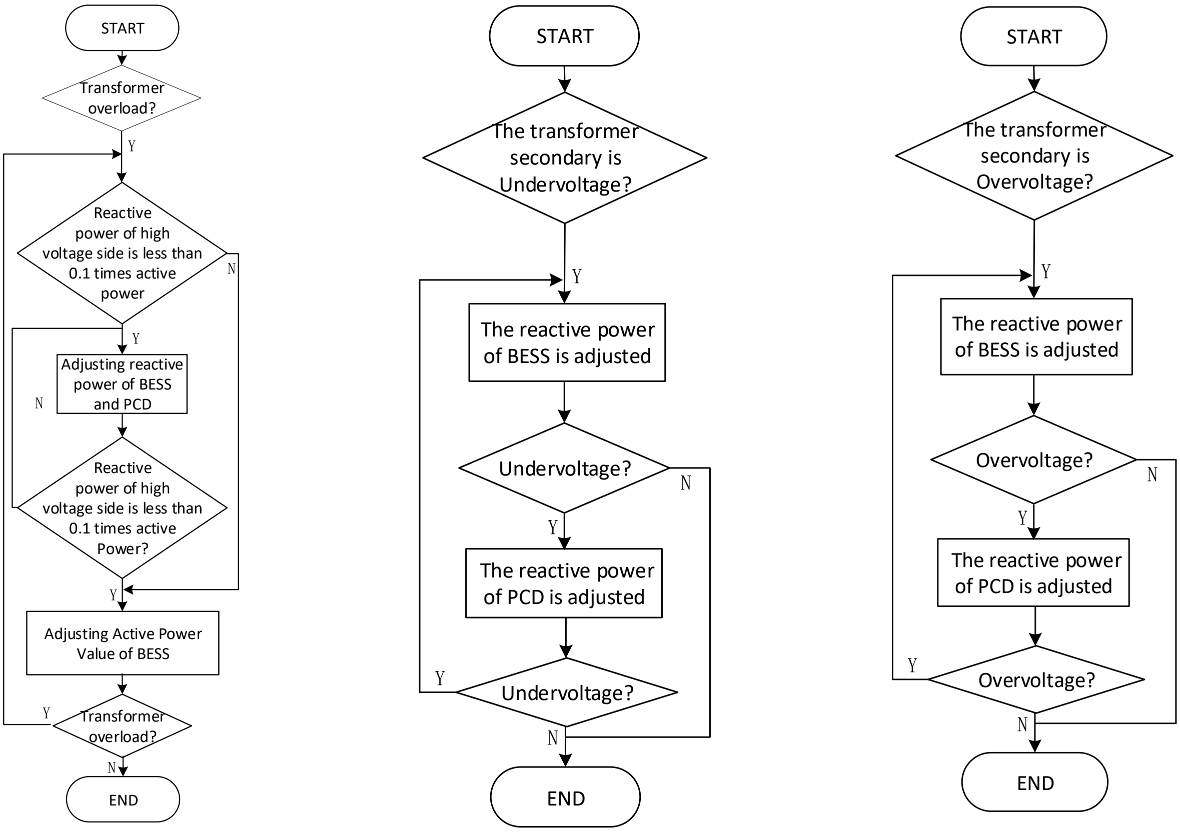


Figure 5.5. High level flowchart showing coordinated control of PCD and BESS (only part control schemes shown)

5.7 Status of BESS

As the CC is connected to Jemena's SCADA system, analogues, events and alarms of BESS are remotely monitored by Jemena's control room. A control function is implemented to allow Jemena control room to turn the BESS on/off. Automation logics of the BESS is contained inside the CC.

AMPSa 33.6 A
AMPSb 21.5 A
AMPSc 14.0 A
PF 0.9 PF
UNBAL 0.5

PSD8
Phase A PT Break OFF
Phase B PT Break OFF
Phase C PT Break OFF
Phase L PT Break OFF
Phase Seq Error OFF
Comms Fail OFF
Phase Position 10.0
Va 245.3 V
Vb 246.9 V
Vc 246.6 V
LOAD 4.5 A

PSD9
Phase A PT Break OFF
Phase B PT Break OFF
Phase C PT Break OFF
Phase L PT Break OFF
Phase Seq Error OFF
Comms Fail OFF
Phase Position 10.0
Va 245.3 V
Vb 247.5 V
Vc 246.6 V
LOAD 3.2 A

PSD10
Phase A PT Break OFF
Phase B PT Break OFF
Phase C PT Break OFF
Phase Position 10.0
Va 244.0 V
Vb 246.0 V

BESS		A	B	C
Grid Side Volts		239.7 V	239.7 V	242.6 V
PCS OUTPUT	WATTS	-34.6 kW	-32.8 kW	-33.3 kW
	VARs	34.6 kVAr	32.8 kVAr	33.3 kVAr
	PF	1.0 PF	-1.0 PF	-1.0 PF
BATTERY VOLTS		690.4 V		
BATTERY SOC		54.0 CNT		
Grid Side FREQ		50.0 Hz		
PCS DC VOLTS		693.5 V		
PCS OUTPUT W		-100.7kW		
PCS OUTPUT Q		0.2 kVAr		
BESS on/off		* ON		

Figure 5.6. SCADA screen showing BESS charging at 100kW

6. Approach to Implementation of Innovation Projects

6.1 New Network Technologies

The project is implementing three new technologies that have not been used on either electricity network for the purpose of increasing DER hosting capacity. As such, it is useful to describe the approach that Jemena and AST has each taken to implement the project, and learning where there are differences in approach.

6.2 Approach to Risk Assessment

Risk assessment is conducted for every new piece of equipment before it is purchased, and before it is put into service.

As this project is a trial of new technologies, it is treated as a one-off project. While managing health & safety risks remain paramount, there is perhaps lesser focus on equipment conformance to internal operational standards.

Compliance with relevant Australian Standards was specified in the equipment tenders. During post tender negotiations the project team has accepted some IEC standards in lieu of Australian Standards where there are no significant differences between the two. This is primarily due to cost consideration, as overseas product suppliers tend to favour testing to IEC standards from a global market requirement perspective.

Due to the possible effect of phase shifting operation on customers, extensive testing was conducted in UNSW laboratory on common household appliances using a sample phase shifting device. Control algorithms for phase shifting operation were formulated taking into account of the testing results.

Factory acceptance testing (FAT) is a must for new equipment. It was conducted in the equipment vendor's factory in China. Successful completion of FAT was a prerequisite before equipment was shipped to Australia. After the equipment was delivered, additional bench testing was conducted in Jemena/AusNet workshops before the equipment was installed. Field installation and operational staff gained familiarity with the equipment via the bench testing.

6.3 Approach to Operational Procedures

The project team retains operational responsibility of the technologies after the equipment is commissioned into service. Hand over to business-as-usual is only considered when the trial period is over. This approach reduces the amount of upfront operational training that is required.

The system is designed with autonomous operation in mind, with remote supervision:

- AST has installed a standalone PC, with the vendor's master station software communicating to the CC. This set up also allows the project team to remotely interrogate the CC and perform remote firmware upgrade
- The CC vendor, on the other hand, has supplied a DNP3.0 SCADA interface to allow CC to be remotely monitored (and limited control) from Jemena's SCADA system
- For Jemena, interrogation of the CC and firmware upgrade can only be performed locally
- To facilitate local connection of a laptop to the CC, an ethernet box is installed below the CC

- Operational procedures have been developed in the event of faults/alarms from the equipment. The equipment logics are designed to be “fail safe” i.e. equipment stops working when abnormalities are detected. Operational staff is instructed to isolate the equipment when alarms are detected e.g. open the supply FSD, leaving the task of trouble shooting to the project team.

6.4 Approach to Software Development

New software development is required by the equipment vendor to adapt the equipment for use to improve DER hosting capacity. The collaborative approach to functional development was emphasied at both the tender phase and in post tender negotiations.

The phase shifting devices are typically used for load balancing. Adaptation of the control logics is required for the project purpose of balancing generation and load. Appliance testing has also resulted in the decision to implement positive sequence switching, a “day ahead” and a “real time” switching schedules for the phase shifting devices.

The power compensation device is generally autonomous in its operation but would need to coordinate with the operation of the BESS for voltage control, when both systems are in service.

In addition, the CC offered by the equipment vendor does not have a standard DNP3.0 SCADA interface and has to be developed specifically for this project.

To ensure that the software development will meet the project requirements, design workshops were held in Australia with the supplier on the functional specifications of the control logics. Furthremore, the control logics were tested during the FAT.

Control logics are now being tested post installation and commissioning. As issues are found the project team work with the supplier for rectification and refinement.

7. Conclusions

The Jemena DER hosting capacity project has successfully installed and commissioned the three technologies that promise to make our electricity distribution networks solar friendly.

It has not been an easy task to deliver a project that deploys new equipment with a high degree of complexity. This interim knowledge sharing report dsecribes the challenges encountered and the lessons learnt. One word that sums up the achievement of this project milestone is TEAMWORK. The project has 6 project partners: Jemena, AusNet Services, UNSW, State Grid International Development, the equipment vendor (XJ Group), and ARENA. Each plays its unique role and contributes to the success of this project.

We warmly recommend this interim knowledge sharing report to you, and trust you will find it informative and useful.

Further information about the project can be obtained from the following sources:

Jemena: peter.wong@jemena.com.au; Jiangxia.zhong@jemena.com.au; Jignesh.patel@jemena.com.au

AusNet Services: tian.ting@ausnetservices.com.au; asanka.paranamana@ausnetservices.com.au; allan.truman@ausnetservices.com.au

UNSW: joe.dong@unsw.edu.au; bin.liu@unsw.edu.au; cuo.zhang@unsw.edu.au

Web sites: www.jemena.com.au/solarfriendly, https://www.ausnetservices.com.au/Innovation/Enabling-Solar-and-Battery-Future

Appendices (Powerpoint Slides)

- Interim knowledge sharing – project overview
- Interim knowledge sharing – network modelling
- Interim knowledge sharing – bench testing
- Interim knowledge sharing – AST LV phase balancing
- Interim knowledge sharing – battery energy storage system
- Interim knowledge sharing – approach to implementation of innovation projects