Household Battery Network Impact Assessment

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Executive Summary

The Victorian Government is providing a rebate on the Solar Homes Battery Program (Battery Program). Distribution Network Service Providers (DNSPs) have noticed a number of issues, including limited visibility over existing batteries installed in the network and uncertainty around battery behaviour on the network. This project aims at studying the electricity consumption behaviour of households with batteries and investigating its impact on the distribution network. The project is completed in collaboration with the Centre for New Energy Technologies (C4NET), the Department of Environment, Land, Water and Planning (DELWP), Victorian DNSPs (Powercor, Jemena, AusNet Services), Origin and AGL. The project outcomes will help DELWP and Victorian DNSPs to gain more insights into the effective operation of batteries within the Victorian distribution networks. The project will also empower DELWP to effectively adjust the Solar Homes battery program and Distributed Energy Resources (DER) policy for the benefit of both consumers and DNSPs.

The report includes our analysis of real, de-identified electricity consumption data collected via smart meters from sites suspected to have batteries operating in the network. Consumption data of customers with rooftop Photovoltaics (PV) but without batteries and those without PV are also analysed to establish baseline profiles. Typical customer load profiles under different settings are incorporated into a power flow simulation study where both balanced and the unbalanced loadings of a practical distribution network are considered for impact assessment. The load profiles identified through the data analytics phase of the project are then used to perform a quasi-dynamic simulation, and extreme event study on the practical distribution network in order to quantify the network impact associated with the observed customer load, battery and PV behaviours. A summary of our key findings and some recommendations are as follows.

Key Findings

Household batteries support the hosting capacity of the distribution grid.

- Installing a household battery results in at least a 20% reduction in power exports during the peak sun hours on cool and pleasant days (i.e. ambient temperatures less than 30˚C). This has a direct impact on mitigating the unwanted side-effects of increased rooftop solar photovoltaic penetration (e.g. an increase in distribution feeder voltage levels during peak export periods), and this enables more photovoltaic installations to be accommodated in Victorian suburbs.
- Power imports during the evening peak (i.e. 18:00-22:00) are significantly reduced by at least 60% due to the action of a household battery on mild temperature days.
- The battery discharge has a positive effect on the distribution feeder voltage profile under peak load events. For example, on hot summer days where the residential load peaks due to appliances such as air-conditioners, household batteries can reduce the feeder voltage profile variation by as much as 2% to 8.5%. This significantly ameliorates outside limit voltage excursions (the limits are set to +10% and -6%). With high PV-penetration, voltage violations could be similarly mitigated by charging the batteries during high PV generation periods rather than in the morning.
- A large penetration of household batteries can enable a flatter voltage profile to be achieved in the low voltage distribution feeder under high rooftop solar generation, provided that the battery charging regime is coordinated with the solar production. Quasi-dynamic simulation models showed that this could reduce overvoltage limit excursion at the solar illumination peak (midday) by lowering the worst-case feeder voltage by 3% on average. This enables the voltage gradient across the feeder to be minimised which increases the hosting capacity for distributed energy resources.
- Household battery integration was shown to alleviate the per-phase voltage limit and unbalance factor violations that would otherwise be associated with unbalanced residential rooftop PV connections alone. For example, the simulation models showed that a power unbalance equivalent to 20% of the distribution transformer rating could be tolerated without exceeding the 2% voltage unbalance factor limit.

Household batteries may need some level of orchestration.

- On hot days (i.e. temperatures greater than 35˚C) approximately 79% of households with batteries showed a considerably larger export peak (approximately double) compared to customers with rooftop solar PV systems only, which can result in upper limit voltage violation events on the distribution feeder. This is most likely a consequence of household battery installations being associated with higher capacity rooftop PV systems, and the associated fast charging of the battery before midday. Introducing an incentive to slow-charge the battery could be further investigated as a solution to this problem.
- Customers at the end of LV distribution feeders may experience large voltage excursions resulting from PV import from other households and/or charging and discharging patterns of the other household batteries. These customers may be prioritised in offering battery incentives.
- Unbalanced simulation models showed the ability of household batteries to improve the voltage unbalance factor in distribution networks that contain significant imbalance of customer connections across the phases can be constrained by the thermal ratings of the upstream transformers. This inhibits the coordination of battery charging regimes under heavier loading scenarios to mitigate the unbalanced feeder loading. The simplest strategy to address this problem is for the DNSPs to balance customer connection points, or alternatively to establish special time-of-use pricing strategies for household batteries.
- The magnitude of the voltage variation in feeders due to solar and battery installations is strongly coupled to the feeder cable impedance properties. As such different profiles tend to be observed for underground (used in urban/semi-urban) or overhead (used in semi-urban and rural) cables. Hence the impact of household batteries on distribution networks is significantly affected by the region where the feeder is located.

Recommendations

1. Tariffs structures may need to be designed to account for the charging and discharging behaviours of battery systems which adversely impact the network voltage profile. For example, battery discharge is strongly encouraged during the evening peak hours (6 – 10 pm) and battery charging is encouraged where the solar-PV systems generate high solar power (12 – 4 pm in summer months). The charging of batteries can be discouraged by introducing a special tariff or a time-of-use pricing strategy. This will also allow higher levels of battery penetration to be achieved.
2. A rebate can be introduced to encourage slow charging, especially during hot summer days. This may reduce midday power exports to the grid, and thus minimise the voltage rise issues identified. Similarly, tariff structures may need to be designed to encourage specific charging and discharging regimes for household batteries which could improve the network voltage profile. For example, the battery owners could be rewarded if they help to maintain the feeder voltage profile within the limits specified in IEC60038 (i.e., -6% to 10%).
3. The end points of distribution feeders must be properly managed to avoid large voltage variations, in particular for long distribution feeders. Larger battery installations at the end point of the feeder would be beneficial to avoid such large voltage variations at these locations.
4. Special Tariff/Time-of-Use (TOU) pricing for Battery Charging: The implementation of a battery controller to facilitate the charging of household batteries during the afternoon PV-export period (and discharging batteries during evening peak consumption), will help to resolve several DER problems locally to avoid a negative grid impact and network augmentation.
5. In order to compensate for possible voltage rises that happen because of household PV exports in hot days, aggregate control of batteries in the form of virtual power plant and (three phase) community batteries can be potentially considered. They may also mitigate adverse impact from unpredictable loads, such as EVs, if appropriate control algorithms are applied. In order to have a virtual power plant being effective for voltage control, there should be a high density of batteries in a single feeder. That might not be practical as there are often few batteries within the network of any feeder. Therefore, community batteries could be a viable solution to mitigate voltage rise issue of excess power export from households with large PV systems. It is recommended that these community batteries are installed as the end of feeder network.

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1. Introduction.

Distributed Energy Resources (DERs), such as rooftop Photovoltaics (PV) and batteries, currently have an important role in electricity generation, and their share of the National Electricity Market (NEM) is characterised by an increasing trend over the past decade. According to the Australian PV Institute, there have been over 2.46 million PV installations in Australia as of end of June 2020, and it is increasing. Residential DERs are often behind the meter, i.e. the consumption/generation is managed behind the households' electricity meters. They have introduced some technical challenges to the distribution and transmission networks. Technologies, such as Energy Storage Systems (ESS) and Electric Vehicles (EV), are becoming more popular and will introduce further challenges/opportunities to the grid. Fig. 1.1 shows how DERs are integrated into residential supply network.

With advancements in battery technologies as well as reductions in their costs, the expectation is to have an increased uptake of ESS and EVs in the residential sector. With these storage systems, households can generate about 60-80% of their electricity needs on average and become partially independent from the grid, although all but a tiny minority still need a connection to the grid to be able to operate. Distribution grids have not been originally designed to support significant levels of bi-directional power flow, and they may only tolerate some level of bi-directional power flow. Although batteries are normally considered as compensators in the case of imbalance between generation and consumption, the policy under which they can profitably contribute to the stability and reliability of the power distribution network is still not clear.

In this project we study the impact of batteries on the voltage profile of power distribution grids.

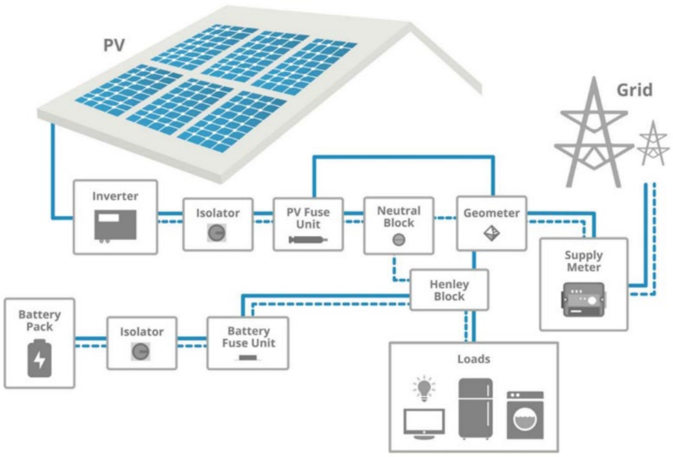

Fig.1.1 Typical schematic of a residential PV and storage system[1].

1.1. Background.

In this section, we provide a brief overview on how batteries may impact different stakeholders including customers, regulators and DNSPs. Here, the focus is to review the relevant literature on three streams: Customer benefits, tariffs and grid stability.

1.1.1. Customer benefit of batteries.

This class of studies mainly focuses on how residential customers can save, or even earn, more from their DERs. The existing techno-economic national and international studies[1-9] show that consumers can save money by adding a battery to their PV system. However, the amount of this saving depends on many other parameters, such as weather conditions and tariff structures. A study in Queensland found that a range of non-financial and financial reinforcing feedback loops, which are currently encouraging battery adoption, would make rapid battery uptake highly likely in coming years[1]. The study found that by 2036, approximately 570,000 batteries would be installed in Australia, exceeding $8 billion of investment and representing 5,444 megawatt hours of capacity[3].

Another study in Queensland showed that the economics of combined PV and battery systems is marginal under current battery prices, i.e. about $1,000 per kWh[4]. Therefore, investing in a residential battery does not bring significant economic benefits to households, unless targeted government rebates are introduced and/or aggregated batteries are used for network operations, e.g. the Frequency Control Ancillary Services (FCAS) market, to benefit households. A study among German residential houses showed that additional policy incentives to foster investments in battery storage for residential PV will only be necessary in the short run[2]. In addition, based on an economic study for different electricity price scenarios from 2013 to 2022, the optimal size of both residential PV and battery storage systems will significantly increase in the future provided that no export constraints are considered.

1.1.2. Tariffs and batteries.

With advancements in battery technologies as well as reductions in their costs, their uptake is likely to increase in coming years. In particular, we are likely to witness exponential growth in uptake of Electric Vehicles, that are indeed large batteries. With these storage systems, households are capable of generating about 60-80% of their electricity needs and become partially independent from the grid. Based on an AEMC report "The economic viability of battery systems is sensitive to region, tariff structure and whether PV is already installed" [3]. The report predicts that the payback periods for large-size residential battery and solar PV systems will reach 6–12 years (around 11 years for Victoria) by 2035 on a time-of-use only tariff and 4-6 years on a flat tariff. Batteries often reduce power import from the gird. This demand reduction will likely increase rates for the rest, as there will be less net consumption from the NEM, putting pressure on the network charge. Indeed, increased penetration of ESS adversely impacts vulnerable consumers who mostly rely on the NEM for their electricity, resulting in higher electricity bills for them. Consumers with PV and battery often have excess power that is exported to the grid. Traditional distribution systems have not been originally designed to fully support export from the consumer end. This means that consumers with a battery/EV will put even more pressure on the distribution networks, contributing to increasing the maintenance cost, and thus higher electricity bills for the others.

Consumers with a PV and battery use the grid facilities less than those without them. However, they still choose to stay connected to the grid to assure they have a reliable electricity 24/7. Studies on different tariff schemes, including dynamic and flat tariffs, have been reported for the cases of Italy[4], Switzerland and Germany[5]. However, the results from these studies are contradictory. For instance, while one research article suggests that a dynamic hourly tariff is the optimal choice for households with batteries[10],

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1 Agnew, Scott (2018). *A study of residential solar power and battery energy storage adoption dynamics*. PhD Thesis, School of Earth and Environmental Sciences, The University of Queensland.https://doi.org/10.14264/uql.2018.173

2 Hoppmann, J., et al., *The economic viability of battery storage for residential solar photovoltaic systems – A review and a simulation model*. Renewable and Sustainable Energy Reviews, 2014. 39: p. 1101-1118.

3 Brinsmead, T.S., Graham, P., Hayward, J., Ratnam, E.L., and Reedman, L. (2015). Future Energy Storage Trends: An Assessment of the Economic Viability, Potential Uptake and Impacts of Electrical Energy Storage on the NEM 2015–2035. CSIRO, Australia. Report No. EP155039.

4 Cucchiella, F., I. D'Adamo, and M. Gastaldi, *Photovoltaic energy systems with battery storage for residential areas: an economic analysis.* Journal of Cleaner Production, 2016. **131**: p. 460-474.

5 Parra, D. and M.K. Patel, *Effect of tariffs on the performance and economic benefits of PV-coupled battery systems.* Applied Energy, 2016. **164**: p. 175-187.

another study proposes a flat tariff to help customers to achieve the highest benefit per kWh of the installed battery[6]. However, Australian tariff structures and consumption profiles are rather different from these countries. A comprehensive data-driven cost-benefit analysis for Australian households is still missing from the literature.

1.1.3. Grid stability impact of batteries.

Integrating batteries into residential PV systems can also be studied from the perspective of the stability of the Low-Voltage (LV) distribution grid. Grid reinforcement is a typical approach applied by DNSPs to increase the amount of power injected by PVs into the grid. However, this may result in increased cost for DNSPs, and thus pushing up the network charges for all customers. Instead, the feed-in power can be limited by storing surplus generation into local battery storage systems using intelligent strategies. For example, consider traditional battery-charging operation, in which the battery is charged whenever there is surplus in PV generation. In solar rich days, the battery is likely to be fully charged around midday leading to heavy feed-in to the grid in the afternoon times. Battery storage control algorithms for limiting the feed-in power have been developed based on chopped feed-in and damped feed-in profiles[7]. A slow charging mechanism optimised to minimise the import to the gird could be solution to this problem. A time-dependant grid feed-in limit has been introduced that optimises the daily operational cost that includes both the energy and the battery degradation costs[8]. However, there are still gaps in applying effective optimisation approaches to battery systems, calling for further research in this area.
Large community battery systems connected to local grids are also alternative options for decentralised batteries in single households[9]. The self-consumption ratio increases using shared instead of individual storage which helps distributors to reduce the stress on the grid[10].

1.2. Aims and objectives.

The main objective of this study is to determine how behind the meter batteries impact the grid by:

1. Studying the consumption behaviour of households with battery systems;
2. Investigating the network impact of household batteries under different scenarios (e.g. peak events, supply constraints, export constraints); and studying the potential benefits of battery systems to households and the network.

The project outcome will provide data-analysis and simulation evidence to inform the Distributed Energy Resources Strategy and Solar Homes Battery program offered by the Victorian Government. It will also help DNSPs to obtain insights regarding the impact of batteries on the network, which may assist planning for the network operators. This will be achieved through the following two actions:

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[6] Pena-Bello, A., et al., *Optimizing PV and grid charging in combined applications to improve the profitability of residential batteries.* Journal of Energy Storage, 2017. **13**: p. 58-72.

[7] Zeh, A. and R. Witzmann, *Operational Strategies for Battery Storage Systems in Low-voltage Distribution Grids to Limit the Feed-in Power of Roof-mounted Solar Power Systems.* Energy Procedia, 2014. **46**: p. 114-123.

[8] Ranaweera, I. and O.-M. Midtgård, *Optimization of operational cost for a grid-supporting PV system with battery storage.* Renewable Energy, 2016. **88**: p. 262-272.

[9] Zeh, A., M. Rau, and R. Witzmann, *Comparison of decentralised and centralised grid-compatible battery storage systems in distribution grids with high PV penetration.* Progress in Photovoltaics: Research and Applications, 2016. **24**(4): p. 496-506.

[10] Luthander, R., et al., *Self-consumption enhancement and peak shaving of residential photovoltaics using storage and curtailment.* Energy, 2016. **112**: p. 221-231.

- A1) Analysing electrical energy consumption (kWh) profiles of customers with a battery system installed in their properties.
- A2) Applying real consumption profiles to a realistic network model to study the impact of battery installations on the distribution network voltage performance.

A1 will derive:

- A comprehensive framework to identify the households with battery systems;
- A detailed analysis of the consumption behaviour of customers with battery systems;
- A comparison of the consumption behaviour of households with a battery with the baselines, i.e. customers with PV but without battery and those without PV;

A2 will derive:

- An assessment of the energy storage hosting capacity for different operating scenarios, consumer loads and PV/battery penetration levels;
- The impact of various levels of energy storage penetration on the DER hosting capacity in a given network;
- The impact of various levels of energy storage penetration on the distribution grid voltage profile and voltage unbalance.

1.3. Datasets.

Data was obtained from approximately 2200 Victorian residential customers with batteries installed in their properties. These customers belong to Powercor, Jemena, AusNet Services, Origin and AGL:

Distributor	Number of customers	Period of time
Powercor	1130	01/05/2019 – 30/04/2020
Jemena	846	01/07/2018 – 30/06/2019
AusNet Services	321	01/07/2018 – 30/06/2020
Origin	71	01/04/2020 – 31/08/2020
AGL	10	01/09/2019 – 01/09/2020

We have also studied baseline consumption profiles of customers with PV but without a battery and those without PV:

Distributor	Number of customers	Period of time
Powercor	1953 (with PV only)	01/01/2019 – 31/12/2019
Powercor	1044 (without PV)	01/01/2019 – 31/12/2019

Consumption data is in kilo-Watt-hours (kWh) with the resolution of one sample per 30 minutes for each customer. It is worth mentioning that the baseline data belongs to households with controlled loads (e.g. hot water system). This does create a significant bias in the data due to the large increase in night-time consumption. In the study we have used statistical methods to approximate the controlled load consumption so as to remove the effect of the bias. Since the majority of Victorian customers do not possess controlled loads there would be merit in obtaining additional data sets to ensure that the base-line comparison is in fact representative.

1.4. Alignment with C4NET Focus Areas.

This project is aligned with the following C4NET focus areas:

- Harnessing the value of Victoria's comprehensive smart meter coverage and other energy data resources
- Accelerating the uptake of new energy technologies to enhance consumer control over energy use, electricity costs and carbon footprints
- Providing evidence-based input to policy development

2. Methodology.

This project uses real load profiles from customers with a PV/battery, those with PV but without a battery and those without PV. The data is used to, first, conduct an analysis on behaviour of households with a battery, and then, perform data-informed simulations to study the impact of battery installations on the distribution network. The project is composed of two main tasks: data analytics and DIGSILENT Power Factory simulation modelling with realistic settings. Fig. 2.1 shows a schematic of the project workflow.

- **Data Analytics –** Consumer electricity consumption data from Victorian DNSPs (Powercor, Jemena and AusNet Services) are analysed. Consumption profiles of households with a PV and a battery are analysed and benchmarked with load profiles of consumers with PV but without a battery and those without PV. State-of-the-art machine learning tools are used for the data analytics task. This work-package not only provides detailed analysis of the behaviour of customers with a battery prior to installation of the battery and after the battery is installed, but it also provides benchmark load profiles (under different temperature conditions) for the simulation work-package. For a portion of customers, we could identify the first date of battery installation and compared the pre-installation load profiles with those post-installation. Our results show that after the installation of a battery, the peak of energy export and import substantially reduce, as part of the solar energy is used to charge the battery.
- **Balanced Simulations –** Network simulations are conducted using a balanced network LV feeder (the customer load on each phase is the same) to understand the voltage performance and loading profile of the LV feeder for the entire feasible operating range for consumers/prosumers and to set the base line cases for the simulation investigations to follow. Therefore, this simulation will capture scenarios from very high probability to very low probability using a radial distribution feeder to characterise its voltage profile.
- **Unbalanced Simulations –** In this case, networks with a different number of consumers on each phase (phase connection unbalance) are simulated to characterize the impact on voltage unbalance with battery system installations.
- **Quasi Dynamic Simulations** – 24-hour dynamic simulations are conducted with the customer net load profiles extracted from the data analytics phase of the project and the unbalanced network models, to understand the network impact at different times of the day with batteries in customer premises.
- **Network Event Simulations** – Extreme network event simulations have been performed by considering an extreme hot day and assigning an extreme profile for all customers throughout the LV feeder. The voltage profiles over 48 half-hourly intervals have been presented for customers without PV, with PV and with PV + Battery.

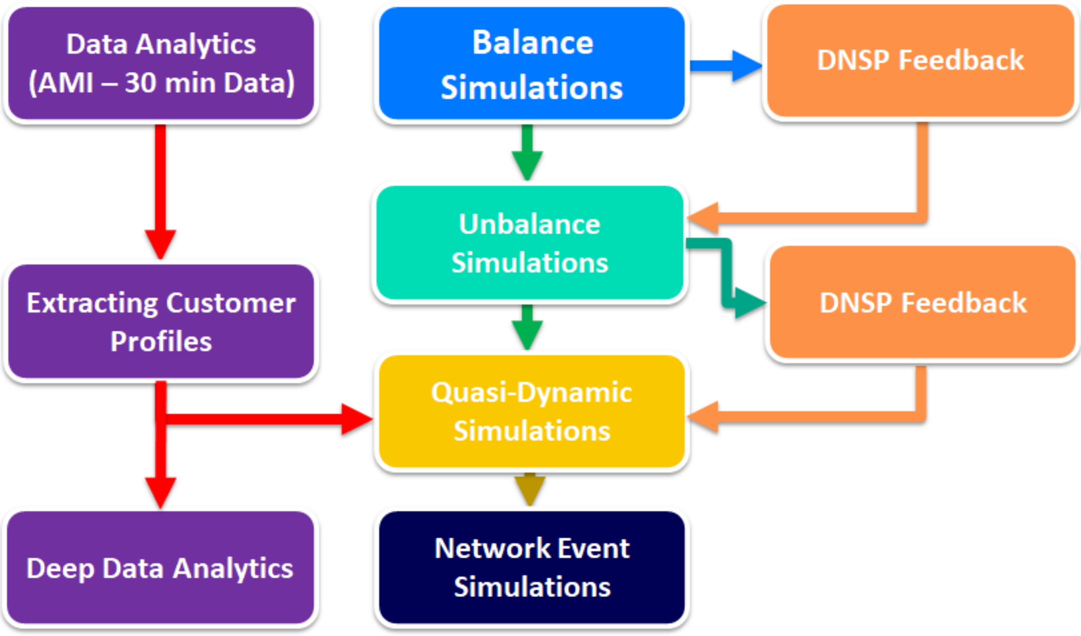


Fig.2.1 - Workflow diagram of the project.

The detailed methodology can be found in the Appendix (section 6.1).

3. Results and Discussion.

This section presents the results and discussion of this study following the methodology presented in Fig. 2.1. The results and discussion are presented under two main sections; 1) Data Analytics, and 2) Network Simulation study. The data analytics section presents the key findings based on analysing the available datasets. The network simulation studies section presents the simulation results of balanced, unbalanced, quasi-dynamic and network event simulation results and discussion.

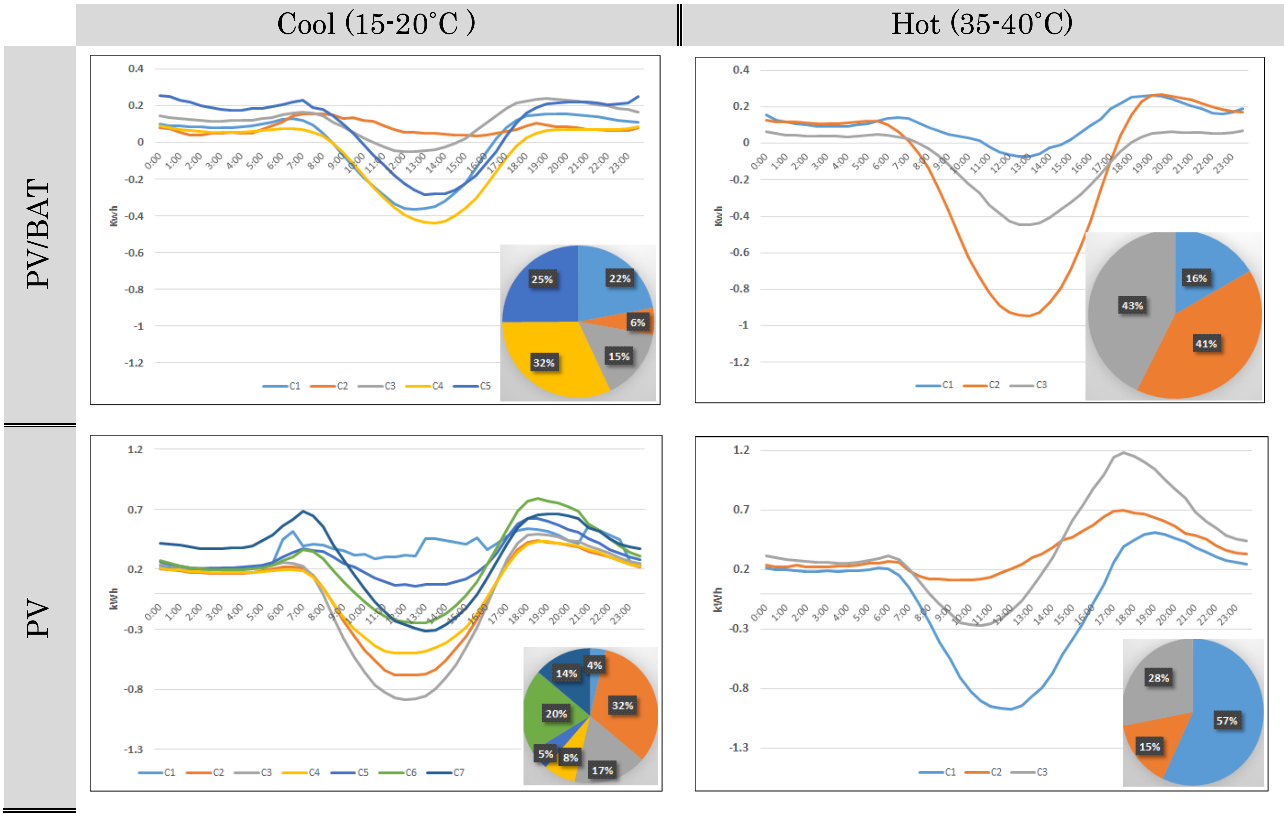
3.1. Data analytics.

Analysis of customer cluster and their average load profiles

As the first experiment, we classify all consumers based on their net electricity consumption in days with different temperatures. Six temperature zones are considered: <15˚C, 15-20˚C, 20-30˚C, 30-35˚C, 35-40˚C and >40˚C. Consumers are classified for their consumptions during weekdays and weekends separately. We show two typical load cluster analyses in cool and hot weekdays with more comprehensive results provided in the appendix. Figures 3.1 and 3.2 show typical cluster analyses for cool and hot days in weekdays and weekends, respectively. Clusters for other temperature zones are provided in the Appendix, section 6.3. In our clustering analysis, the cluster with the largest customer size is denoted by C1, the one with the second largest customer pool is denoted by C2 and so on. For example, the top-left panel of Fig. 3.1. shows that in hot days, PV/BAT customers can be classified in three clusters based on their consumption behaviour. Consumers in the C2 cluster, which are 41% of all customers we studied, export maximum of 1kWh at daily peak time.

Battery installation is expected to result in reduced power exports to the grid. Our analysis shows that battery customers have at least a 20% reduction in export to the grid in peak sun hours during days where the temperature less than 30˚C. This will have a positive impact on mitigating voltage rise due to export of the excess power generated from PVs, and thus increasing the hosting capacity of the networks. However, during hot weekends with higher than 35˚C temperatures, 79% of battery customers showed considerably more power export in the peak sun hours compared to PV customers. This is likely due to higher capacity of rooftop PV systems in battery customers and fast charging of the battery before midday. Some of the retailers confirmed that customers with a battery often increase their PV capacity or install solar PVs with more capacity to offset the low generation in winter. This results in more export to the grid, when the battery is fully charged. A recommendation to address this issue would be to introduce a rebate for slow charging the batteries. PV sizing can also be limited when a request is made for a new PV (and battery) installation.

Generally, adding a battery to a PV system results in a peak reduction in early evening consumption. This reduction is more than 50% on cool days and is reduced as the temperature increases. This peak reduction is not significant during hot days. It seems that customers do not start discharging their batteries in the afternoon times (often the sunset is after 8:30pm on hot summer days), and thus no significant reduction in the afternoon peak consumption is observed. Our recommendation is to implement smarter ways of battery discharging for the benefit of both customers and networks. Targeted incentives (similar to those used in demand response programs) can also be offered to customers to encourage their behavioural change.



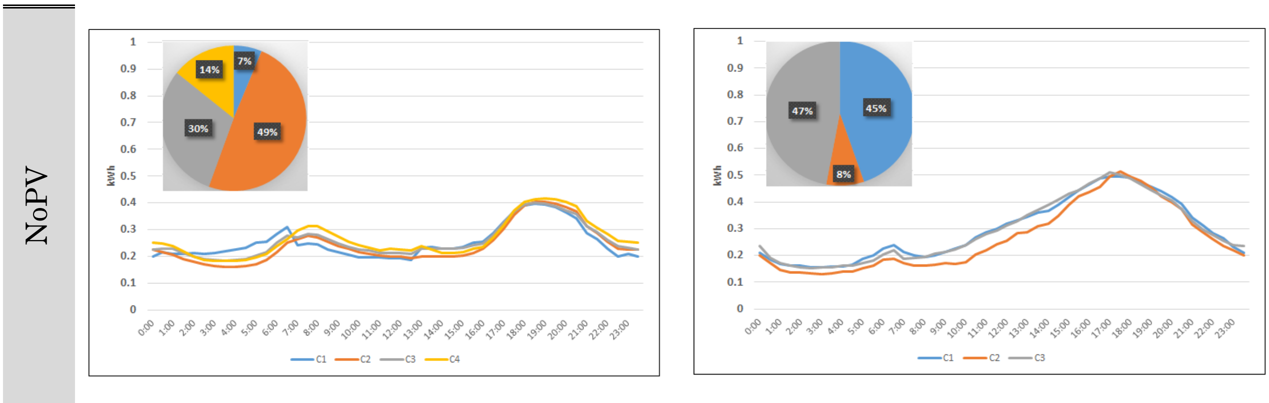


Fig.3.1 - Consumption behaviour of residential customers in cool and hot weekdays.

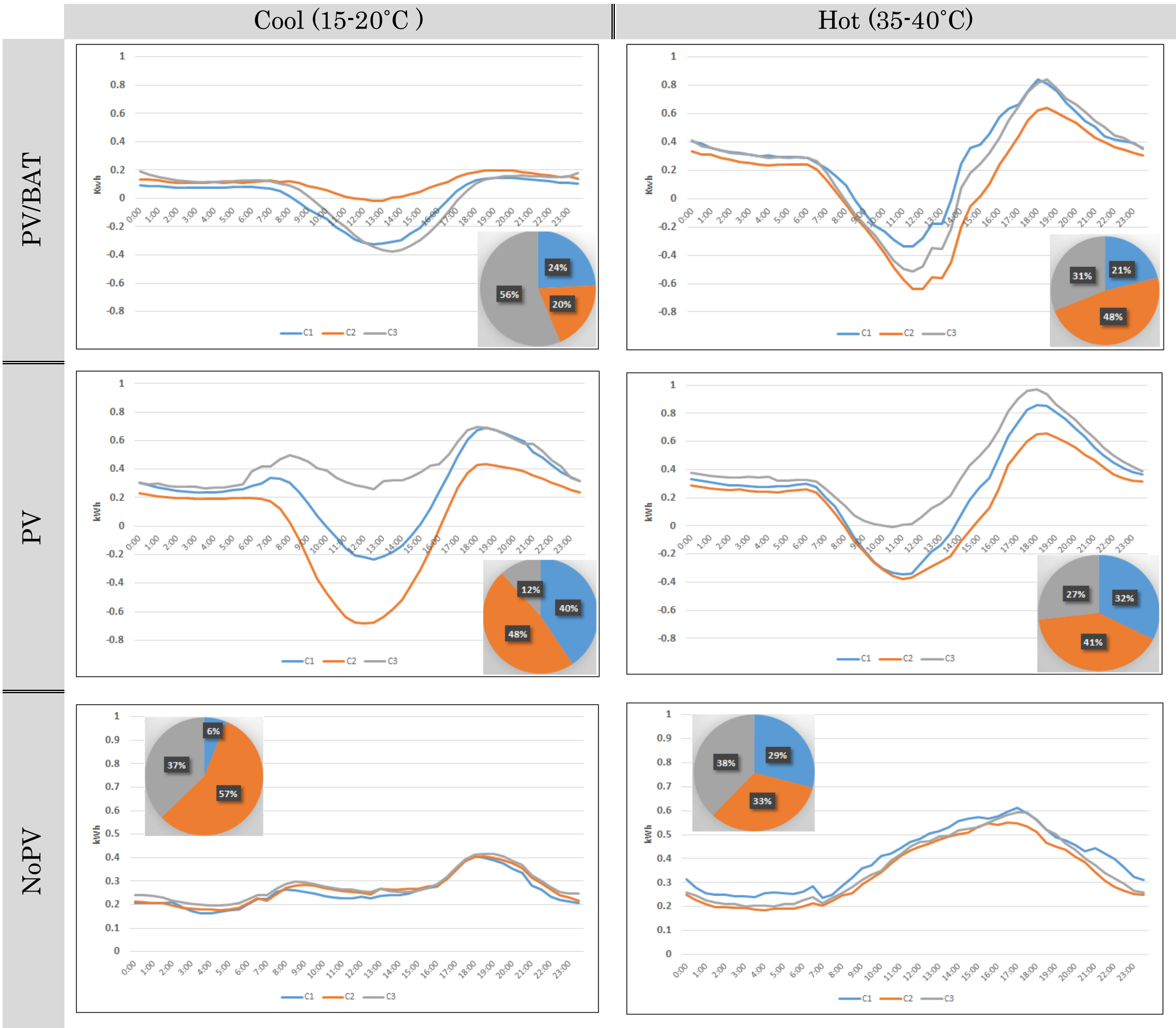


Fig.3.2 - Consumption behaviour of residential customers in cool and hot weekends.

To further analyse the impact of batteries on energy consumption, we compare the net energy consumption/export of battery consumers to those of PV only consumers. Fig. 3.3(A) compares net export of battery and PV customers from May to Dec 2019. It also includes daily averages. It is seen that while battery customers export slightly less than PV customers in winter times (May-Aug), their export is significantly more than PV customers on hot summer days. This is likely due to larger rooftop PV sizes for battery customers. In low-generation days, despite generating more than PV customers, the energy generated from PV cells is largely stored in the battery and the excess generation exported to the grid is less than PV customers. However, on hot summer days, the excess generation in battery customers exported to the grid are significantly more than PV customers. Fig 3.3(B) compares net consumption of all three types of customers. As expected, battery customers save much more than PV and non-PV customers during hot summer days.

Household batteries reduce the evening peak by at least 60%.

To further analyse the above observation, we plot the average net consumption in typical cold and hot days in Figs 3.4. An interesting phenomenon observed in the analysis is that while batteries generally help to flatten the afternoon peak during hot days, battery customers export more during midday. This is likely because of fast charging of the battery where it is fully charged well before midday, resulting in more export to the grid as compared to PV only customers. This may lead to severe voltage rise for such cases. A solution could be to introduce an incentive for slow charging to change the customer behaviour.

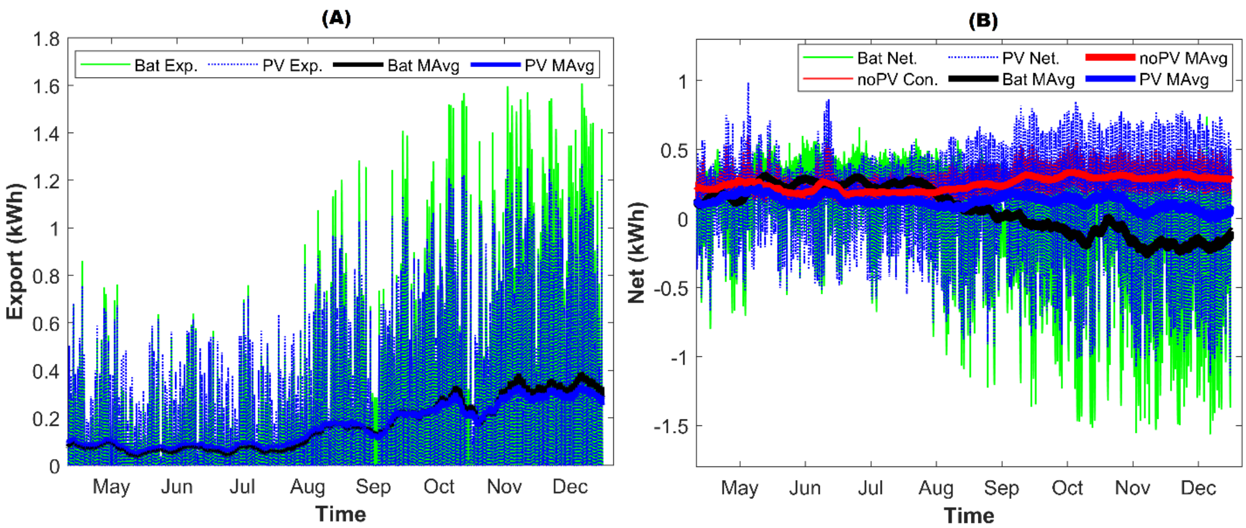


Fig.3.3 - (A) Energy export of Battery and PV consumers, (B) Net energy consumption of Battery, PV and NoPV consumers, between May and Dec 2019. MAvg indicates daily average export.

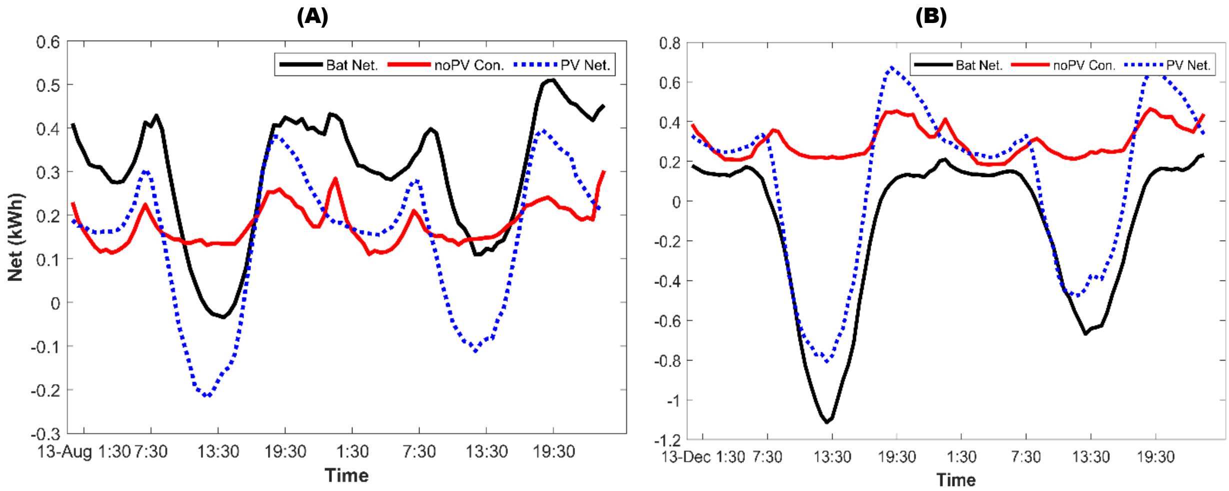


Fig.3.4 – A 2-day snapshot of energy consumption (A) starting from 2/8/2019 00:00 (cold season) and (B) starting form 13/12/2019 0:00 (hot season).

Analysis of customers with battery system controlled by retailer

We analysed two sets of data for customers for which their battery system was controlled by a retailer (Virtual Power Plant Trials). We have not been given details of the trials and their target. Our analysis is solely based on the observations made from the data. The first data (71 customers) can be segregated into three distinct clusters (Fig. 3.5A). A small cluster of 6 customers shows a different charging behaviour where batteries reach their maximum state of charge in the early morning (charging in night-time). The other two clusters reach their maximum state of charge at around 14:00, which seems to be an optimal time for a typical winter day. However, batteries are charged to about 70%-85% of their full capacity in almost all cases (Fig. 3.5B). This could be because of the winter period and a lack of sufficient PV generation to achieve a full state of charge.

The battery control algorithm should be precise enough to keep feeder voltages within the permissible range all the time.

The second dataset for controlled batteries that was provided included more operational details such as voltage data. Our analysis shows that voltages for these consumers are always close to the high acceptable voltage threshold and indeed violating this limit at times (Fig. 3.6). The voltage rise happens in almost all temperature bands, but less in higher temperatures. It is likely that better control over charging/discharging is made during hot days. It is highly likely that these households will almost certainly experience worse voltage rise events without the mitigating effects of the battery. However, as this is for a virtual power plant trial, further details are required to make a detailed analysis on the battery impact on the network voltage profiles.

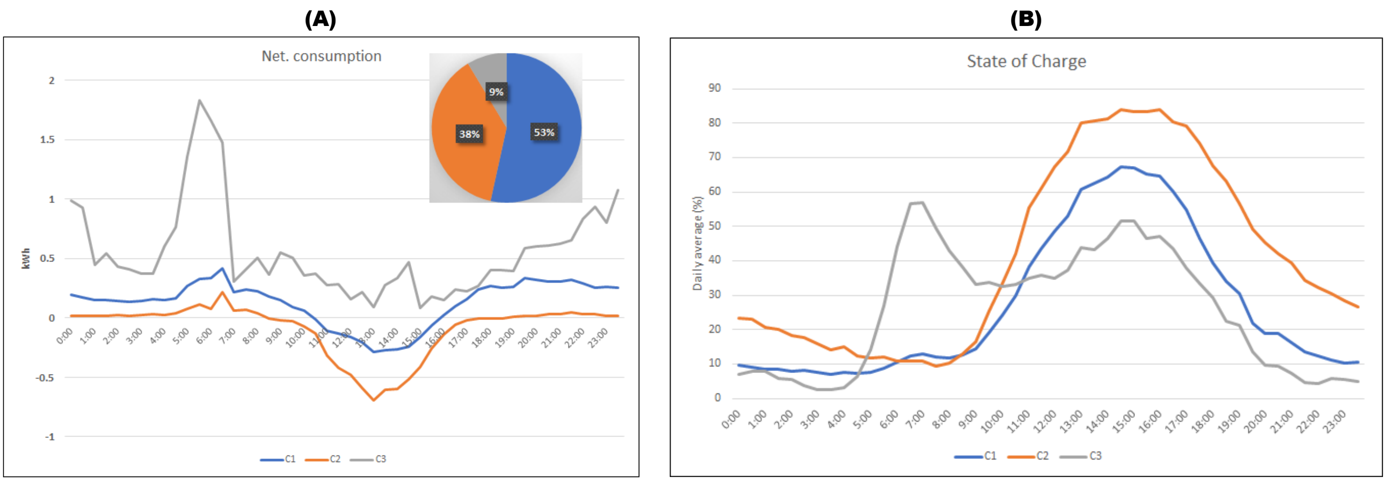


Fig.3.5 – (A) Average network consumption profiles of customers in three distinct clusters. (B) Average state of charge of batteries for customers belongings to the three clusters. The data includes information of 71 customers in winter-time for a controlled-battery program.

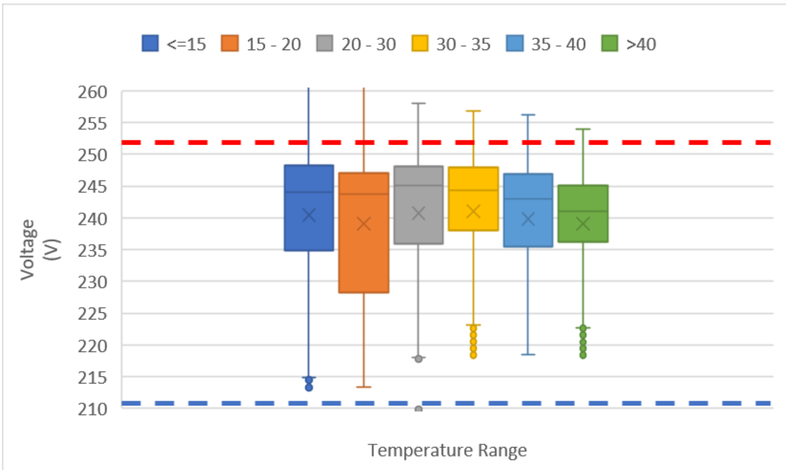


Fig.3.6 – Variation of voltage in consumers with battery over days with different temperatures. The data includes information of 10 customers for a controlled-battery program.

3.2. Network simulation studies

This section details the simulation results and discussion conducted on four different types of network simulation studies conducted in this project. The balanced and unbalanced network simulations are carried out based on the typically accepted load demand values for the distribution feeder (low, medium and high), solar-PV and battery sizes. Then the quasi dynamic and network event simulations are conducted using the net load profiles extracted from the data analytic studies for the different consumer clusters.

3.2.1. Balanced Network Simulation Study

The balanced network simulations are carried out to characterise the feeder voltage performance under ideal balanced network conditions. Therefore, customer connections and loads are assumed to be equally distributed among three phases. The following configuration (Fig. 3.7) is assumed for a customer having a solar-PV and a battery system:

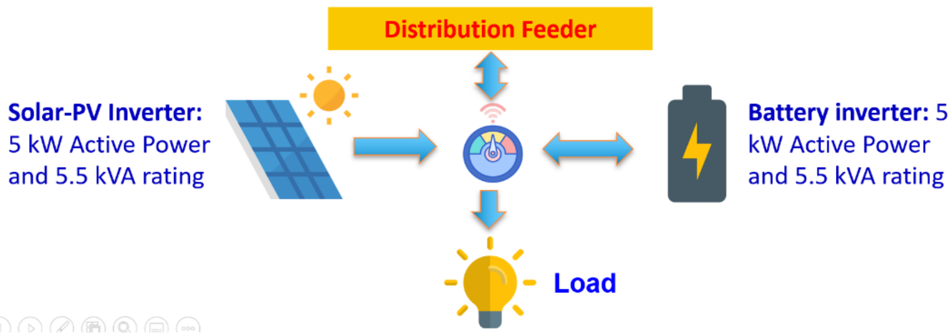


Fig.3.7 - Internal configuration for each customer

- Three load scenarios are considered: 1.8 kW, 3.4 kW, and 8.4 kW, representing average low load, medium load and average high load, respectively, for LV connected customers[11]. In addition, it is assumed that each customer is operating at 0.95 lagging power factor:

Table 3.5 - Active power and reactive power of each customer

Active power	Power factor (pf)	Reactive power
Low load: 1.8 kW	0.95 lagging	0.59 kVAr
Medium load: 3.4 kW	0.95 lagging	1.12 kVAr
Heavy load: 8.4 kW	0.95 lagging	2.76 kVAr

- The following battery and solar-PV system sizes are assumed for a customer connected to the feeder, which represent the commonly installed solar-PV and battery energy storage system sizes in domestic households[12]:
  - **Solar-PV:** 5 kW Active Power Rating and 5.5 kVA inverter
  - **Battery:** 5 kW Active Power and 5.5 kVA inverter
- The following operating scenarios are considered for battering and solar-PV systems:

Table 3.6 - Operating Scenarios for Batteries and PV

Scenario No:	Battery Charging		Battery Discharging	
	PV (kW)	Battery (kW)	PV (kW)	Battery (kW)
Scenario 1	5	-5		
Scenario 2	1	-5		
Scenario 3			0	5
Scenario 4			1	5

The following sub-sections discuss the results obtained for the balanced network simulation studies for two different integration scenarios:

- **Integration Scenario (IS1):** 25% of households have PVs and 33% of them have a battery
- **Integration Scenario (IS4):** All Customers have Batteries and PV

The results of the integration scenarios 2 and 3 are provided in the Appendix.

IS1: 25% of households have PVs and 33% of them have a battery.

Three load scenarios are simulated under these load conditions (e.g., 1.8 kW, 3.4 kW, 8.4 kW), considering operating scenarios listed in Table 3.6 for solar-PV and battery systems at each household. It is also

[11] The low, medium and high load for customers have been confirmed by Jemena.

[12] The typical solar-PV and battery sizes were determined based on the clean energy council report available at https://www.cleanenergycouncil.org.au/.

assumed that all households in the feeder have the same load and operating scenarios[13]. The solar-PV and battery locations for IS1 are shown in Fig. 3.8.

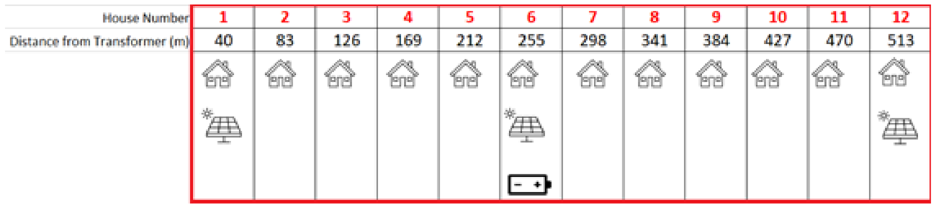


Fig. 3.8 - The solar-PV and battery locations for IS1 for an individual phase.

The voltage profiles for low load scenarios (1.8 kW) are shown in Fig. 3.9.

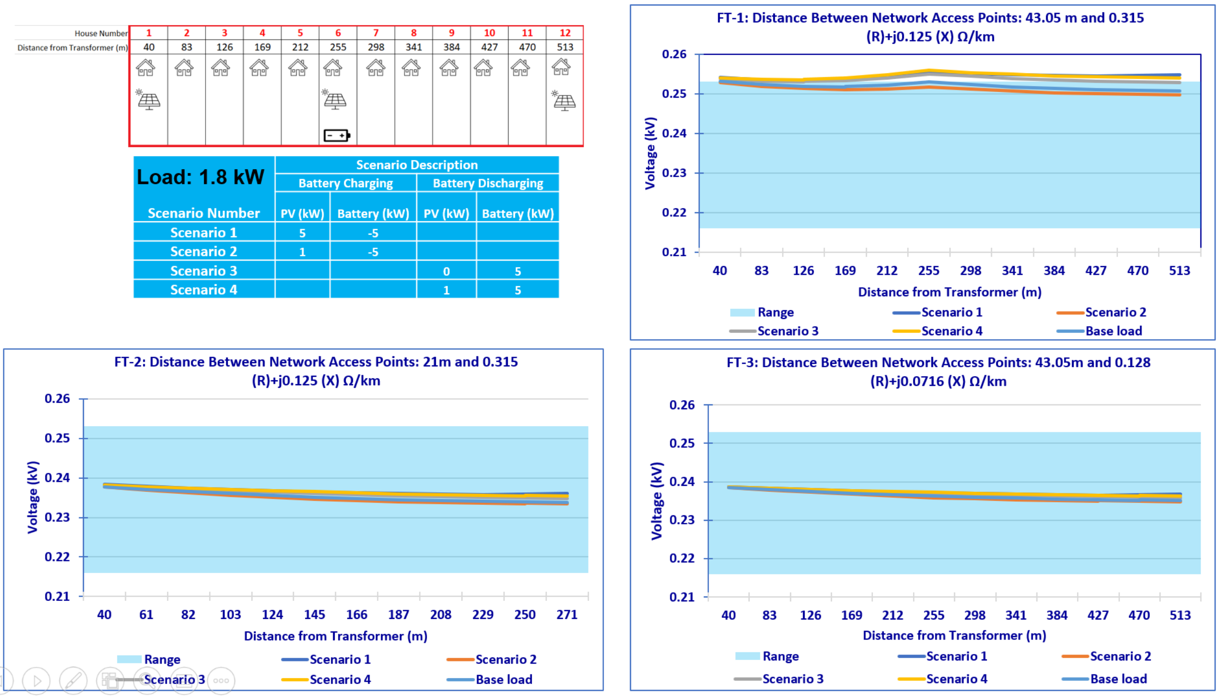
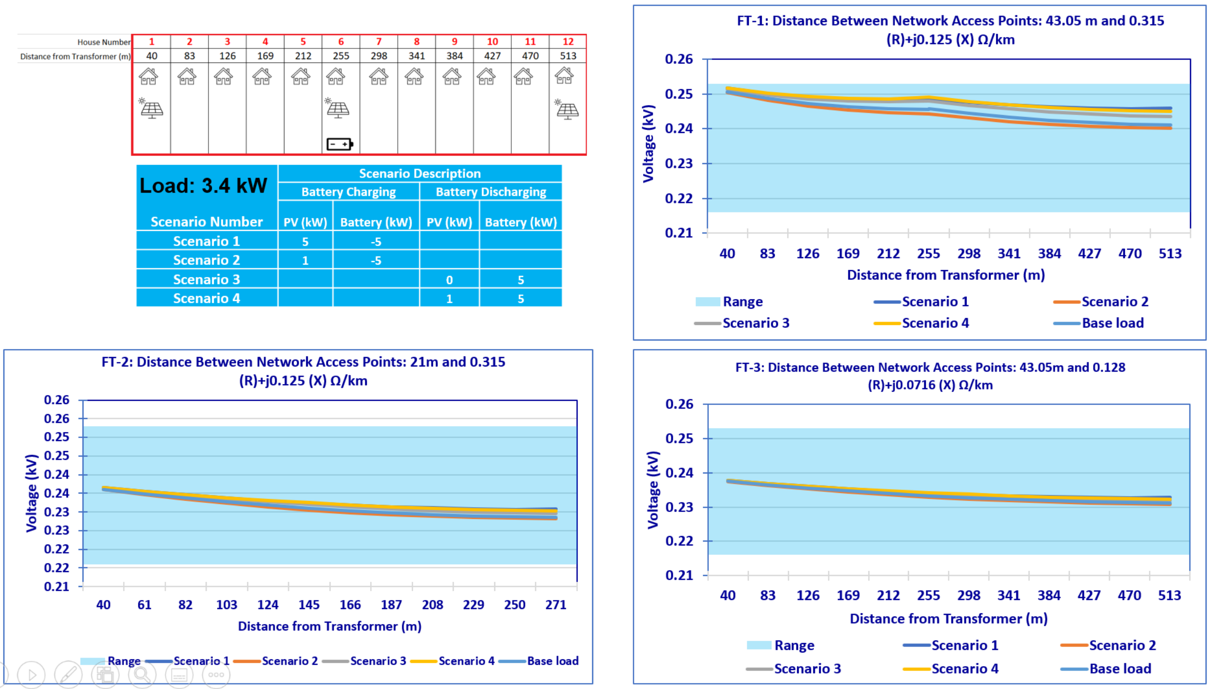


Fig. 3.9. The voltage profiles for low load scenarios (customer load 1.8 kW).

According to Fig. 3.9, the LV feeder voltage profiles stay within the voltage limits stipulated in IEC60038 for all operating scenarios. However, the voltage gradient along the feeder is different for each feeder type (i.e., FT-1 to FT-3) and it is slightly affected due to the battery charging and discharging regimes. It must be noted that only one battery per phase is considered here. For example, the worst voltage gradient between the two ends of the feeder for FT-1 is around 2.60% while the worst voltage gradient is around 1.74% for FT-3. The voltage profiles for medium load scenarios (3.4 kW) are shown in Fig. 3.10.

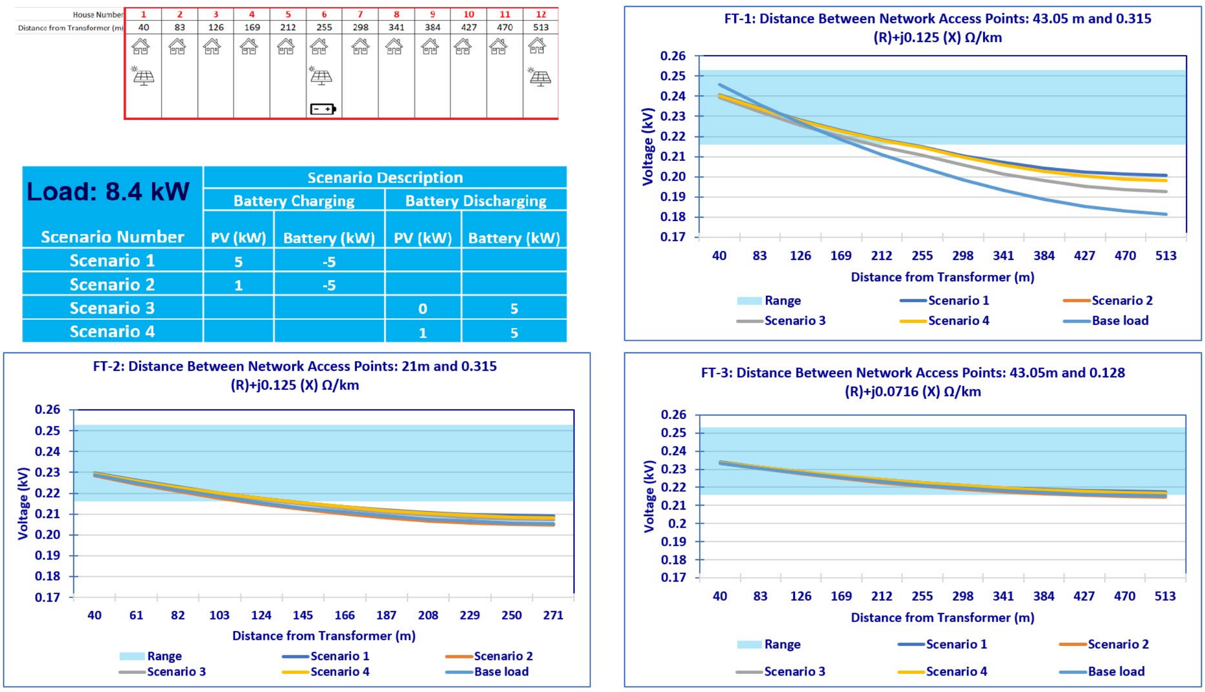
[13] Different net load profiles are considered in quasi-dynamic simulations, hence variation between different customers are not considered in balance simulations.



Load: 3.4 kW	Scenario Description			
	Battery Charging		Battery Discharging	
Scenario Number	PV (kW)	Battery (kW)	PV (kW)	Battery (kW)
Scenario 1	5	-5		
Scenario 2	1	-5		
Scenario 3			0	5
Scenario 4			1	5

Fig. 3.10. The voltage profiles for low load scenarios (customer load 3.4 kW).

The results in Fig. 3.10 are similar to Fig. 3.9 for the medium load (3.4 kW) scenario, except that the voltage gradients are higher with medium voltage scenarios. For example, for FT-3 with the 1.8 kW load the voltage gradient is 1.74% and that has been increased to 3.5% with 3.8 kW. This indicates the sensitivity of PV and battery operating scenarios with the customer load. The voltage profiles for medium load scenarios (8.4 kW) are shown in Fig. 3.11, which is a very low probability and high impact scenario.



Load: 8.4 kW	Scenario Description			
	Battery Charging		Battery Discharging	
Scenario Number	PV (kW)	Battery (kW)	PV (kW)	Battery (kW)
Scenario 1	5	-5		
Scenario 2	1	-5		
Scenario 3			0	5
Scenario 4			1	5

Fig. 3.11. The voltage profiles for low load scenarios (customer load 8.4 kW).

According to Fig. 3.11, when the high load is considered for each consumer the lower voltage limited has been breached by each feeder configuration. However, battery discharge has assisted to improve the voltage profile (2 – 8.5% improvement).

IS4: All Customers have Batteries and PV.

The solar-PV and battery locations for IS4 are shown in Fig. 3.12.

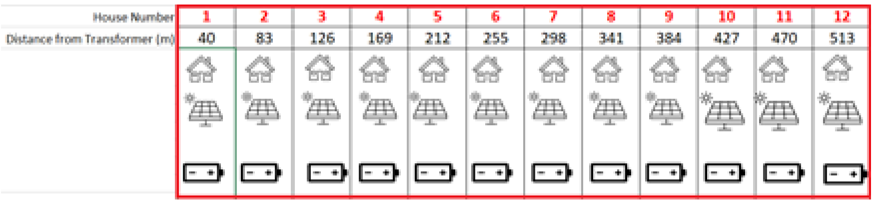
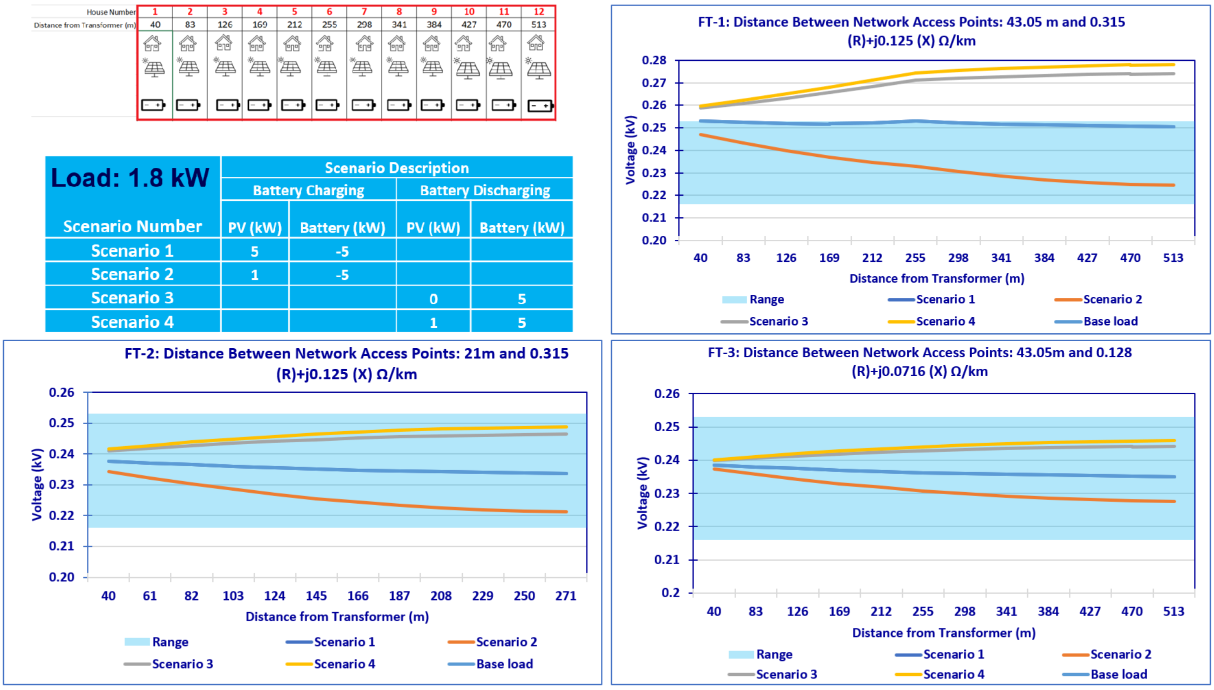


Fig. 3.12. The solar-PV and battery locations for IS4 for an individual phase.

The results shown in Fig. 3.11 present the cases where the internal load of each household is 1.8 kW. Comparing Fig. 3.13 (A), (B) and (C), the feeder voltage profile is heavily affected based on the feeder type (underground or overhead feeder). It may result in voltages higher than the acceptable range (i.e., 253 V) in the distribution networks with overhead lines when the batteries are discharged under low load conditions.



Load: 1.8 kW	Scenario Description			
	Battery Charging		Battery Discharging	
Scenario Number	PV (kW)	Battery (kW)	PV (kW)	Battery (kW)
Scenario 1	5	-5		
Scenario 2	1	-5		
Scenario 3			0	5
Scenario 4			1	5

Fig. 3.13. The voltage profiles for low load scenarios (customer load 1.8 kW).

The voltage profiles for low load scenarios (3.4 kW) are shown in Fig. 3.14.

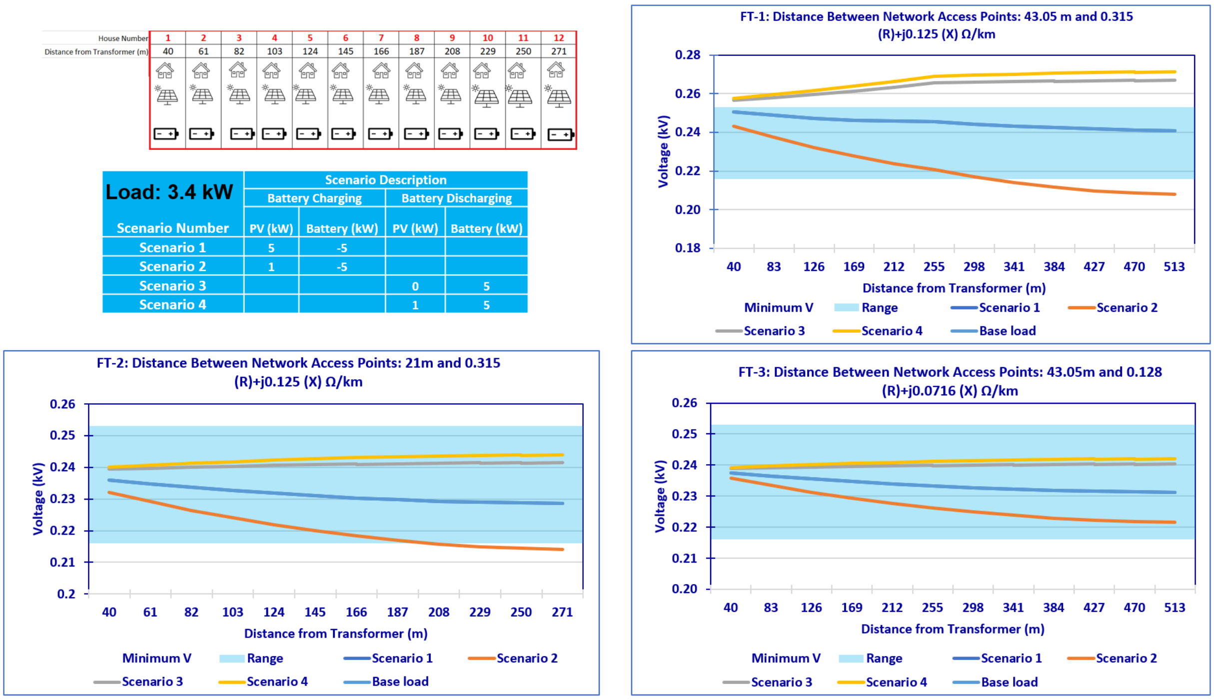


Fig. 3.14. The voltage profiles for low load scenarios (customer load 3.4 kW)

According to Fig. 3.14, the voltage profiles are significantly affected by the feeder characteristics and the battery operational scenarios. However, the gradients are much higher for net import scenarios and the gradients are reduced for net export scenarios when compared with Fig. 3.13. The voltage profiles for low load scenarios (8.4 kW) are shown in Fig. 3.15.

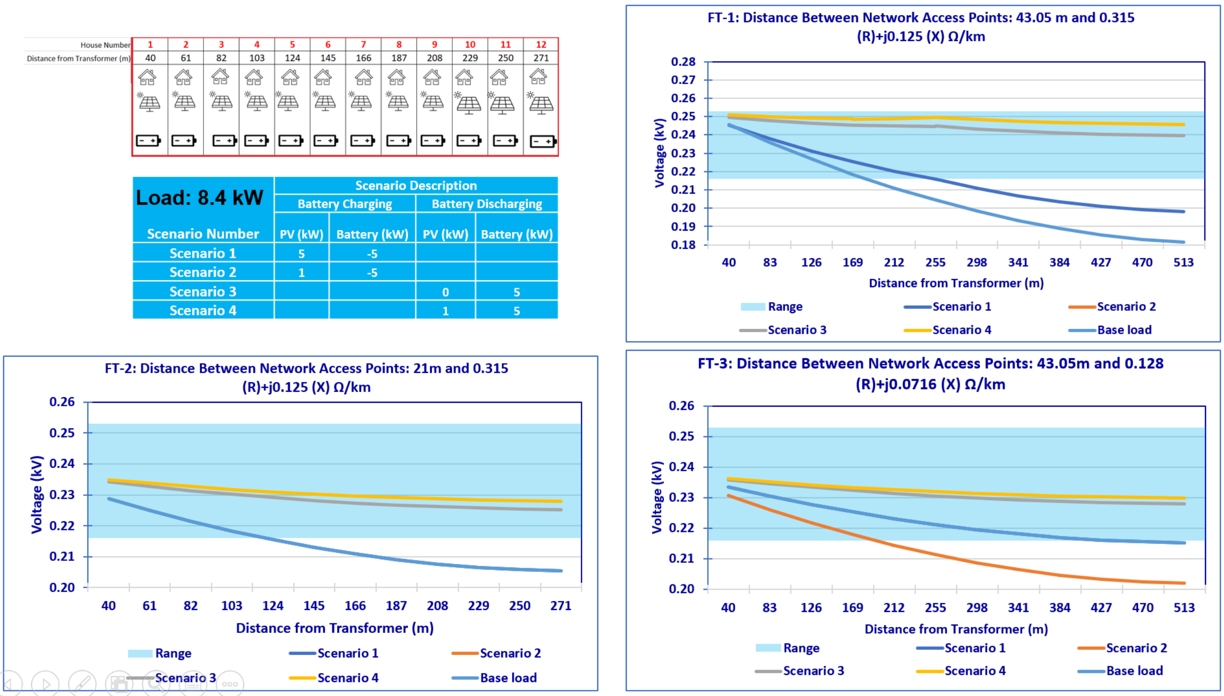


Fig. 3.15. The voltage profiles for low load scenarios (customer load 8.4 kW)

According to Fig. 3.15, when the load at each household is increased to 8.4 kW the feeder voltages remain within the acceptable voltage range for battery discharging scenarios, but not for the battery charging scenarios, where the lower voltage limits have been violated when the batteries are charged high load conditions. Therefore, the impact on the LV feeder voltage due to battery charging and discharging depends on the consumer load at a given time instance.

The entire voltage profiles for the feeder configuration-3 (FT-3: Distance Between Network Access Points: 43.05m and 0.128 (R)+j0.0716 (X) Ω/km) for all integration scenarios are illustrated in Fig. 3.16. The vertical-axis represents the net-load at customers who have PVs and batteries at their premises. According to Fig. 3.16, when the network has low penetration of solar-PV and battery systems, the voltages violations mostly occur at the lower voltage limit (216.2 V). When the solar-PV and battery system penetration increases, voltage violations have been recorded both at both high and low limits stipulated in IEC IEC60038. However, the probability of occurrence of such adverse conditions are extremely low for a LV feeder. In terms of the medium net load case (e.g. 3.4 kW, which is the most probable scenario for the LV feeder), the voltage profiles are varied between 230 – 238 V, indicating less impact caused by batteries. Batteries have also assisted to mitigate adverse effects caused by high load and high PV penetration levels, by assisting to maintain the voltage profile within standard limits. The customers at the end points of the feeder were shown to have high sensitivities towards the net-load, for example, the customer located closer to the transformer (i.e., 40 m), experiences a voltage variation of 9.5 V for the net-load variation from 12.4 kW to – 4.2 kW, whereas the voltage variation at the end of the feeder (i.e., 513 m) is 44 V for the same net-load variation.

High battery penetration with PV installations could flatten the voltage profile in the LV feeder under high PV generation.

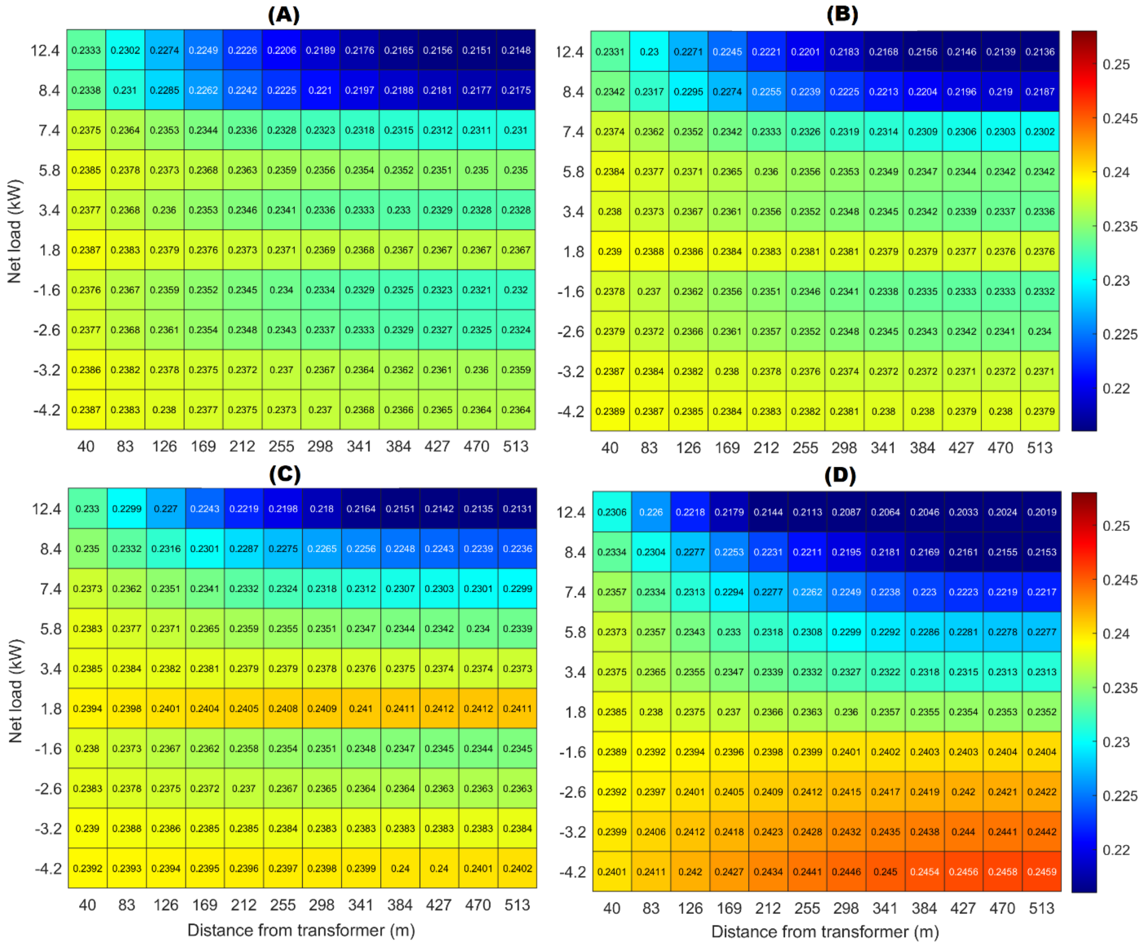


Fig. 3.16 - Balanced simulation results summary– (A) IS1, (B) IS2, (C) IS3 and (D) IS4.

Balanced Simulation Study Conclusions:

Key conclusions of this balanced network study can be summarised as:

- High battery penetration with PV could assist to flatten the voltage profile in the LV feeder under high PV production, hence the voltage gradient along the feeder could be minimised.
- The LV feeder voltage profile is significantly affected by the impedance characteristics of the LV feeder (Underground Feeder (FT-3) vs Overhead Feeder (FT-1)).
- Battery discharge under low load scenarios is likely to cause violations in the upper limit of the voltage (1.1 pu or 253 V), however at high load conditions battery discharge could assist to mitigate these upper voltage violations. Battery charging at high load conditions violate the network lower voltage limit and impact is more when more batteries are installed in the network.
- High battery penetration with PV could assist to flatten the voltage profile in the LV feeder under high PV production if the battery charging is coordinated with the PV production, hence the voltage gradient along the feeder could be minimised.
- The LV feeder end point voltages are more sensitive towards net-load variations at the customer premises, hence the customers at the end points of the feeder could experience large voltage variations during charging and discharging of their batteries.

Balanced Simulation Study Recommendations:

- Tariff structures may need to be designed to account for the charging and discharging behaviours of battery systems which adversely impact the network voltage profile. For example, battery discharge is strongly encouraged during the evening peak hours (6 – 10 pm) and battery charging is encouraged where the solar-PV systems generates high solar power (12 – 4 pm in summer months).

- Similarly, tariff structures may need to be designed to encourage charging and discharging of batteries which could improve the network voltage profile. For example, the battery owners could be rewarded if they maintain the voltage profile within the limits specified in IEC60038 (i.e., -6% to 10%).
- Coordinated battery charging and discharging (based on voltage) will make a positive effect on the distribution feeder, hence such capabilities may need to be built into the battery operating algorithms.
- Battery rebate schemes may need to be designed considering the location of customers (urban, semi-urban, rural), as the feeder characteristics determine the potential impact and benefits of battery installations.
- The end points of the feeder should be properly managed to avoid large voltage variations, in particular for long distribution feeders. Larger battery installations at the end point of the feeder would be beneficial to avoid such large voltage variations at these locations.

Battery installations at the end point of the LV feeders would be beneficial to avoid large voltage variations.

3.2.2. Unbalanced Simulation Study.

Following the balanced network simulation study, further studies have been carried out considering unbalanced LV network models to assess the impact of battery system installations on the network Voltage Unbalance Factor (VUF). The primary results are presented in this section while additional supporting results are provided within the Appendix, section 6.2.

3.2.2.1. Analysis of Typical Distribution Network

The typical distribution network used for the unbalanced study is shown in Fig. 3.17 where the number of customers with a battery are 24 (out of total 36), 36(out of total 54), and 48(out of total 72), and they are adjusted by using the scaling factor SF=1, 1.5 and 2, respectively. The maximum feeder length in this network is 258m.

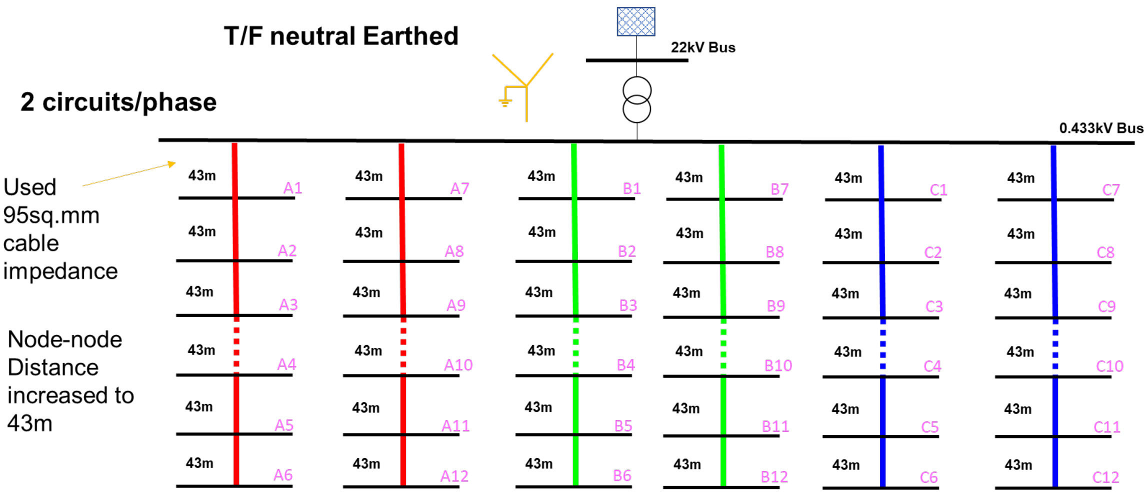


Fig. 3.17 - Revised Model "Typical Network B"

Battery discharging scenarios.

The simulation results for the battery unbalanced Integration & Operational Scenario “PV100_B66_UB12.8.4” are shown in Fig. 3.18. In this scenario, the battery power unbalance ratio between consecutive phases is 12:08:04 with SF=1, 18:12:08 with SF=1.5 and 24:16:08 with SF=2, and respectively, the battery penetration level is 24%, 36%, and 48% of the transformer rating i.e., 500kVA or 400kW.

The results show that,

- The voltage unbalance factor (VUF) for the battery discharging scenario is less than with the charging scenario.
- The VUF is 0.98%, 1.27% and 1.54% at the far end in the LV feeder (T6/T12) and is 0.51%, 0.67% and 0.82% at the start of the LV feeder (433V bus) for the power imbalance of 40kW, 58kW and 76kW, respectively.
- Every **10kW** of battery power imbalance can cause a VUF of ~**0.16%** at T6/T12 and **0.09%** at the 433V bus, as shown in Fig. 3.19.

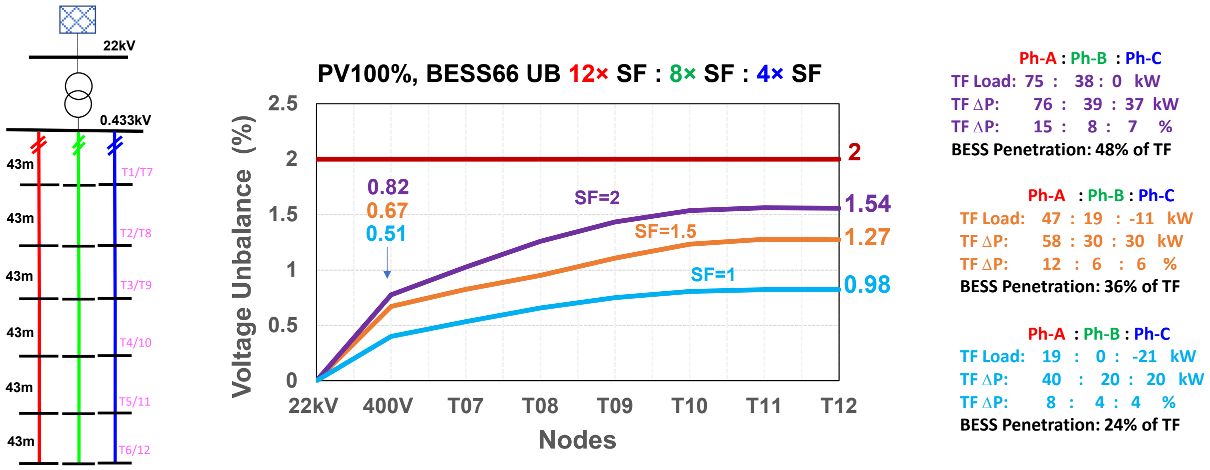


Fig. 3.18 - Unbalanced Simulation Results for IS: PV100% battery 66% UB 12:08:04 and OS: battery discharging

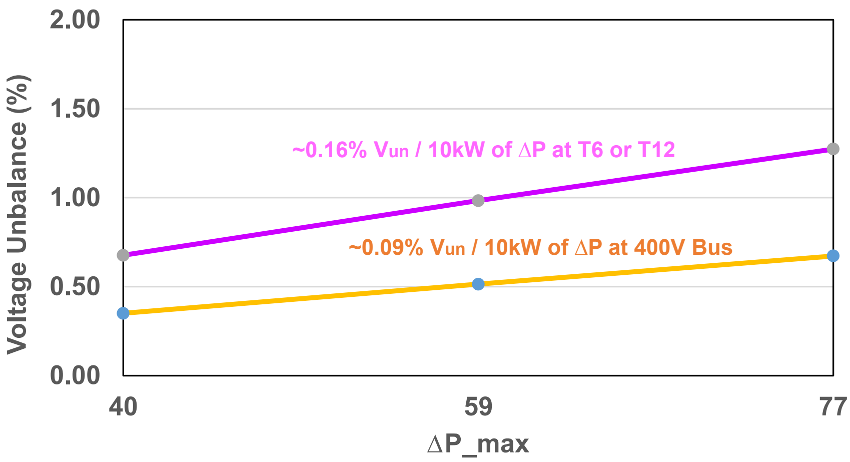


Fig. 3.19 - Unbalanced Simulation Results for IS: PV100% battery 66% UB 12:08:04 and OS: battery discharging.

In addition to the above results, the Integration and Operational scenarios listed in Table 3.7 are simulated to analyse the VUF in the network and results for all these scenarios are given in the Appendix. The results obtained from these scenarios are used to characterise the general behaviour of the considered distribution network. It is concluded that:

- Every **10kW** of battery power imbalance can cause a VUF of **0.16-0.19%** for the most probable Operational Scenario – batteries discharging.
- Every **10kW** of battery power imbalance can cause a VUF of **0.18-0.22%** for a less probable worst-case Operational Scenario – all batteries charging from the grid.

TABLE 3.7 - INTEGRATION AND OPERATIONAL SCENARIOS FOR UNBALANCE SIMULATION STUDY

Integration Scenario (IS)					Operational Scenario (OS)
No.		Number of Customers with Battery Scaling Factor SF=1, 1.5 and 2			
		Ph-A	Ph-B	Ph-C	
1	PV100_B66_UB12.8.4	12× SF	8× SF	4× SF	OS2: Charging
2	PV100_B66_UB12.9.3	12× SF	9× SF	3× SF	
3	PV100_B50_UB11.5.2	11× SF	5× SF	2× SF	
4	PV100_B50_UB11.4.3	11× SF	4× SF	3× SF	
5	PV100_B66_UB12.8.4	12× SF	8× SF	4× SF	OS3: Discharging
6	PV100_B66_UB12.9.3	12× SF	9× SF	3× SF	
7	PV100_B50_UB11.5.2	11× SF	5× SF	2× SF	
8	PV100_B50_UB11.4.3	11× SF	4× SF	3× SF	

Summary of Results

The %VUF verses power imbalance (ΔP) characteristics of the considered typical distribution network suggest that the battery power imbalance of ΔP=100kW (25% of Transformer rating) will create 2% VUF at the far end in LV feeder/network. This maximum level of power imbalance can be allowed if there is no voltage unbalance in the upstream MV network. The allowable battery power imbalance reduces to 80kW (20% of transformer rating) after considering a 0.5% voltage unbalance in the MV network.

The battery power imbalance of ΔP=80kW, i.e., 140kW on Phase A and 60kW on Phase B or C, is significant for the given 500kVA transformer and this level of power imbalance may happen when the customers' connections on the distribution feeder are highly unbalanced.

Household battery integration can alleviate the per-phase voltage limit and unbalance factor violations.

In summary, the VUF limit is less likely to be violated due to the battery power imbalance for practical Integration and Operational Scenarios unless the customers' connections on phases are highly unbalanced. The impact of customers' unbalance connections on battery integration and operation is evaluated using the real distribution network as detailed in the following section.

3.2.2.2. Analysis of Practical Distribution Network

Practical scenarios of battery and load unbalance are studied using the real network as shown in Fig. 3.20. This network comprises 42 nodes, 109 customers and 307m of feeder length. The customers' connection on the phases are highly unbalanced, where the number of single-phase customers on Phase A, B, and C are 46, 30, and 23, respectively.

The load flow results for the practical distribution network show that the worst-case VUF at G9.3 Bus is ~1% when the transformer phase A is loaded at 90%. This implies that for every ΔP=10kW or power imbalance a VUF of 0.23% results, which is slightly higher compared to the typical network. The difference is however small and is expected due to different feeder lengths within the network.

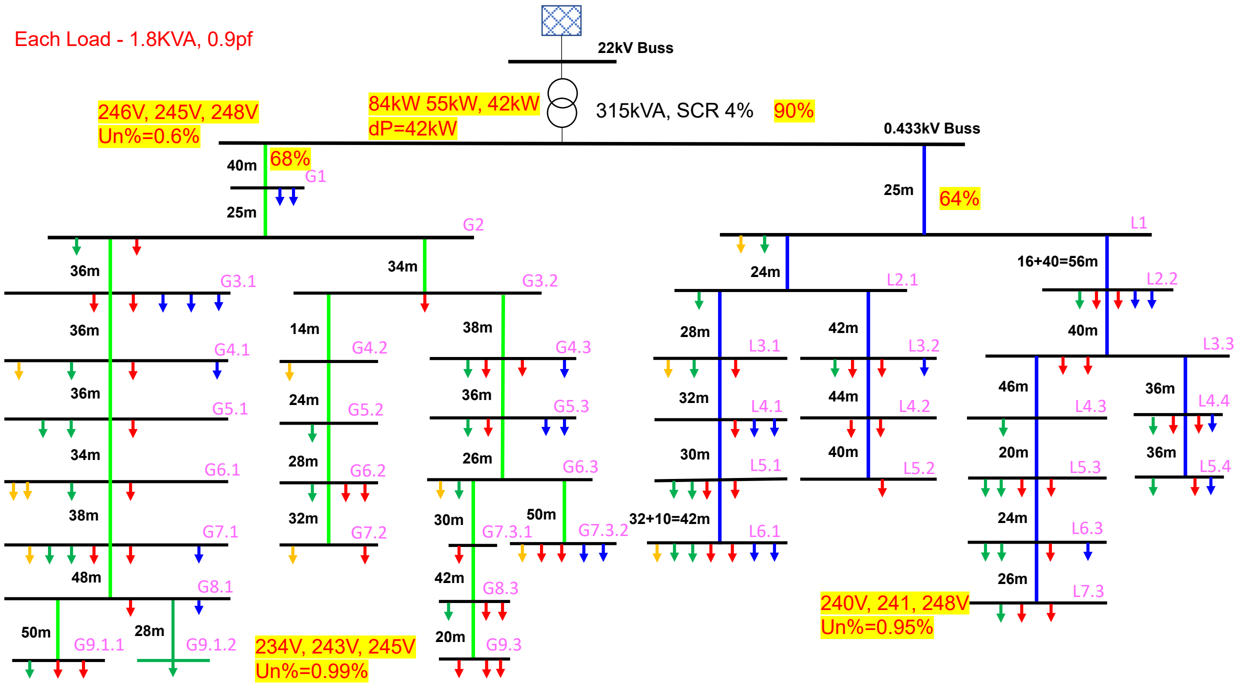


Fig. 3.20. Practical Distribution Network "C" used for Unbalanced Study.

Heavy load and battery discharging scenario.

In this scenario, the battery units are integrated with the same unbalance ratio as the customer connection, i.e., 55 on Phase A, 39 on phase B, and 32 on Phase C, and the battery units are set to discharge.

The results show that,

- The VUF is improved from 1% to 0.58% when the battery is discharging during high load demand.
- Each battery supplies power to the local loads, reducing the flow of power in the network. Consequently, the VUF is improved as compared to the load only case.

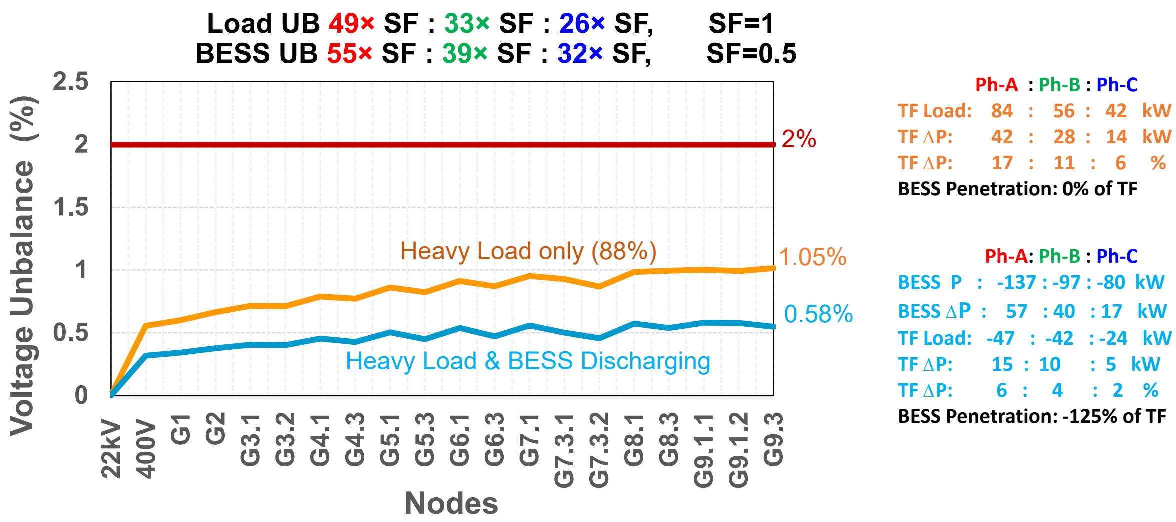


Fig. 3.21 - Unbalanced Simulation Results for IS: battery UB 55:39:32 and OS: battery discharging.

Light load and battery charging scenario.

The unbalance connection of customers may restrict the charging of battery from the grid, especially during the heavy load. Therefore, the charging of the battery is only possible during the light load condition and results for this scenario are in the Appendix. The results suggest that,

- The battery power imbalance of 23kW and overall combined power imbalance of 45kW creates VUF of ~1%, which is far below the regulatory limit, i.e., 2%.
- The practical case of the battery (and load) imbalance will not breach the voltage unbalance limit of 2% for the given unbalance ratio of the customer connections.

3.2.2.3. Summary of Results & Recommendations

The battery improves the VUF in the load-unbalanced network (where load and customer connections are highly unbalanced) while discharging. However, it is not possible to charge the battery from the grid during the heavy load. This also implies that the thermal capacity of the over-loaded phase (with more load or customer connection) will breach at a lower level of battery penetration. Therefore, the unbalanced connections of customers (or unbalance load) may constrain the penetration of battery units. The following are possible strategies that could be adopted to increase the penetration of battery units in the network and will allow higher level of unbalanced battery operation without breaching the VUF limits.

- **Balancing of Customer Connections**: The balancing of customer connections and load in the LV substation will allow for a higher penetration of batteries and a higher level of unbalanced operation.
- **Battery Charge /Discharge Control**: The charging of a battery from the grid may need to be restricted during heavy/moderate load scenarios to avoid breaching of thermal loading capacity of feeders and transformers. This will allow a higher level of battery penetration.
- **Special Tariff/TOU for Battery Charging**: The charging of a battery can be discouraged by introducing special tariff or time-of-use pricing for the battery. This will also allow higher level of battery penetration to be achieved.

3.2.3. Quasi Dynamic Simulation Study.

In quasi dynamic studies, the practical network considered in the unbalanced simulations is adopted. The loads have been modified according to the load profiles derived through the data analysis studies in order to have realistic customer peak loading conditions of around (3 – 3.5 kW). Furthermore, the provided data for non-PV and PV only customers included controlled water heating which dramatically changed their behaviour compared to normal customers. In order to provide consistent results, these data sets were modified to represent typical load profiles of the customers without PV or batteries. The preliminary results showed that the hot and cold days need to be further studied due the possible impact of load and generation by the customers. Therefore, the results of 2 temperature zones for cold days (15 degrees) and hot days (40 degrees) for various operational scenarios detailed in the Appendix are demonstrated here. The voltage profiles of the buses at middle (G5.1, G5.2, G5.3, L4.1, L3.2, L4.3) and end of the feeder (G9.1.1, G9.3, L6.1, L7.3, L5.4) as shown in Fig. 3.23 are analysed to conclude the effect of PVs and batteries on the distribution network.

> **In the case of high penetration of PVs, the midday over-voltage can be significant, and potentially violate the voltage operational limits of the network.**

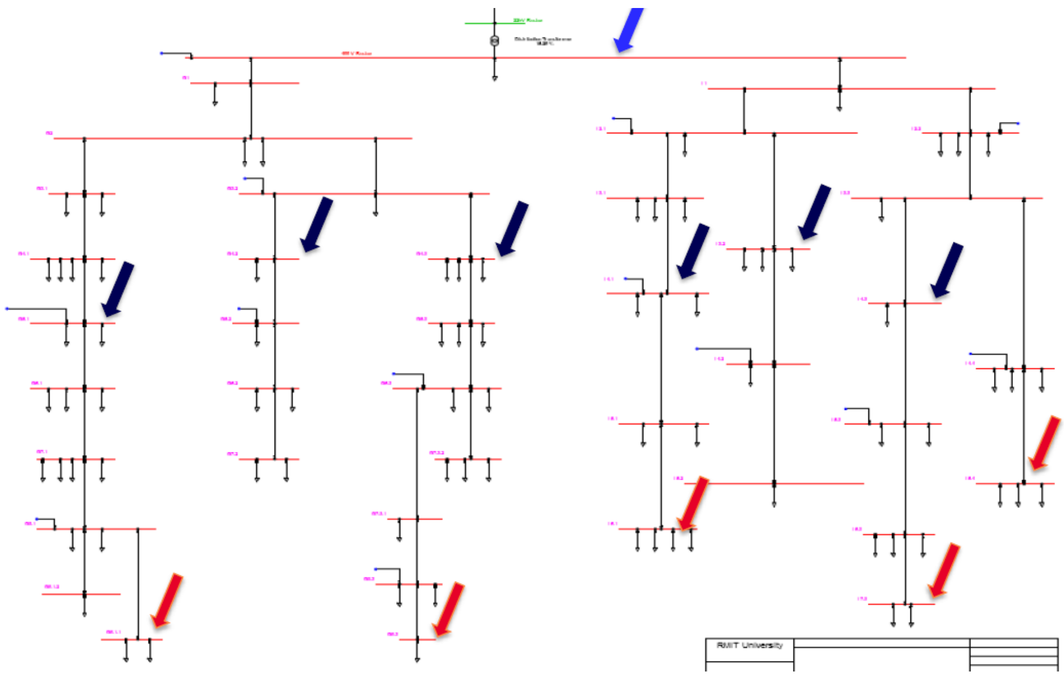


Fig. 3.22 - Practical Distribution Network and the analysed buses.

In each scenario, the loads are randomly assigned to the relevant clusters considering the weighting of each cluster as defined through the data analysis and the results demonstrate the different voltage profiles for the various studies cases. The sample comparative voltage profiles for case 4 (66% PV & Battery , 33% PV Only) and case 5 (33% PV & Battery , 66% PV Only) in cold (below 15 degrees) and hot (above 40 degrees) days are presented through Fig.3.23 – 3.26.

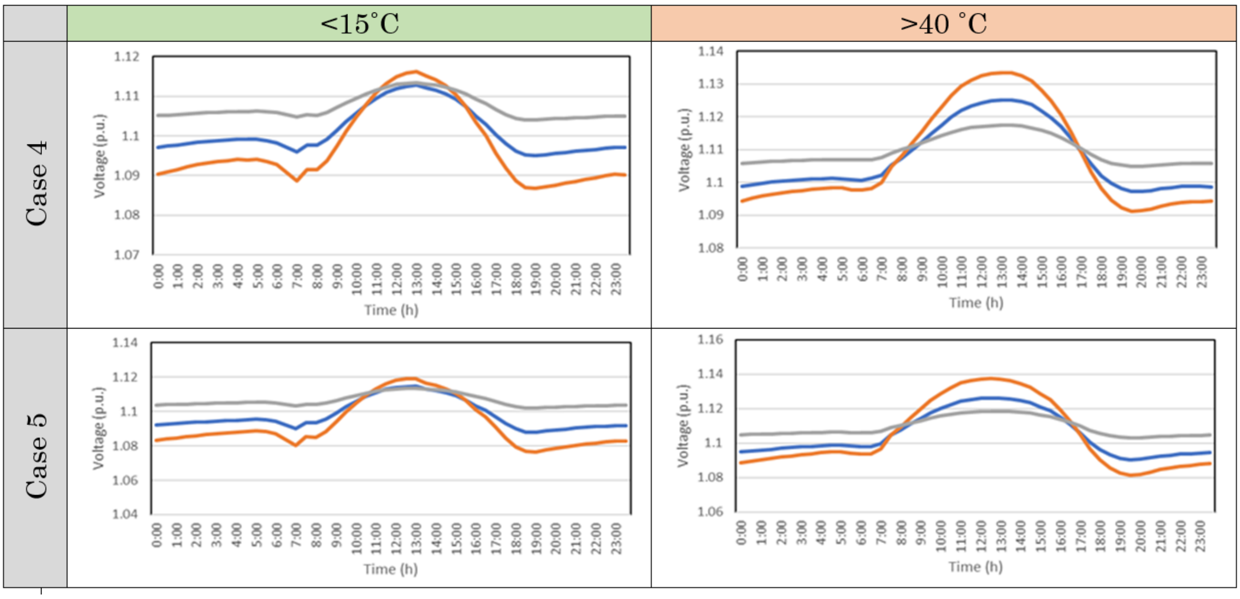


Fig. 3.23 - Voltage profile at 400 V busbar

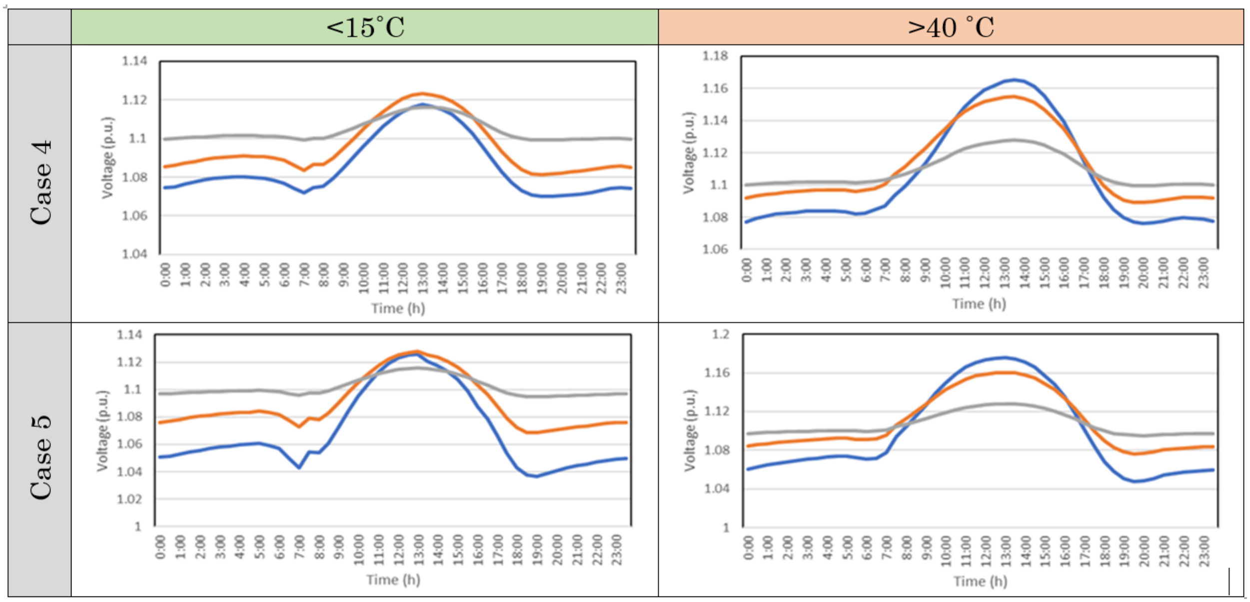


Fig. 3.24 - Voltage profile at the middle point (GS2)

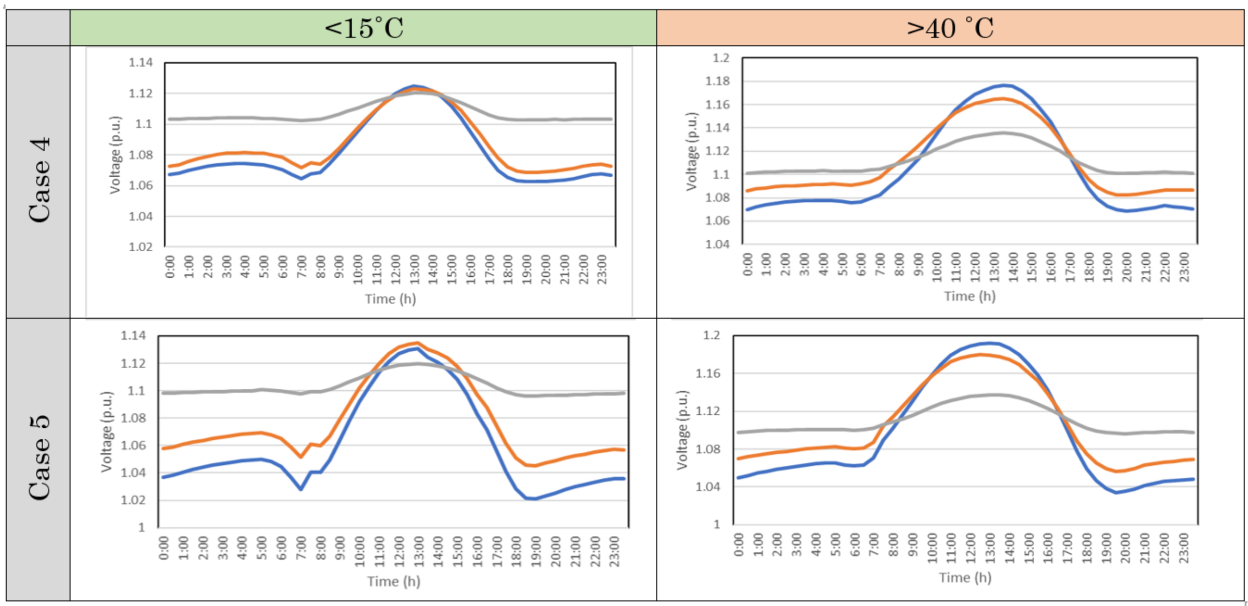


Fig. 3.25 - Voltage profile at the End Point (G9.1.1)

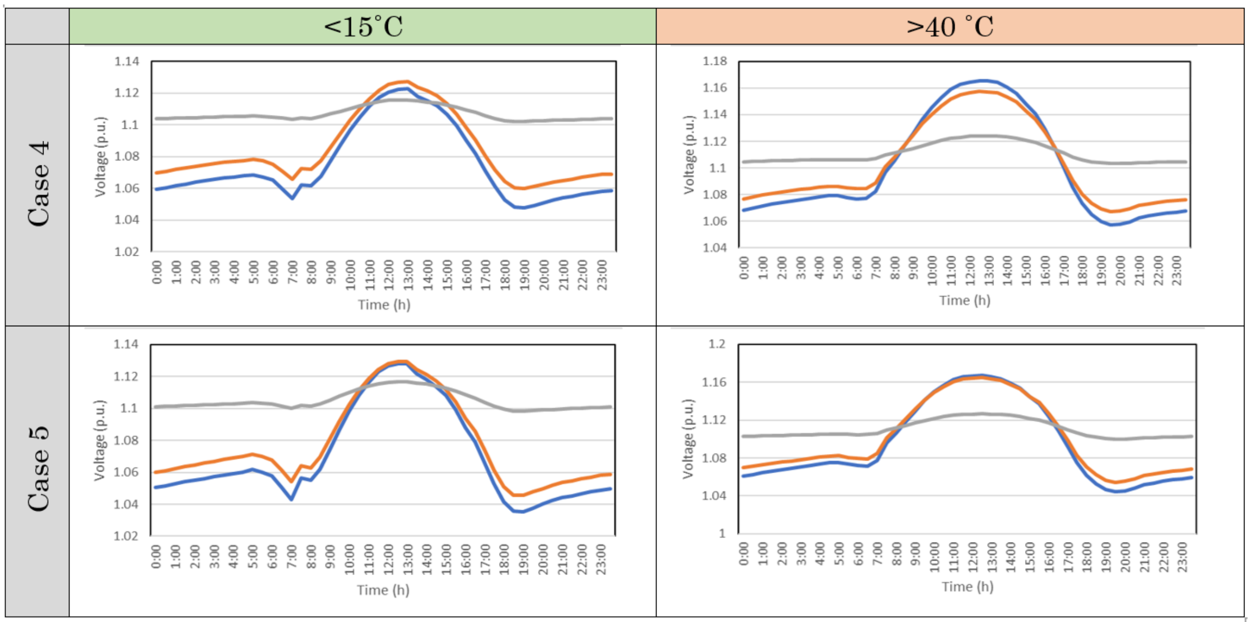


Fig. 3.26 - Voltage profile at the End Point (L5.4)

The presented results consider the scenarios with significant penetration levels of renewable generation (PVs) within the distribution network and demonstrates the effectiveness of the batteries in improving the voltage profile across the network particularly by reducing the peak voltage during midday due to significant PV generation. The comparative numerical results for the various studied cases are summarized in Table 3.8 and Table 3.9 where the voltage at the beginning (400V bus), Midpoint (MP) and Endpoint (EP) are compared.

Table 3.8 - Quasi dynamic result of base Scenarios

Feeder Phase	400 V Busbar	Feeder MP Volt (p.u.)	Maximum % Overvoltage at MP	Feeder EP Volt (p.u.)	Maximum % Overvoltage at EP	Temperature Zone	Integration Scenario
Phase A	1.096	1.08	10.4	1.04		Cold (Below 15)	100% Non-PV
Phase B	1.09	1.086		1.08	8		
Phase C	1.105	1.104		1.09			
Phase A	1.12	1.14	14	1.146		Cold (Below 15	100% PV
Phase B	1.11	1.13		1.13	14.6		
Phase C	1.11	1.12		1.12			
Phase A	1.113	1.12	12	1.12	12	Cold (Below 15	100% PV and Battery
Phase B	1.11	1.12		1.12			
Phase C	1.11	1.117		1.117			
Phase A	1.099	1.064	9.4	1.051	9.5	Hot (Above 40)	100% Non-PV
Phase B	1.095	1.089		1.09			
Phase C	1.105	1.094		1.095			
Phase A	1.128	1.199	19.9	1.217	**21.7**	**Hot (Above 40)**	**100% PV**
Phase B	1.14	1.168		1.169			
Phase C	1.12	1.14		1.138			
Phase A	1.122	1.173	17.4	1.184	**18.4**	**Hot (Above 40)**	**100% PV and Battery**
Phase B	1.132	1.154		1.154			
Phase C	1.117	1.13		1.129			

Table 3.9 - Quasi dynamic result of mixed integration Scenarios

Feeder Phase	400 V Busbar	Feeder MP Volt (p.u.)	Maximum % Overvoltage at MP	Feeder EP Volt (p.u.)	Maximum % Overvoltage at EP	Load Profile	Integration Scenario
Phase A	1.133	1.175	17.2	1.187	**18.7**	**Hot (Above 40)**	**Case 4** **66% PV &**
Phase B	1.125	1.156		1.156			
Phase C	1.117	1.13		1.13			
Phase A	1.137	1.192	19.2	1.209	**20.9**	**Hot (Above 40)**	**Case 5** **66% PV Only**
Phase B	1.126	1.162		1.161			
Phase C	1.118	1.129		1.127			
Phase A	1.116	1.182	18.2	1.199	19.9	Hot (Above 40)	Case 3 33% PV &
Phase B	1.122	1.147		1.146			
Phase C	1.115	1.126		1.125			
Phase A	1.12	1.193	19.3	1.21	21	Hot (Above 40)	Case 2 66% PV Only
Phase B	1.124	1.153		1.153			
Phase C	1.115	1.137		1.134			
Phase A	1.109	1.112	13.1	1.1	13.3	Hot (Above 40)	Case 1 33% PV Only
Phase B	1.107	1.131		1.133			
Phase C	1.112	1.122		1.123			

These results demonstrate that when the system has significant penetration of PVs, the midday over-voltage can be significant and potentially violate the voltage operational limits of the network. The batteries have been shown to reduce the overvoltage and improve daily voltage profiles across the distribution network which demonstrates the significant of integrating batteries into the renewable rich distribution networks.

3.2.4. Extreme Event Simulation Study.

In the extreme event simulation study, an extreme hot day (over 40˚C) has considered. Three types of customer load profiles have been identified, which are extreme profiles for 'No PV', with PV, with PV + battery. Then, the same profile has been assigned to all customers in the LV feeder. In this consideration, the peak of all PV in the afternoon (or load in the afternoon and evening) occurs at the same time. Assigning the same loading curve for all customers may be unlikely, but if ever it happens, it might have a detrimental impact on the network. This type of event is known as High Impact Low Probability (HILP) event in power system studies.

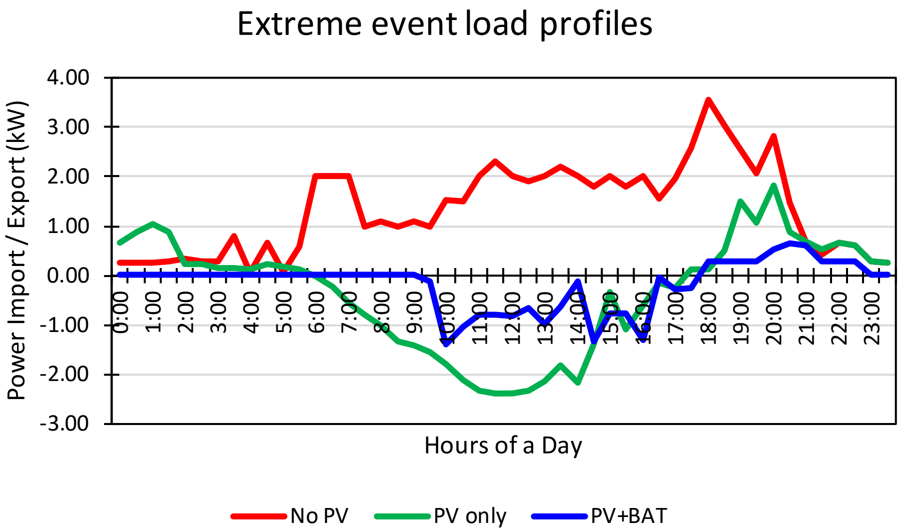


Fig. 3.27. Extreme event load profiles on a peak summer day for 'No PV', 'PV only' and 'PV+Battery' customers

Extreme Event Load Profiles

It can be observed from Fig. 3.26, that the 'No PV' customers shows high afternoon and evening peak demand in a hot summer day. On the other hand, the 'PV only' customers demonstrate high export during afternoon time. Finally, the 'PV+ Battery' customers can essentially reduce the peak afternoon export and peak evening import, as they export the difference between the PV generation and household consumption.

3.2.4.1. Extreme Event (quasi-dynamic) Simulation (in DIgSILENT PowerFactory)

The extreme event simulation study has been performed with the same network and keeping all simulation settings same as quasi-dynamic simulation except the extreme load profiles. By performing the quasi-dynamic simulation for HILP event, the voltage profiles over 48 half-hourly intervals have been presented. Results will highlight the contribution of the battery in managing grid voltage profile during extreme network events.

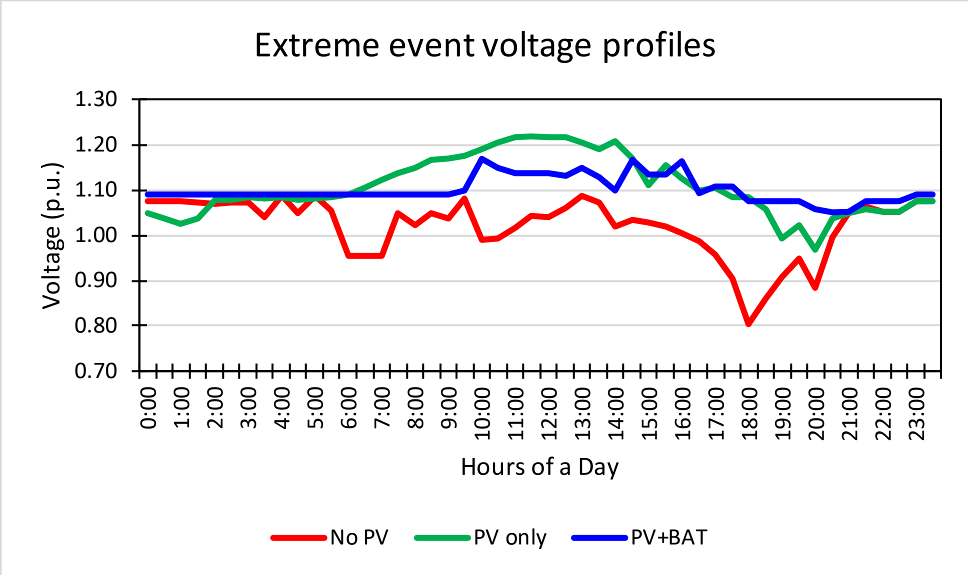


Fig. 3.28. Extreme event voltage profiles on a peak summer day for 'No PV', 'PV only' and 'PV+Battery' customers

Extreme Event Voltage Profiles

It can be observed from Fig. 3.28, that the 'No PV' customers exhibit the risk of voltage violation due to their high consumption in the prolonged hours in the afternoon and evening in a hot summer day. Specifically, voltage violation can be seen during evening hours from 17:00 to 20:00. On the other hand, the 'PV only' customers demonstrate high export during afternoon time, and subsequent risk of voltage violation. Finally, the 'PV+ Battery' customers have reduced the voltage violations that occurred for the abovementioned two cases. 'PV+Battery' scenario have been able to reduce the afternoon voltage violation by limiting the PV-export and evening voltage violation by limiting the power-import (during peak time).

Hence, implementation of the battery controller to facilitate charging batteries during afternoon PV-export (and discharging batteries during evening peak consumption), may alleviate local DER problems and potentially avoid negative grid impact and network augmentation.

4. Conclusions

This project analysed the electricity consumption profiles of approximately 2,200 households who have installed a residential battery system. These consumption profiles were segmented into distinct statistical clusters and benchmarked against load profiles associated with customers with a rooftop PV system only, and also to customers with no PV and no battery. Our analysis showed that the installation of a battery results in a 16-25% reduction in the peak energy export of each household. This provides benefits to the distribution network and increases the distributed energy resource hosting capacity of the low voltage feeder. Furthermore, the household battery system reduces the evening power import substantially by 60-85%. The cluster segmentation strategy applied to the electricity consumption data considered different climatic conditions, and produced typical customer profiles that were used as inputs into DIGSILENT power system network simulation models. These simulations showed that household batteries improve the voltage unbalance factor (VUF) in networks with significant imbalance associated with the customer connections (i.e. the non-uniform connections of PV and battery systems across phases) during battery discharging events. However, thermal ratings can constrain the ability of batteries to mitigate voltage unbalance during high load and charging scenarios. This issue can be solved by balancing the customer connection points and/or introducing strategies like charge/discharge control and special tariff or time-of-use pricing for the battery. Quasi-dynamic simulation studies were also performed to investigate the daily voltage fluctuation of distribution feeders based on the typical cluster consumption profiles. These models show that under high PV penetration scenarios the peak solar export period leads to over-voltage feeder profile limit violations. The presence of household batteries ameliorates this effect, and can further support unbalanced voltage violation events, providing significant benefits to both DNSPs and customers. Despite these benefits the data analysis has also revealed that a significant proportion (79%) of customers with household batteries export considerably more power during hot climatic conditions compared to PV only customers. This data indicates that the battery is not providing significant network support in these conditions, and is likely because the battery is rapidly charged before the export peak. Controlled battery responses may alleviate over-voltage events associated with these peak export periods. The simulation models also showed that particular locations within the feeder (e.g. end-points) were more sensitive to the battery operating regime.

5. Recommendations for Future Studies

Our investigations show that the interaction between the grid, rooftop photovoltaic systems and household batteries is dynamic and complex, and has significant dependencies on weather and distributed energy source penetration levels, the latter of which is rapidly evolving. Several aspects of this project indicate that there are benefits to be realised by conducting additional studies, including:

- On-going monitoring, analytics assessments and matching simulation investigations to quantify customer behaviour are recommended. This will empower DNSPs and government agencies to make assessments about the current hosting capacity of distribution networks as penetration levels change over time. It will also enable adverse or beneficial customer behaviours to be identified which can then inform operational decisions.
- The significant excess PV export power that has been observed during hot summer conditions has the potential to cause over-voltage violations on days with the maximum solar energy harvest potential, which limits the PV hosting capacity. Most likely this is due to fast battery charging and also larger PV sizes in households with residential batteries. Further research is recommended to explore mitigation strategies for this issue, which might include slow charging rebates.
- Electric Vehicles (EVs) are an emerging disruptive technology. Their storage capacity is typically much larger than conventional residential batteries. Furthermore, EV grid connection points are not necessarily fixed geographically, and their load profile can be complex depending on the vehicle usage. Further research is recommended to study their impact on the grid, and to integrate charging profiles with mobility data in order to develop more effective coordinated charging, locating charging stations, individual tariff structure for EV owners.
- Future studies may focus on the eligibility criteria under the battery program which requires households to have an income of $180,000 or less. As batteries help DNSPs to increase their PV hosting capacity, income-independent rebates can be produced to benefit both consumers and DNSPs. Further research is needed to fully study the impact of such policies.

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6. Appendix

6.1. Detailed Methodology.

Data analytics.

In order to derive detailed electricity consumption/export behaviour for consumers with batteries, advanced machine learning algorithms are applied to analyse the load profiles. In the following, we provide a summary of the data processing steps and preliminary findings.

Data pre-processing: The first step is to prepare the data for segmentation of customers into distinct clusters. Customers belonging to a cluster behave similarly in their consumption/export profiles. We combine all three datasets from Powercor, Jemena and AusNet Services into one large dataset. The first energy export at night times is considered as the sign to show the battery is first installed and is in service. This is because the data does not include details on the battery installation date, and no supervised learning-based model could be stablished in the absence of ground-truth data. Thus, the only possible solution is to check the first after-sunset export to the grid to determine the approximate installation time. All the net consumption, i.e. the consumption power subtracted by the export power, before the battery identification date has been set to zero as the purpose of the clustering is to group the customers with batteries into clusters.

Clustering algorithm: A k-means clustering algorithm is used to cluster the net consumption into K clusters. The k-means clustering, or Lloyd's algorithm, is an iterative, data-partitioning technique that assigns *n* observations to exactly one of *k* clusters defined by cluster centres, where *k* is chosen before the algorithm starts. This is a well-known algorithm for data clustering, which has been used in many applications. The algorithm proceeds as follows:

1. *Choose k initial cluster centres at random*
2. *Compute point-to-cluster-centroid distances of all observations to each centroid.*
3. *There are two ways to proceed:*
    - *Batch update — Assign each observation to the cluster with the closest centroid.*
    - *Online update — Individually assign observations to a different centroid if the reassignment decreases the sum of the within-cluster, sum-of-squares point-to-cluster-centroid distances.*
4. *Compute the average of the observations in each cluster to obtain k new centroid locations.*
5. *Repeat steps 2 through 4 until cluster assignments do not change, or the maximum number of iterations is reached.*

We determine the optimal cluster size and plot cluster representative profiles, which is the average of the net consumption of all customers within the same cluster. The clustering step is performed to get insights on the behavioural pattern of the customers and the typical individual load patterns (and not the cluster representative load patterns) are used in the network simulation tasks.

It has been frequently reported that customer behaviour is correlated with the temperature and weekend/weekday. Therefore, we process weekdays and weekends/public holidays separately. Furthermore, the analysis is conducted on six temperature zones including, less than 15°C, 15°C -20°C, 20°C-30°C, 30°C-35°C, 35°C-40°C, and more than 40°C.

Balanced network simulations.

A distribution network including 12 households on each phase with a 500kVA 22/0.415KV transformer is modelled in DIGSILENT power factory software tool (Fig.6.1).

Three different network configurations are considered for the balanced network simulations:

- Network Configuration-1: Distance Between Network Access Points: 43.05 m and 0.315 (R)+j0.125 (X) Ω/km [**Overhead**]
- Network Configuration-2: Distance Between Network Access Points: 21 m and 0.315 (R)+j0.125 (X) Ω/km [**Overhead**]
- Network Configuration-3: Distance Between Network Access Points: 43.05 m and 0.128 (R)+j0.0716 (X) Ω/km [**Underground**]

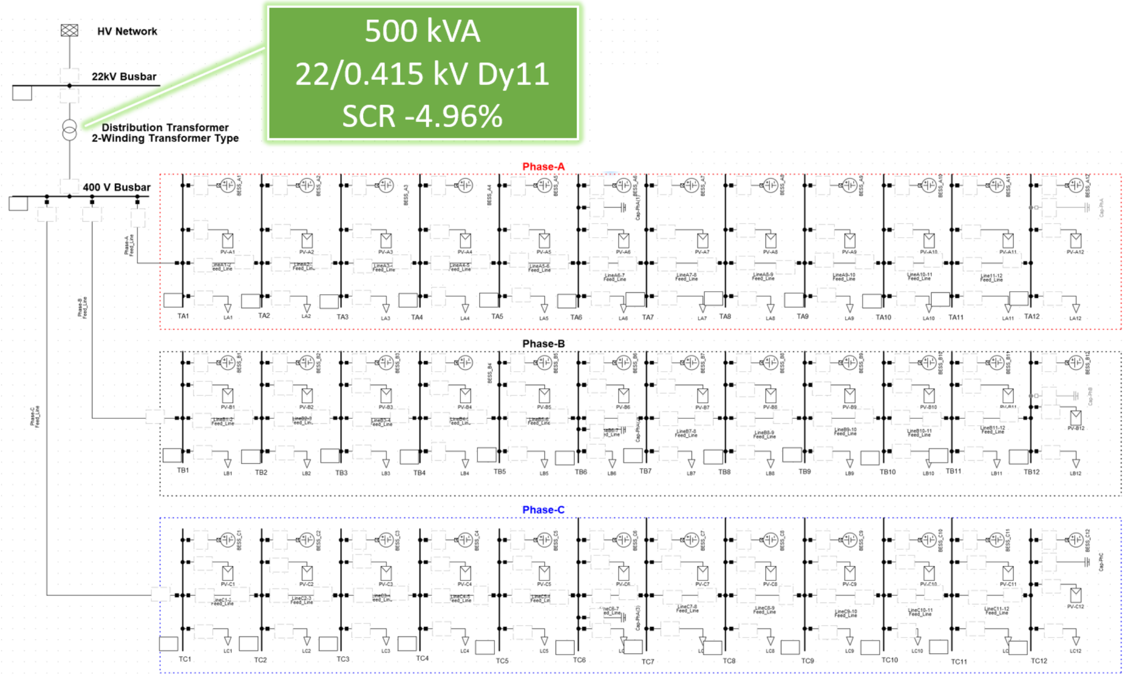

Fig.6.1 - DIgSILENT PF network model.

In each of these configurations, four different integration scenarios (including both low and high probability scenarios) are considered. These integration scenarios show different levels of penetration of PVs and Batteries in households. For each of these integration scenarios, different operational scenarios to cover PV and battery charging and discharging conditions as well as different internal consumptions of households are considered. Figure 6.2 summarise all 151 simulation scenarios (from very high probability to very low probability) for the balanced network simulations.

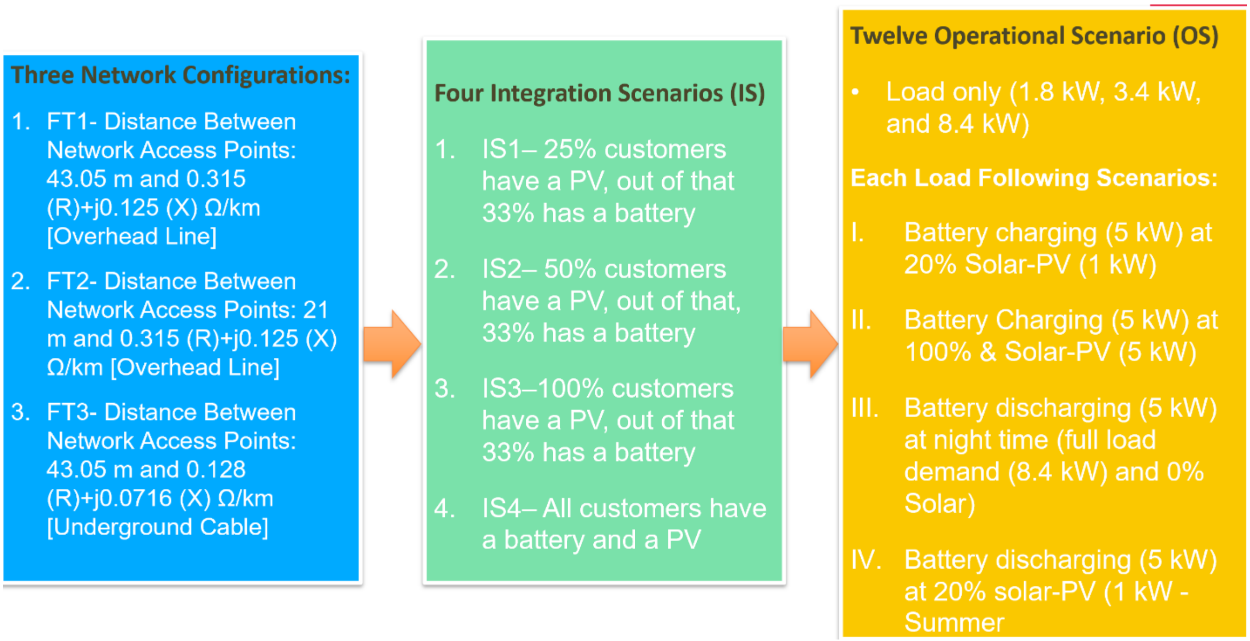

Fig. 6.2 - Balanced Network Simulation scenarios

Unbalanced simulations

Practical LV networks are naturally unbalanced due to unbalanced phase connections, upstream unbalance propagation and unbalanced load and generation of customers[14]. Therefore, it is essential to investigate the feeder voltage profile characteristics under unbalance network conditions. The purpose of this unbalanced simulation study is to analyse the impact of the battery power imbalance on the distribution network voltage and thermal limits. More specifically, this study identifies the Integration and Operational Scenarios of battery power imbalance that can cause the network voltage to breach 2% Voltage Unbalance Factor (VUF) limit[15], and thereby, estimates the allowable level of battery power imbalance in a typical and real distribution network. This study also analyses the impact of battery imbalance operation on VUF when the customers' connections or load are unbalanced.

The methodology used for the unbalanced study is shown in Figure 6.3. A wide range of battery Integration (IS) and Operational Scenarios (OS) are simulated with the typical and practical distribution network in order to characterise their ΔVUF/ΔP behaviour. The VUF characteristics of the networks are then used to estimate the allowable level of battery power imbalance in the network. The Integration Scenarios used in this study include 8%, 25%, 33%, 50%, and 66% customers with battery, and 10-100kW power imbalance between consecutive phases (e.g., between phase A and Phase B/C). The considered Operational Scenarios include battery charging and discharging, while the network load demand is light and also heavy.

Why Voltage Unbalance Factor?

Unequal integration of battery, solar PV and/or loads on phases affects the RMS values of the phase voltages and/or the phase angles between consecutive phases and may produce undesirable unbalanced voltage in the network. According to the Ausgrid N238 and AS/NZS 61000.2.2, the Voltage Unbalance

[14] D. Perera, P. Ciufo, L. Meegahapola, S. Perera, "Attenuation and Propagation of Voltage Unbalance in Radial Distribution Networks," *International Transactions on Electrical Energy Systems*, vol. 25, no. 12, pp. 3738-3752, Dec. 2015.
[15] IEC61000-3-13 stipulates 2% as the VUF compatibility level for LV and MV networks and 3% for the areas with significant single-phase loads.

Factor (VUF) needs to be maintained within 2% limit during the normal operational conditions[16]. In this part of the project, the VUF in the network is thoroughly analysed for a wide range of battery imbalance Integration and Operational Scenarios.

In this study, the voltage unbalance factor is calculated according to the IEC definition, i.e., the ratio of negative-to-positive sequence voltage, i.e.,

$$VUF = \frac{V_n}{V_p}\%$$

where V_n and V_p are the negative and positive sequence voltages.

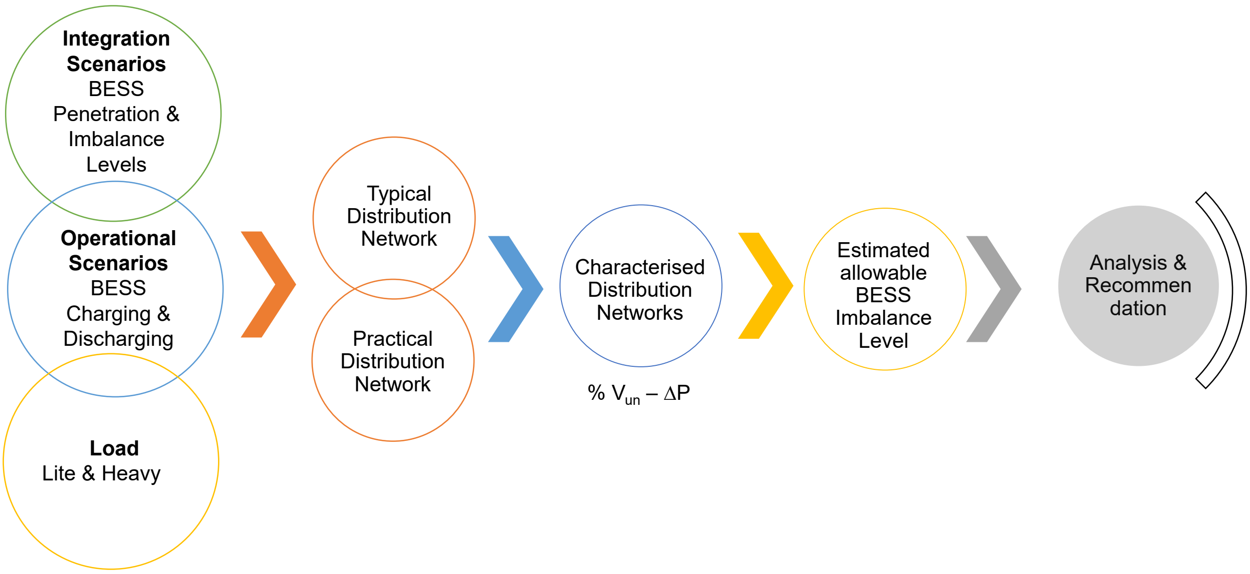

Fig. 6.3. Methodology for the Unbalanced Simulation Study.

6.2. Quasi Dynamic Simulations

In order to integrate the data analysis with network simulations, Quasi dynamic simulations are performed on the distribution network. In these simulations, various load profiles and clusters obtained through data analysis are considered for the system loads to provide the daily load and voltage profiles of the network in different temperature zones. These simulations provide an insight to the effectiveness of the batteries in the distribution networks which are seeing a significant increase in the penetration of PVs. The 24-hour simulation (30 mins intervals) quasi dynamic simulations are performed on the practical network as shown in the diagram in Fig. 6.4 where the voltage at middle and end of the feeders were considered for the analysis.

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[16] NS238: SUPPLY QUALITY, Document Number: NW000-S0040, Ausgrid
https://www.ausgrid.com.au/-/media/Documents/Technical-Documentation/NS/ns238.pdf?la=en&hash=C9AC61391301F48E1F6CCE3F5800A244812FC997
[16] Table-6 at page10/16 of the document,
https://www.endeavourenergy.com.au/wps/wcm/connect/2428f41e-83cd-4f8d-b902-22c9ef9c3216/MDI0050.pdf?MOD=AJPERES

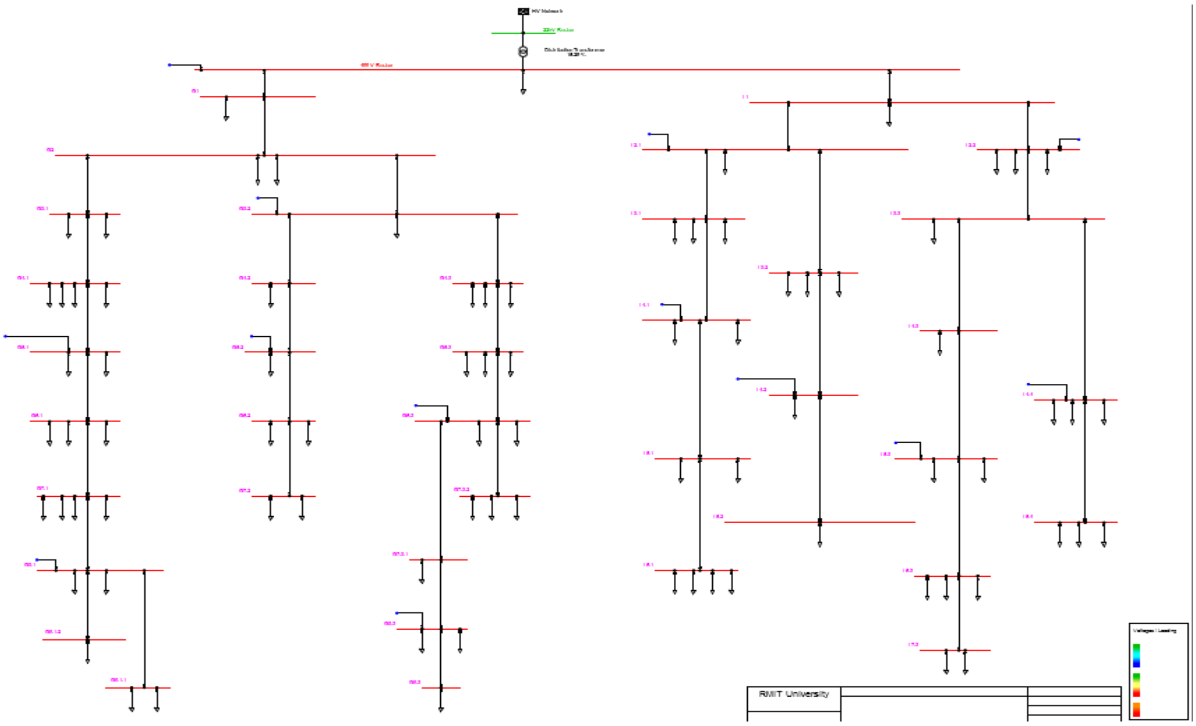

Fig. 6.4. Practical Network for Quasi Dynamic Simulations.

Based on the preliminary results from balanced and unbalanced simulations, the following scenarios for customer types were considered in the quasi dynamic simulations in different temperature zones:

Base Scenarios:

a) 100% No PV/Battery costumers
b) 100% PV costumers
c) 100% PV & Battery costumers

Mixed Operational Scenarios:

- Case 1: 33% PV Only and 66% No PV costumers
- Case 2: 66% PV Only and 33% No PV costumers
- Case 3: 33% PV & Battery, 33% PV, and 33% No PV costumers
- Case 4: 66% PV & Battery and 33% PV Only costumers
- Case 5: 33% PV & Battery and 66% PV Only costumers

6.2. Data Analytics Results for Different Temperature Zones.

Very cool days (temperature < 15˚C).

Fig.6.5 - Consumption behaviour of residential customers in very cool days (< 15˚C)

In the clustering process, customers with consumption profiles close to each other are put in one cluster. Then, a representative for each cluster is shown in the figure which is the central point of the cluster. Higher number of clusters means that consumers behaviours are considerably different from each other. It means that we should expect different number of clusters when temperature changes or when battery is added to PV system. For example, in Fig. 6.5., consumers with PV can be separated in three clusters in very cool weekdays. However, we need 5 clusters to cover all PV/BAT consumers in these days, meaning that people use the energy stored in the battery in different ways and times.

Observations:

1. Peak consumption at early evening for 45-55% of customers is significantly reduced (more than 50%) when battery is added to PV. This is clear by comparing the PV and PV+BAT cases of Fig. 6.5.
2. Batteries have flattened the night consumption profile of the customers.
3. Peak of the energy export in very cool weekends is reduced by about 50% for more than 40% of customers. This peak reduction happens by about 20% for about 25% of customers in very cool weekdays.

Pleasant days (temperature 20-30˚C).

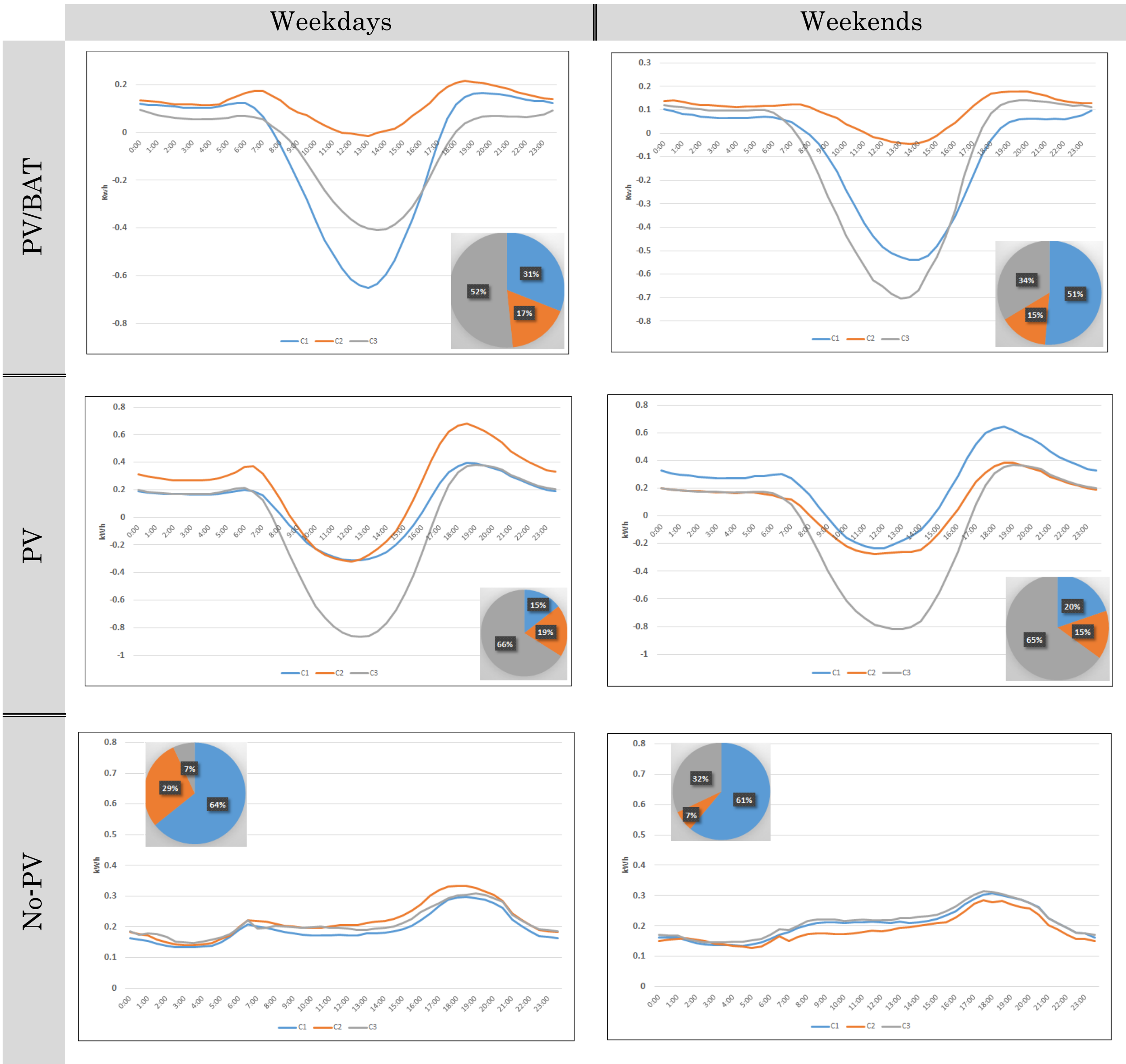

Fig.6.6 - Consumption behaviour of residential customers in pleasant days (20-30˚C).

Observations:

1. The peak consumption at early evening is reduced by more than 50% in pleasant days for PV/BAT comparing to PV consumers.
2. In pleasant weekdays, a reduction of at least 20% happens in the peak energy export when battery is added to PV. In pleasant weekends, this reduction is more than 12%.

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Warm days (temperature 30-35˚C).

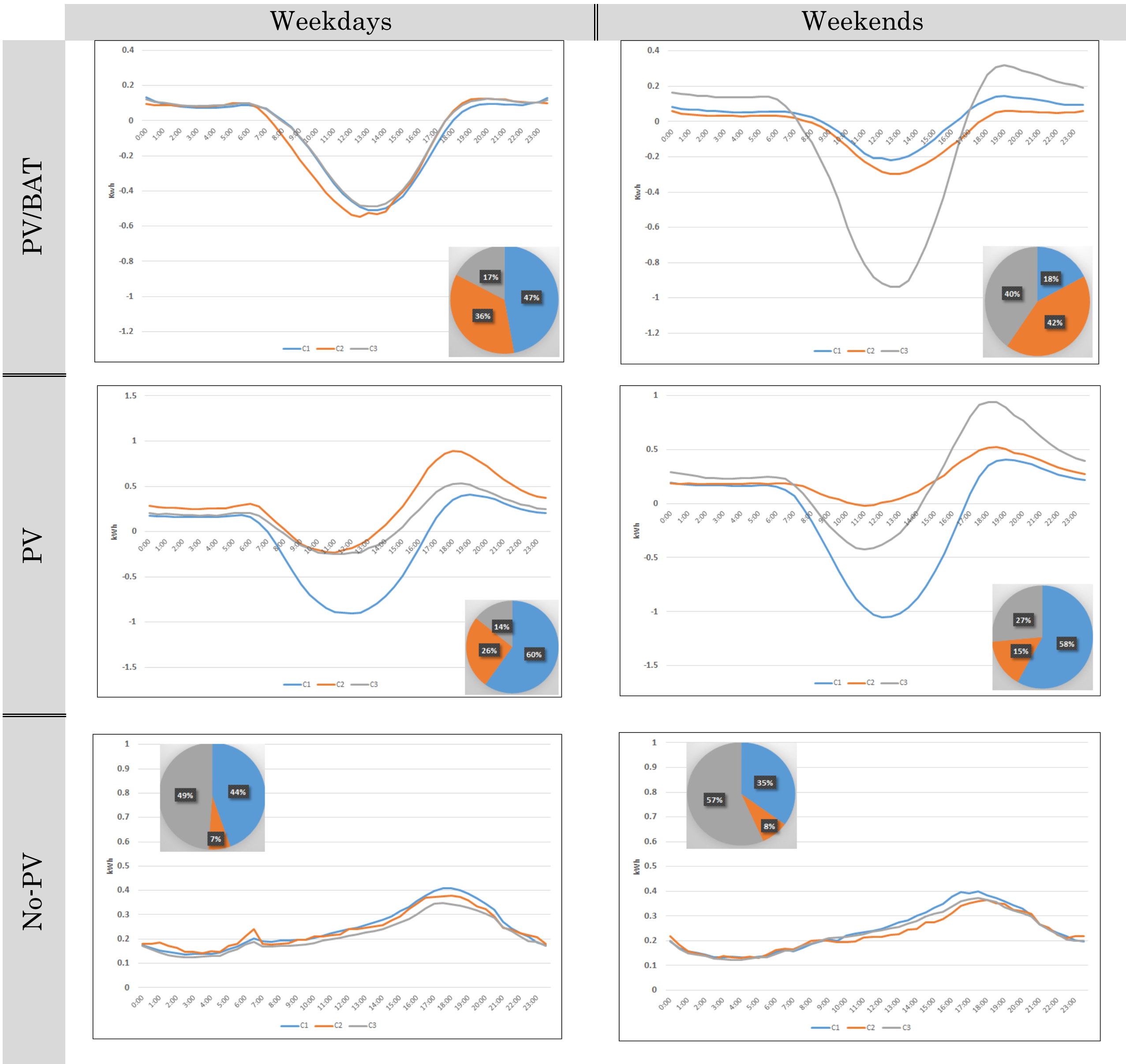


Fig.6.7 - Consumption behaviour of residential customers in warm days (30-35˚C).

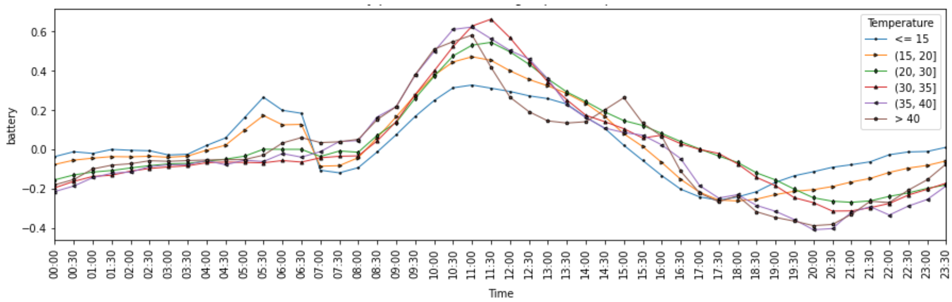
Observations:

1. The peak consumption at early evening is reduced by more than 50% in warm weekdays for PV/BAT comparing to PV consumers. This happens for almost 75% of customers in in warm weekends.
2. Although the peak energy export of 60% of PV/BAT customers in warm weekdays is less than PV consumers by at least 40%, no significant daily export peak reduction is observed in warm weekends.

Battery charging/discharging profile in different temperature zones (battery controlled by retailer)

Battery energy import/export as well as the state of charge for a data set with controlled battery consumers in shown in Fig. 6.8. It shows that, batteries reach maximum 65-85% of their full charges except in very cool days in which 40% of their full charges are achieved. Fig. 6.9 shows that charging profiles of batteries in consumers with and without PV are almost the same in days with temperature higher than 20˚C and slightly different otherwise. State of charge in consumers with PV is increased comparing with No-PV peers.

(A)



(B)

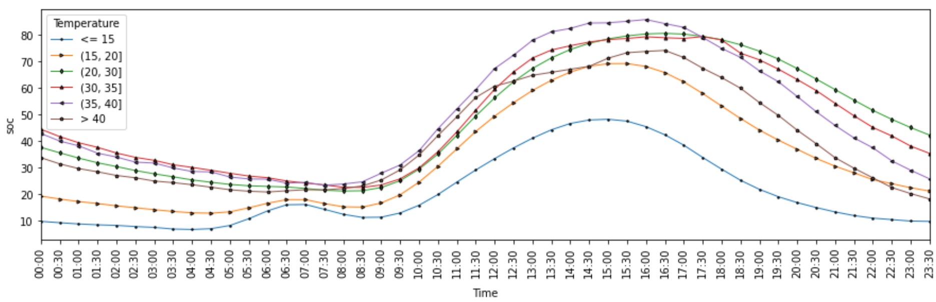


Fig. 6.8. (A) Battery energy profile, (B) batter state of the charge, over different temperature ranges

(A) **(B)**

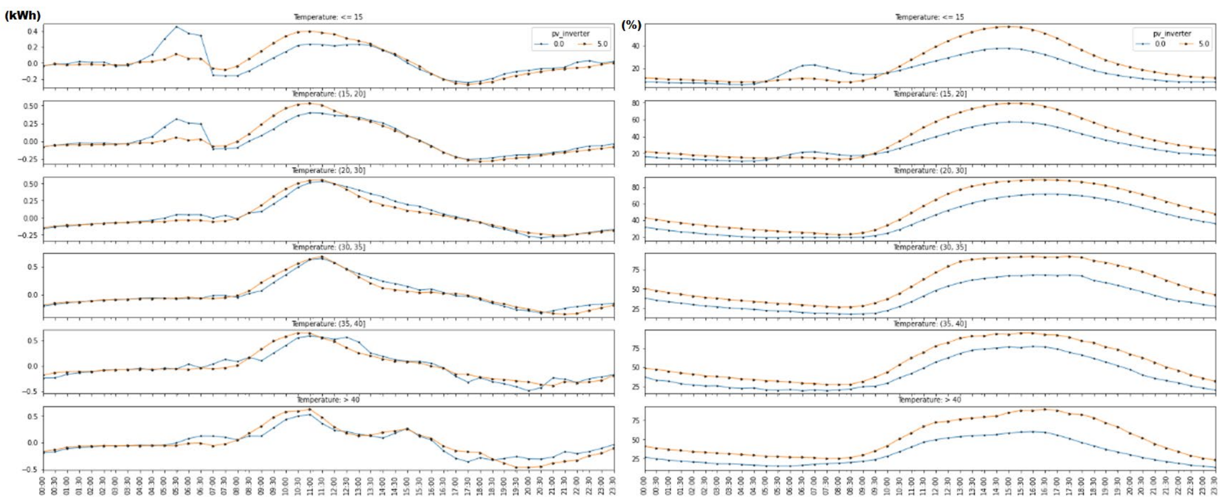


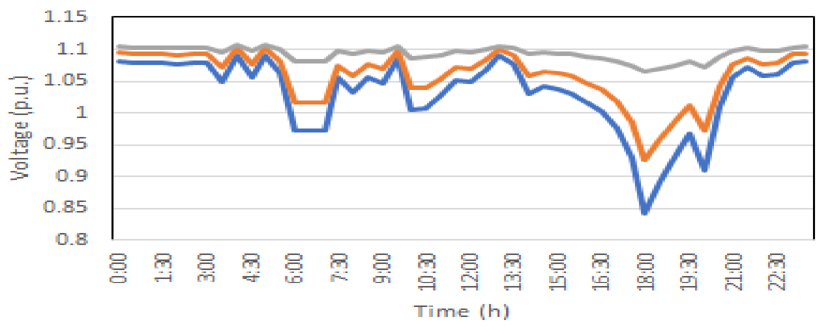
Fig. 6.9. Comparing daily profiles of (A) battery energy, (B) battery state of the charge, for consumers with/without PV.

6.3. Extreme Event Simulations.

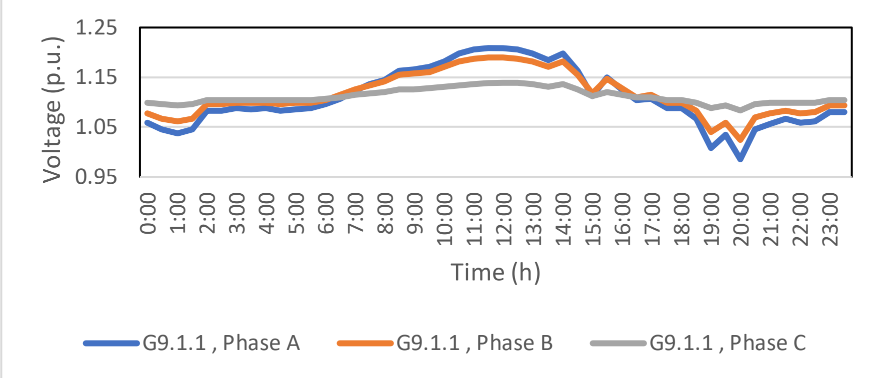
Detail simulation results of the extreme events showing all three-phase voltages at different locations of the network have been presented below.

Voltage profiles

No-PV



PV Only



PV + BAT

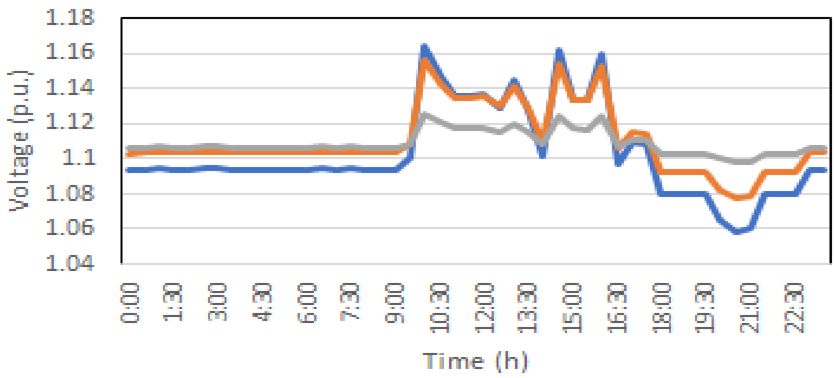


Fig.6.10 – Extreme events voltage profiles of residential customers.

Voltage Profiles at Extreme Events Different Phase Voltages (No-PV)

The extreme network conditions show voltage violations. Extreme voltage violation (lower limit 0.94 pu) is evident at the downstream feeder. It can be for the given network that Phase A experiences the highest voltage drop. Considering the system loading patterns, evening peak demand contributed to voltage violation.

Voltage Profiles at Extreme Events Different Phase Voltages (PV only)

For the PV only scenario, examples of extreme (upper limit 1.1 pu and lower limit 0.94 pu) voltage violations are evident at the downstream feeder. Similar to No PV scenario, Phase A experiences the highest voltage rise, and voltage drop. Afternoon PV export contributed to (upper threshold) voltage violations and evening peak demand contributed to (lower threshold) voltage violations.

Voltage Profiles at Extreme Events Different Phase Voltages (PV + Battery)

For the PV+Battery scenario, battery contributions to limit the voltage violations (upper limit 1.1 pu and lower limit 0.94 pu) are evident at the downstream feeder. Battery is supporting the network during afternoon time to restrict (upper threshold) voltage violations and during evening peak demand to restrict (lower threshold) voltage violations.

Hence, the implementation of the battery controller to facilitate charging batteries during afternoon PV-export (and discharging batteries during evening peak consumption), will solve local DER problems locally to avoid negative grid impact and network augmentation (during extreme network conditions).

6.4. Unbalanced Simulation Study Results

Typical Distribution Network Model B

The typical network is simulated for a wide range of unbalance Integration and Operational Scenarios of BESS as defined in table 6.1 and results are given below.

TABLE 6.1 - INTEGRATION AND OPERATIONAL SCENARIOS FOR UNBALANCE SIMULATION STUDY

Integration Scenario (IS)					Operational Scenario (OS)
No.		Number of Customers with			
		Ph-A	Ph-B	Ph-C	
1	PV100_B66_UB12.8.4	12× SF	8× SF	4× SF	OS2: Charging
2	PV100_B66_UB12.9.3	12× SF	9× SF	3× SF	
3	PV100_B50_UB11.5.2	11× SF	5× SF	2× SF	
4	PV100_B50_UB11.4.3	11× SF	4× SF	3× SF	
5	PV100_B66_UB12.8.4	12× SF	8× SF	4× SF	OS3: Discharging
6	PV100_B66_UB12.9.3	12× SF	9× SF	3× SF	
7	PV100_B50_UB11.5.2	11× SF	5× SF	2× SF	
8	PV100_B50_UB11.4.3	11× SF	4× SF	3× SF	

1. **Integration Scenario PV100_B66_UB12.8.4 and Battery Charging**

   In this scenario, the battery power unbalance ratio between consecutive phases is 12:08:04 with SF=1, 18:12:08 with SF=1.5 and 24:16:08 with SF=2, and respectively, the battery penetration level is 24%, 36%, and 48% of the transformer rating i.e., 500kVA.

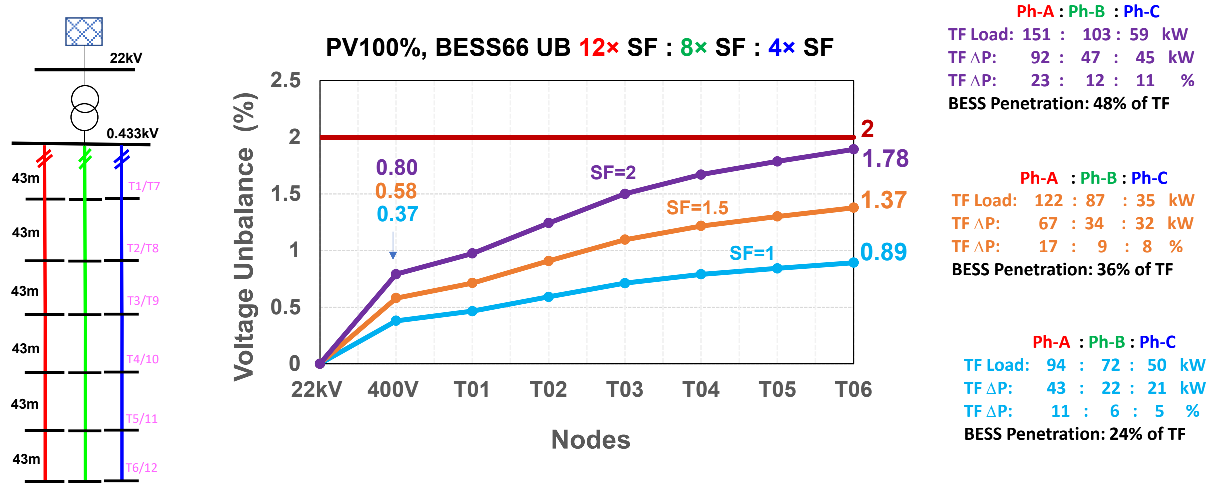


Fig. 6.11. Unbalanced Simulation Results for IS: PV100% battery 66% UB 12:08:04 and OS: battery charging

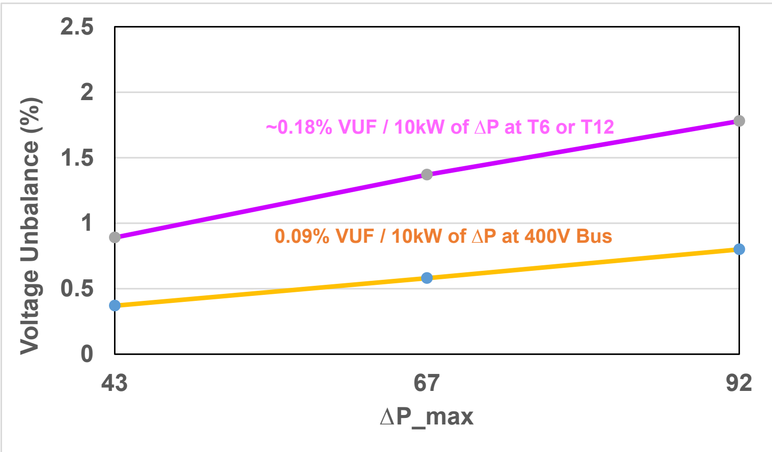


Fig. 6.12. Unbalanced Simulation Results for IS: PV100% battery 66% UB 12:08:04 and OS: battery charging.

2. Integration Scenario PV100_B66_UB12.9.3 and Battery Charging

In this scenario, the battery power unbalance ratio between consecutive phases is 12:09:03 with SF=1, 18:13.5:4.5 with SF=1.5 and 24:18:06 with SF=2, and respectively, the battery penetration level is 24%, 36%, and 48% of the transformer rating i.e., 500kVA.

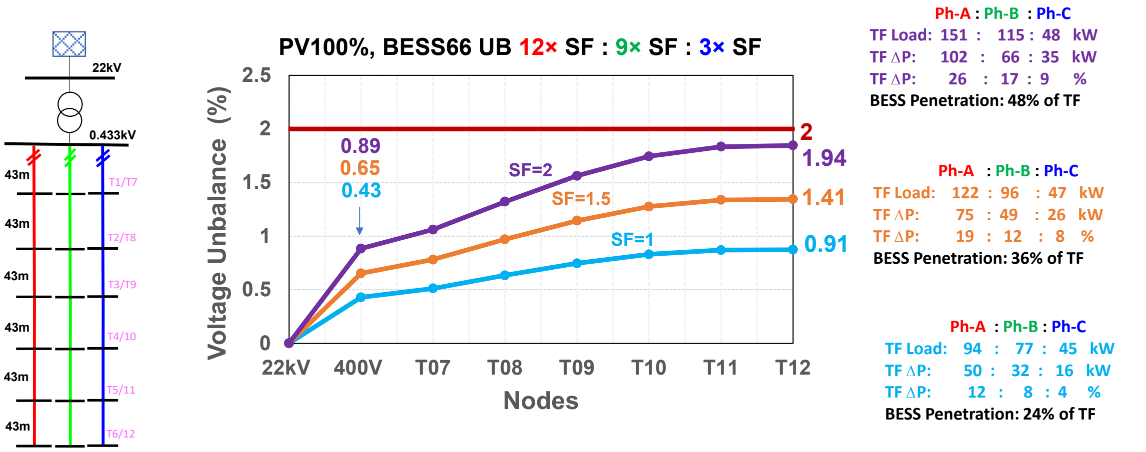


Fig. 6.13 - Unbalanced Simulation Results for IS: PV100% battery 66% UB 12:09:03 and OS: battery charging

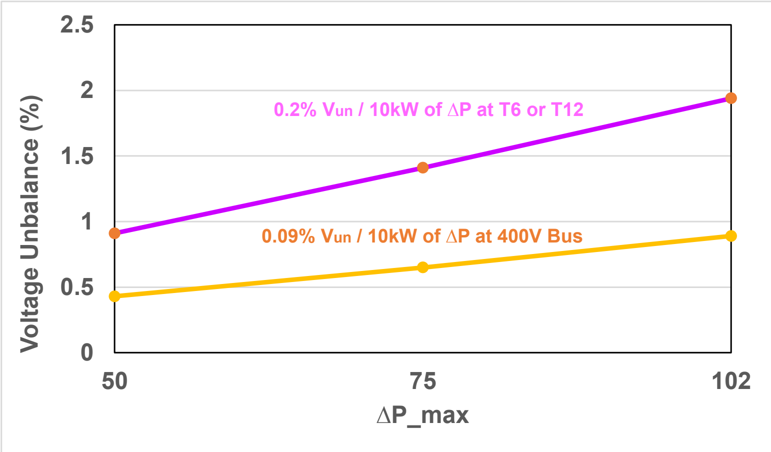


Fig. 6.14 - Unbalanced Simulation Results for IS: PV100% battery 66% UB 12:09:03 and OS: battery charging

3. Integration Scenario PV100_B50_UB11.5.2 and Battery Charging

In this scenario, the battery power unbalance ratio between consecutive phases is 11:05:02 with SF=1, 16.5:7.5:3 with SF=1.5 and 22:10:04 with SF=2, and respectively, the battery penetration level is 18%, 27%, and 36% of the transformer rating i.e., 500kVA.

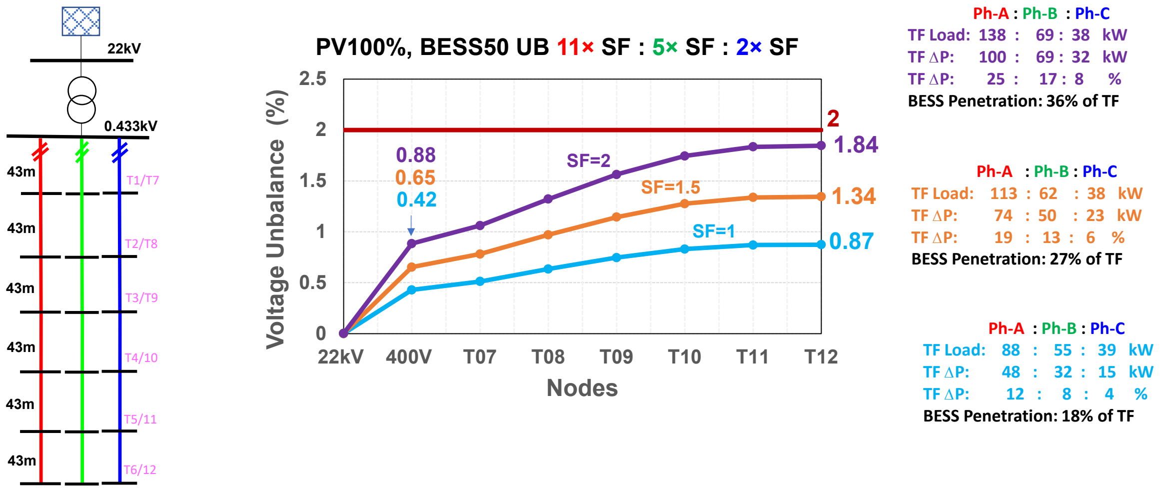


Fig. 6.15 - Unbalanced Simulation Results for IS: PV100% battery 50% UB 11:05:02 and OS: battery charging

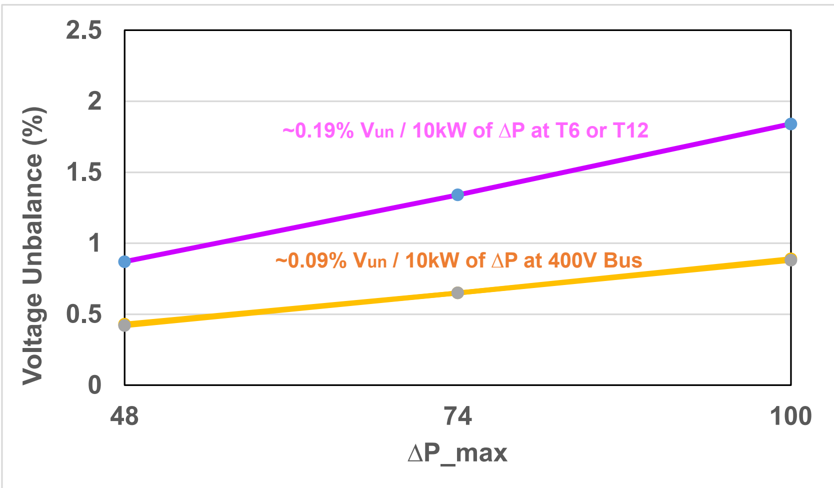


Fig. 6.16- Unbalanced Simulation Results for IS: PV100% battery 50% UB 11:05:02 and OS: battery charging

4. Integration Scenario PV100_B50_UB11.4.3 and Battery Charging

In this scenario, the battery power unbalance ratio between consecutive phases is 11:04:03 with SF=1, 16.5:6:4.5 with SF=1.5 and 22:08:06 with SF=2, and respectively, the battery penetration level is 18%, 27%, and 36% of the transformer rating i.e., 500kVA.

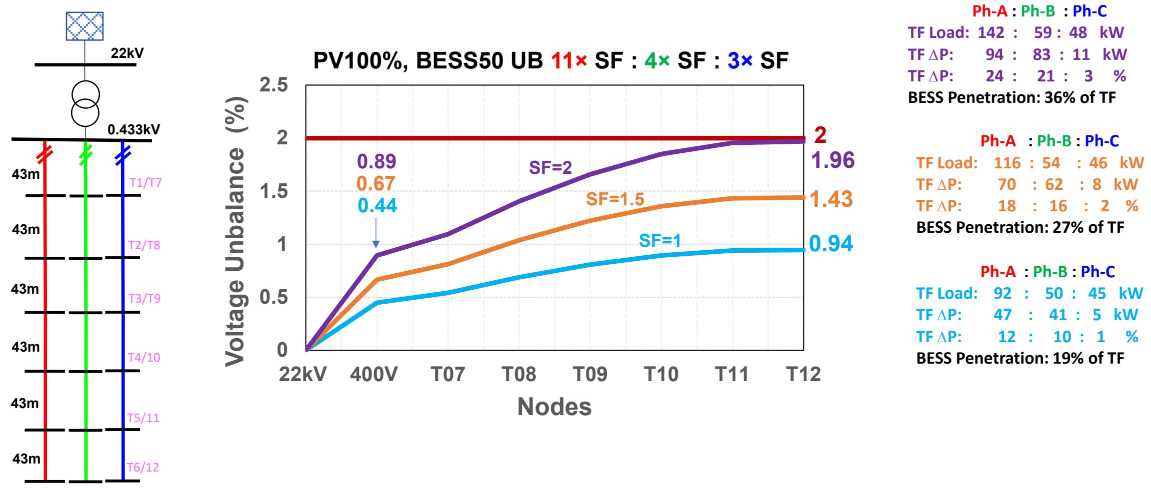


Fig. 6.17 - Unbalanced Simulation Results for IS: PV100% battery 50% UB 11:04:03 and OS: battery charging

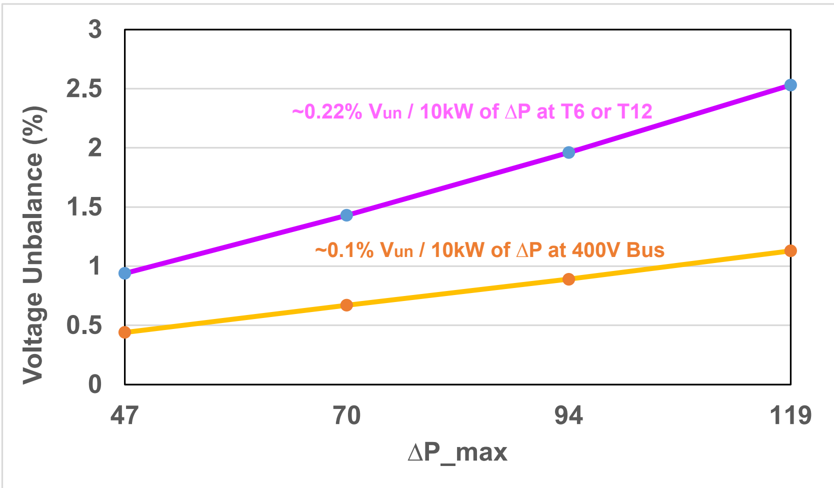


Fig. 6.18 - Unbalanced Simulation Results for IS: PV100% battery 50% UB 11:04:03 and OS: battery charging

5. Integration Scenario PV100_B66_UB12.8.4 and Battery discharging

In this scenario, the battery power unbalance ratio between consecutive phases is 12:08:04 with SF=1, 18:12:08 with SF=1.5 and 24:16:08 with SF=2, and respectively, the battery penetration level is 24%, 36%, and 48% of the transformer rating i.e., 500kVA.

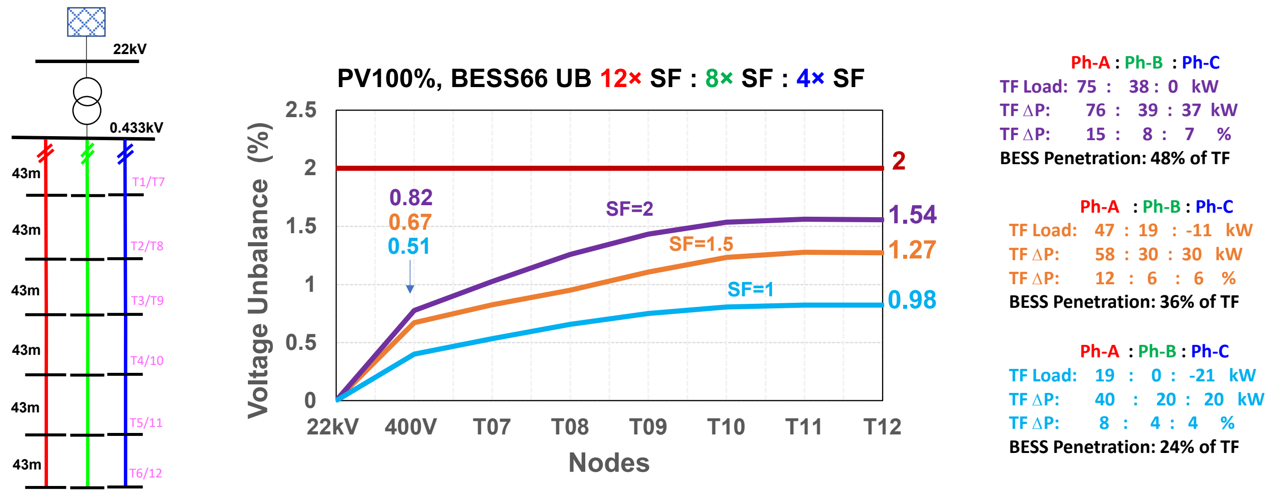


Fig. 6.19 - Unbalanced Simulation Results for IS: PV100% battery 66% UB 12:08:04 and OS: battery discharging

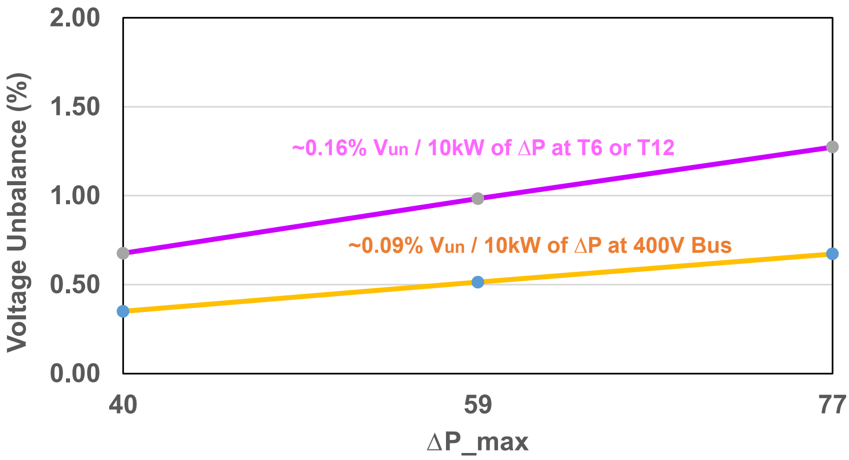


Fig. 6.20 - Unbalanced Simulation Results for IS: PV100% battery 66% UB 12:08:04 and OS: battery discharging

6. Integration Scenario PV100_B66_UB12.9.3 and Battery discharging

In this scenario, the battery power unbalance ratio between consecutive phases is 12:09:03 with SF=1, 18:13.5:4.5 with SF=1.5 and 24:18:06 with SF=2, and respectively, the battery penetration level is 24%, 36%, and 48% of the transformer rating i.e., 500kVA.

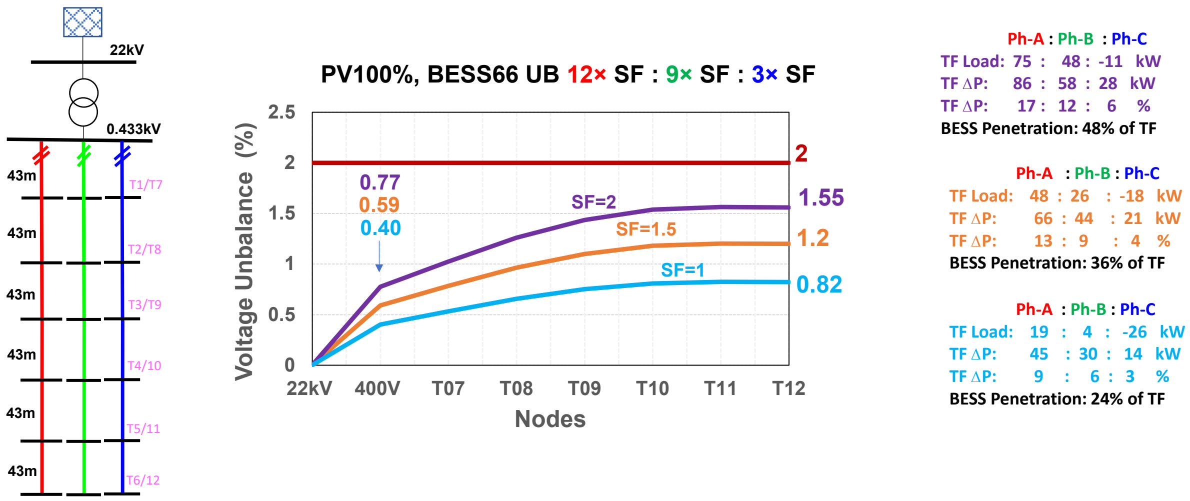


Fig. 6.21 Unbalanced Simulation Results for IS: PV100% battery 66% UB 12:09:03 and OS: battery discharging

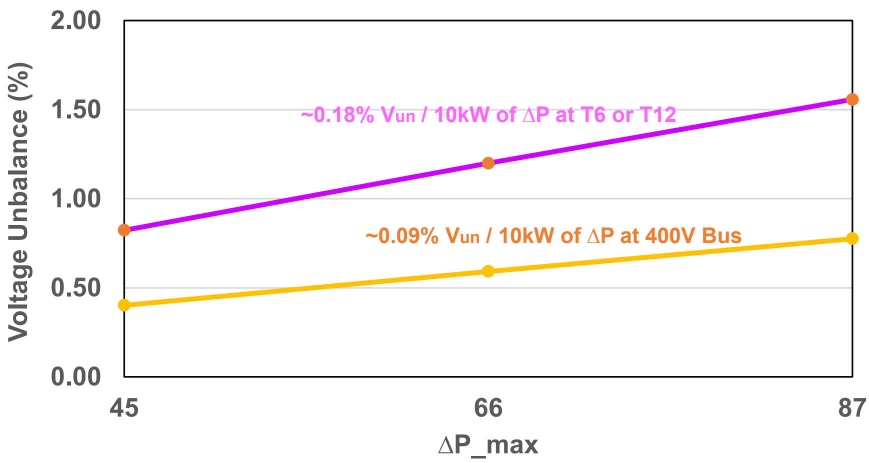


Fig. 6.22 - Unbalanced Simulation Results for IS: PV100% battery 66% UB 12:09:03 and OS: battery discharging

7. Integration Scenario PV100_B50_UB11.5.2 and Battery discharging

In this scenario, the battery power unbalance ratio between consecutive phases is 11:05:02 with SF=1, 16.5:7.5:3 with SF=1.5 and 22:10:04 with SF=2, and respectively, the battery penetration level is 18%, 27%, and 36% of the transformer rating i.e., 500kVA.

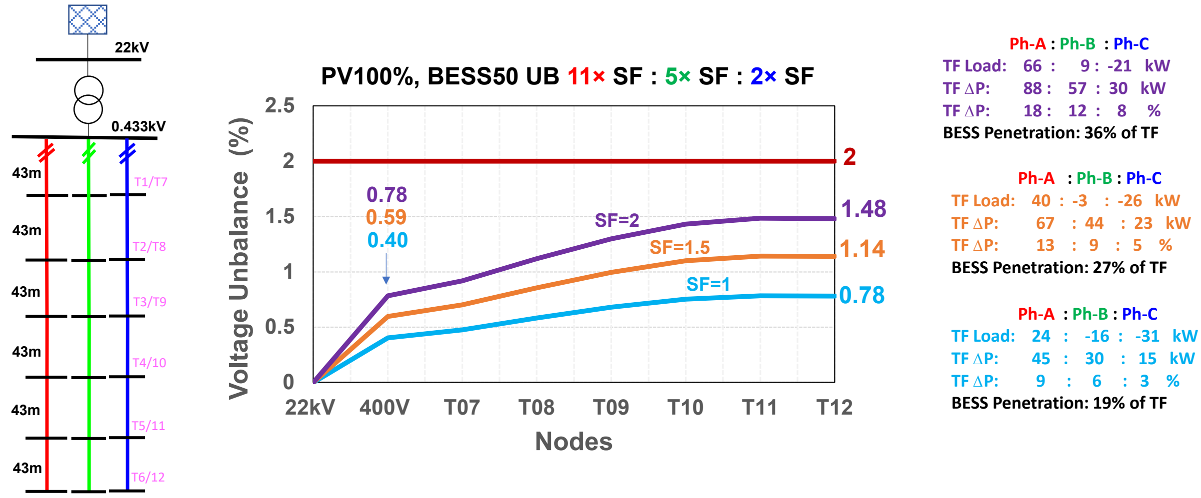


Fig. 6.23 - Unbalanced Simulation Results for IS: PV100% battery 50% UB 11:05:02 and OS: battery discharging

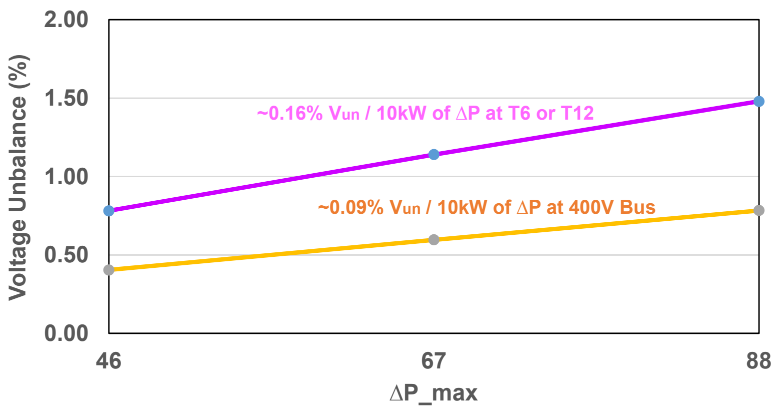


Fig. 6.24 - Unbalanced Simulation Results for IS: PV100% battery 50% UB 11:05:02 and OS: battery discharging

8. Integration Scenario PV100_B50_UB11.4.3 and Battery discharging

In this scenario, the battery power unbalance ratio between consecutive phases is 11:04:03 with SF=1, 16.5:6:4.5 with SF=1.5 and 22:08:06 with SF=2, and respectively, the battery penetration level is 18%, 27%, and 36% of the transformer rating i.e., 500kVA.

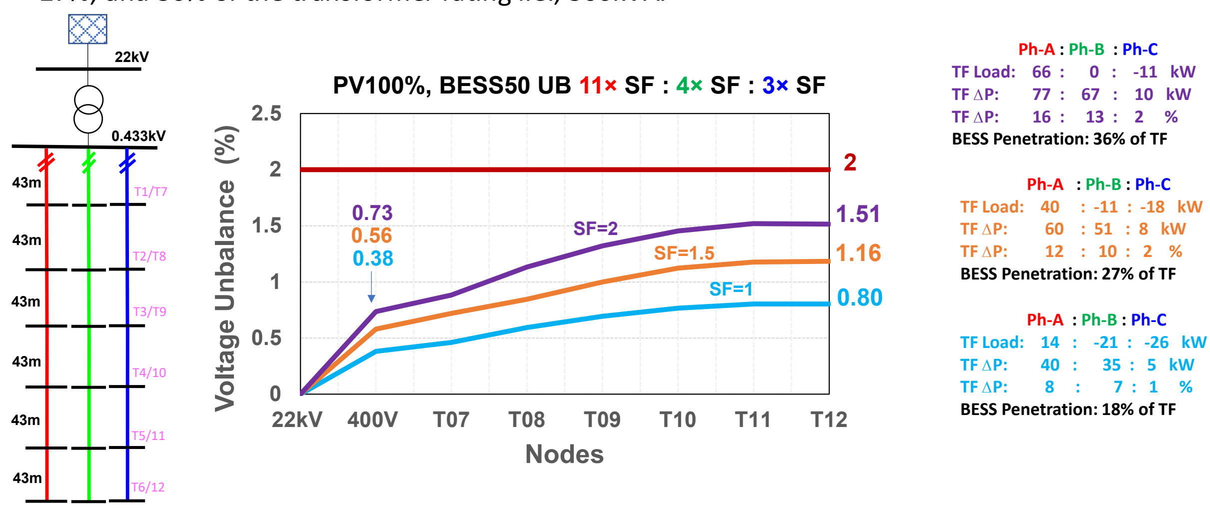


Fig. 6.25 - Unbalanced Simulation Results for IS: PV100% battery 50% UB 11:04:03 and OS: battery discharging

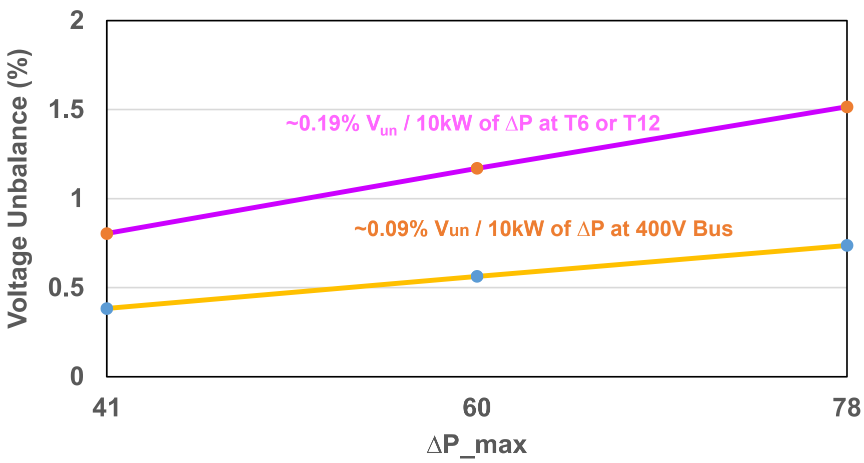


Fig. 6.26 - Unbalanced Simulation Results for IS: PV100% battery 50% UB 11:04:03 and OS: battery discharging

Practical Distribution Network

Load Flow Results

The load flow results for the practical distribution network are shown in Fig. 6.27. The worst-case VUF at G9.3 Bus is ~1% when the transformer phase A is loaded at 90%. This implies that every ΔP=10kW creates VUF of 0.23%, which is slightly higher compared to the typical network. The difference is however small and is expected due to different feeders' lengths in the networks.

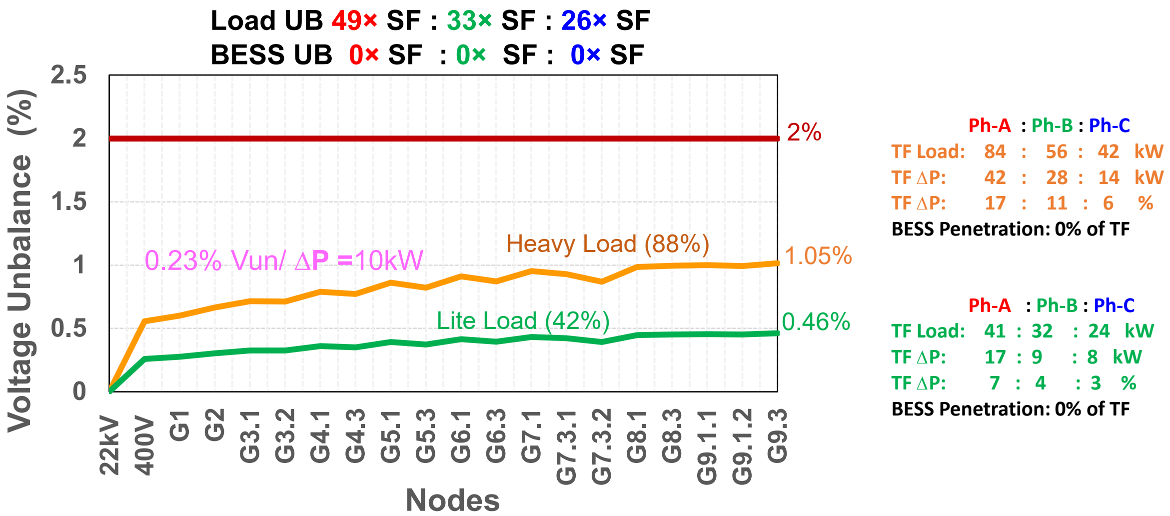


Fig. 6.27 - Load Flow results for the Practical Distribution Network.

Heavy load and battery discharging scenario.

In this scenario, the battery units are integrated with the same unbalance ratio as the customer connection, i.e., 55 on Phase A, 39 on phase B, and 32 on Phase C, and the battery units are set to discharge.

The results show that,

- The VUF is improved from 1% to 0.58% when the battery is discharging during high load demand.

- Each battery supplies power to the local loads, reducing the flow of power in the network. Consequently, the VUF is improved as compared to the load only case.

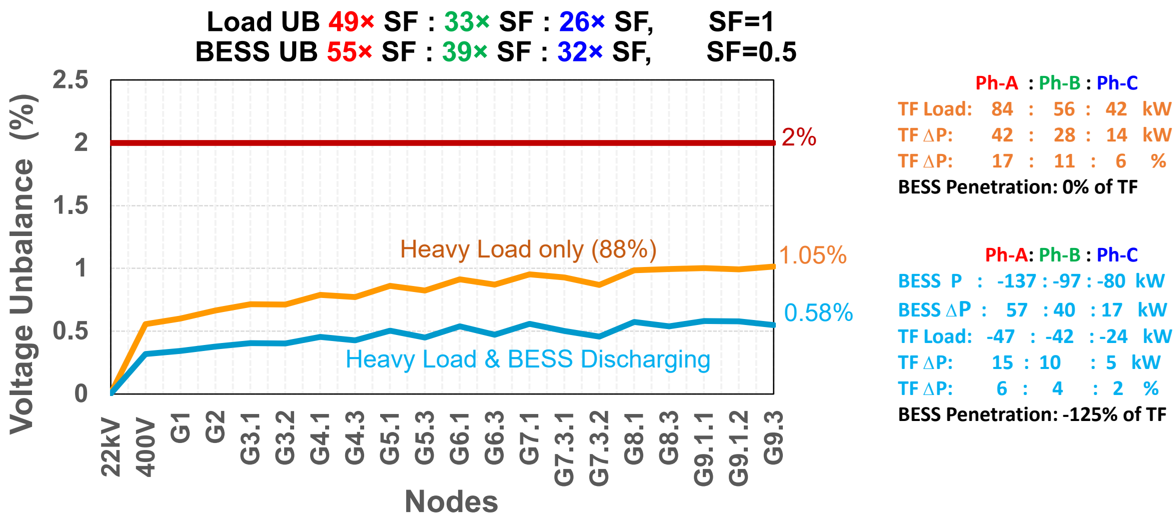


Fig. 6.28 Unbalanced Simulation Results for IS: battery UB 55:39:32 and OS: battery discharging.

Light load and battery charging scenario.

The unbalance connection of customers restricts the charging of battery from the grid, especially during the heavy load. Therefore, the charging of battery is only possible during the light load condition and results for this scenario are shown in Fig. 6.29. The results suggest that,

- The battery power imbalance of 23kW and overall combined power imbalance of 45kW creates VUF of ~1%, which is far below the regulatory limit, i.e., 2%.
- The practical case of the battery (and load) imbalance will not breach the voltage unbalance limit of 2% for the given unbalance ratio of the customer connections.

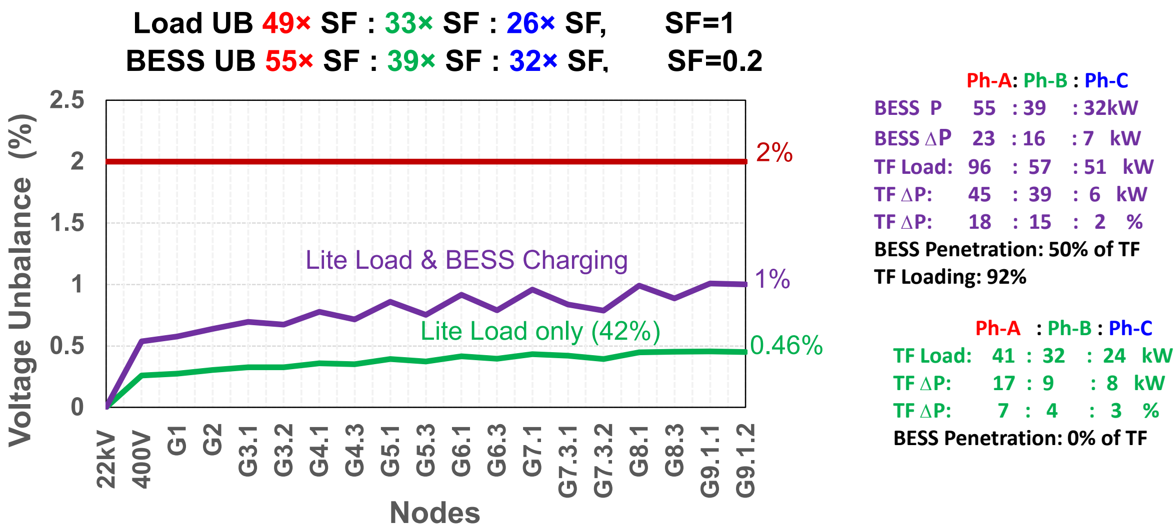
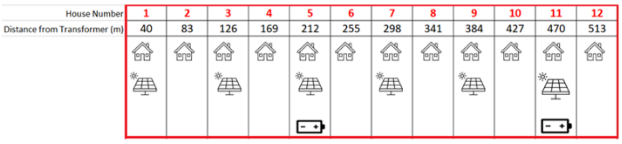


Fig. 6.29 - Unbalanced Simulation Results for IS: battery UB 55:39:32 and OS: battery discharging.

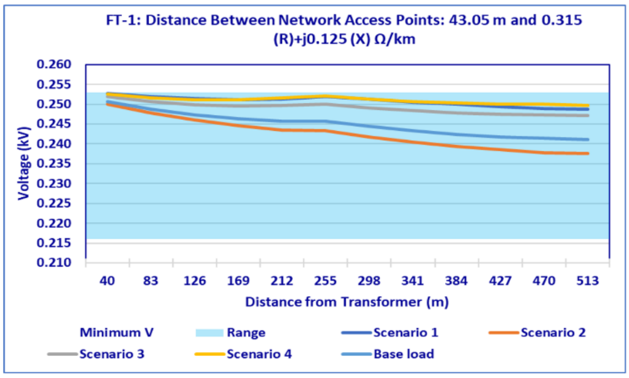
6.5 Balanced Simulation Study Integration Scenarios 2 and 3 Results

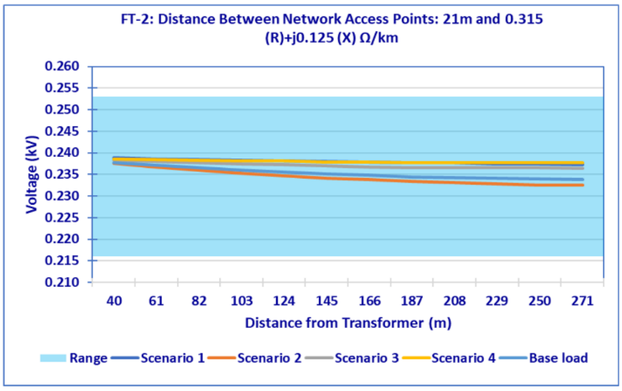
Integration Scenario-2 (IS2– 50% consumers have PV, out of them, 33% has a battery)

The voltage variation for low load scenarios (1.8 kW) are shown in Fig. 6.30.



1.8 kW	Scenario Description			
	Battery Charging		Battery Discharging	
Scenario Number	PV (kW)	Battery (kW)	PV (kW)	Battery (kW)
Scenario 1	5	-5		
Scenario 2	1	-5		
Scenario 3			0	5
Scenario 4			1	5





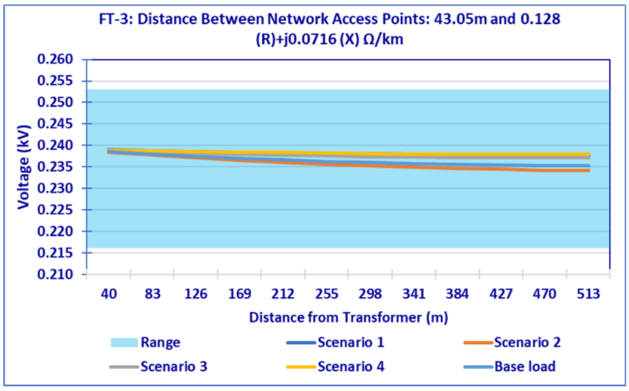
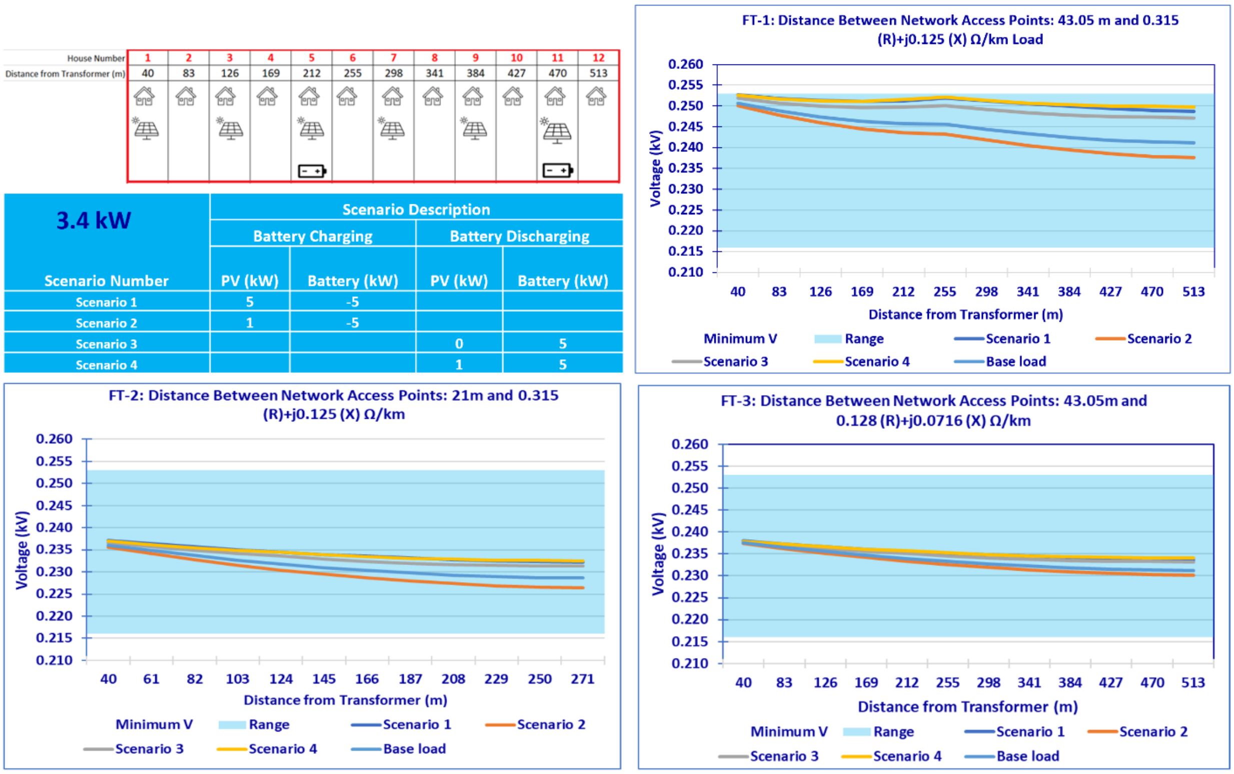


Fig. 6.30 – IS2 voltage variations for low load scenarios (1.8 kW).

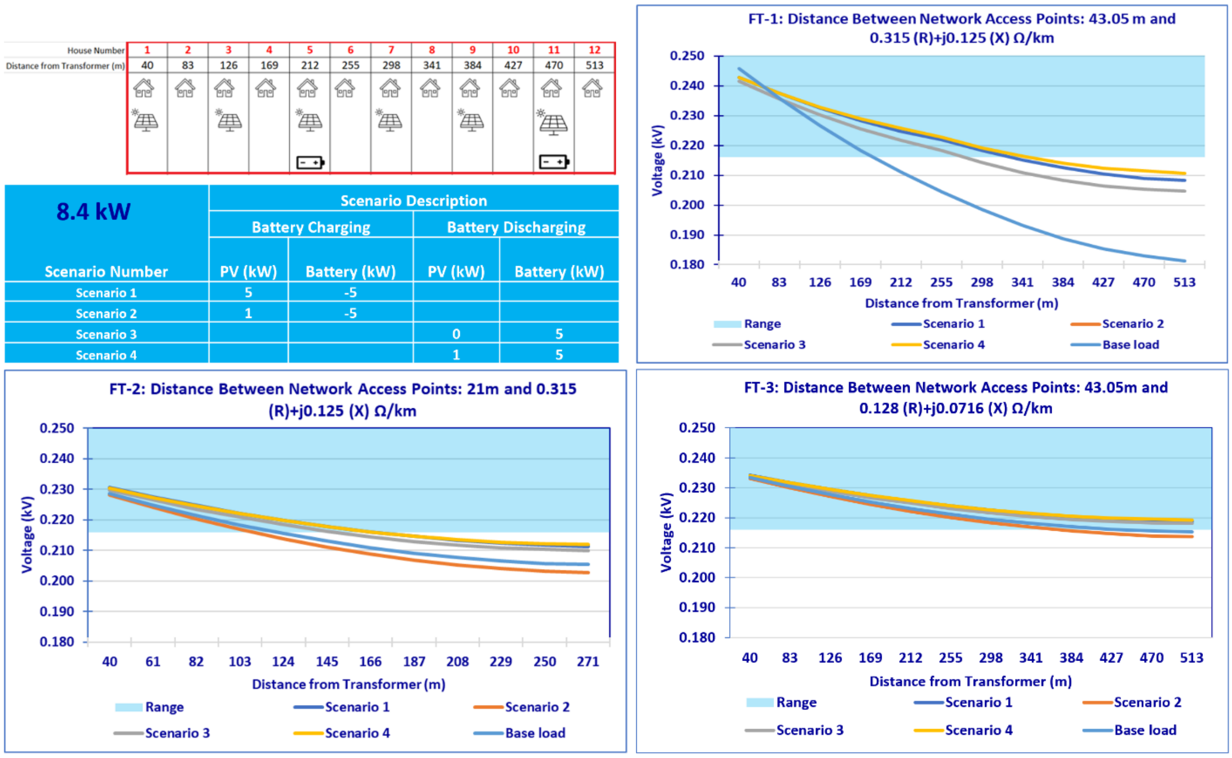
The voltage variation for medium load scenarios (3.4 kW) are shown in Fig. 6.31.



3.4 kW	Scenario Description			
	Battery Charging		Battery Discharging	
Scenario Number	PV (kW)	Battery (kW)	PV (kW)	Battery (kW)
Scenario 1	5	-5		
Scenario 2	1	-5		
Scenario 3			0	5
Scenario 4			1	5

Fig. 6.31 – IS2 voltage variations for medium load scenarios (3.4 kW).

The voltage variation for high load scenarios (8.4 kW) are shown in Fig. 6.32.

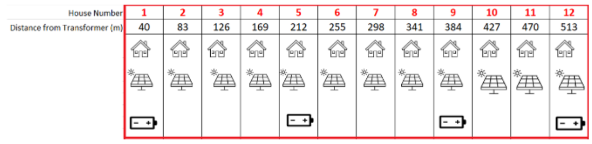


8.4 kW	Scenario Description			
	Battery Charging		Battery Discharging	
Scenario Number	PV (kW)	Battery (kW)	PV (kW)	Battery (kW)
Scenario 1	5	-5		
Scenario 2	1	-5		
Scenario 3			0	5
Scenario 4			1	5

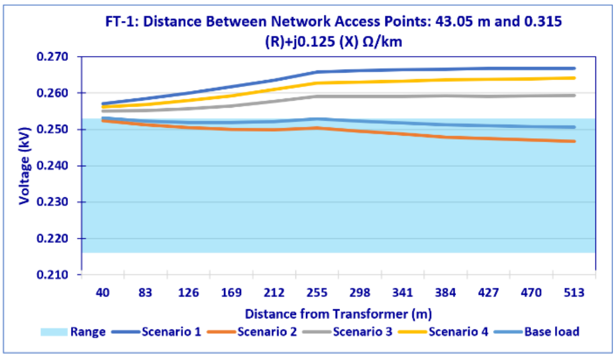
Fig. 6.32 – IS2 voltage variations for high load scenarios (8.4 kW).

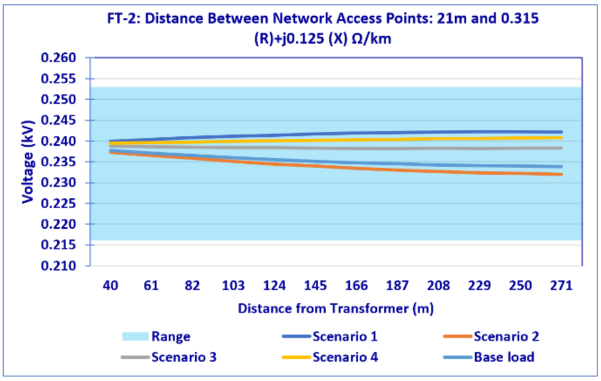
Integration Scenario-3 (IS3–100% consumers have PV, out of them 33% has a battery)

The voltage variation for low load scenarios (1.8 kW) are shown in Fig. 6.33.



1.8 kW	Scenario Description			
	Battery Charging		Battery Discharging	
Scenario Number	PV (kW)	Battery (kW)	PV (kW)	Battery (kW)
Scenario 1	5	-5		
Scenario 2	1	-5		
Scenario 3			0	5
Scenario 4			1	5





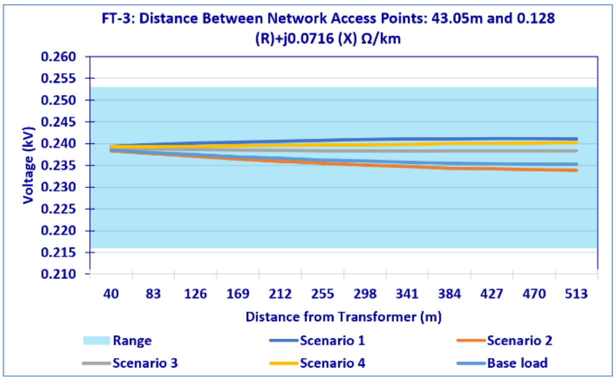
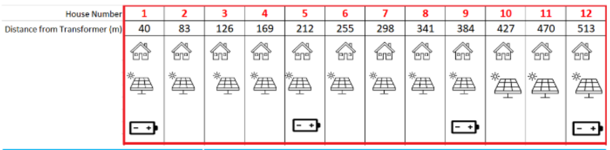
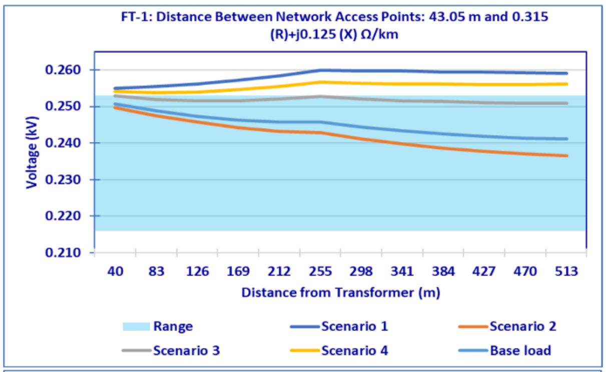


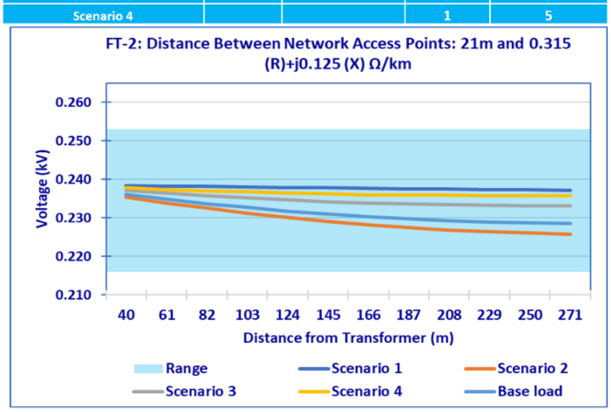
Fig. 6.33 – IS3 voltage variations for low load scenarios (1.8 kW).

The voltage variation for medium load scenarios (3.4 kW) are shown in Fig. 6.34.



3.4 kW	Scenario Description			
	Battery Charging		Battery Discharging	
Scenario Number	PV (kW)	Battery (kW)	PV (kW)	Battery (kW)
Scenario 1	5	-5		
Scenario 2	1	-5		
Scenario 3			0	5
Scenario 4			1	5





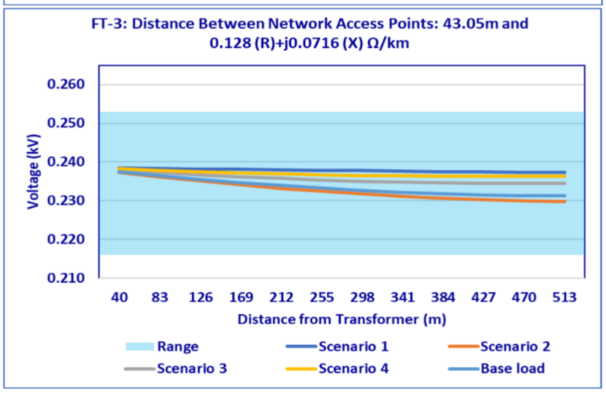
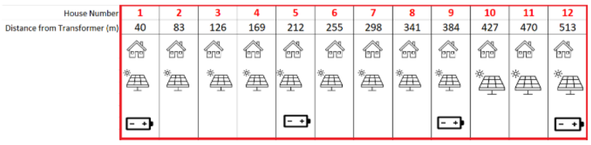
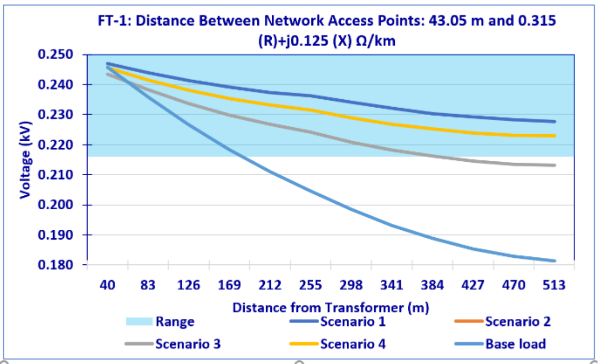


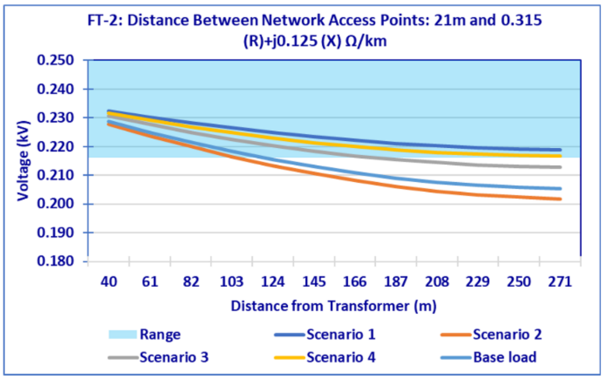
Fig. 6.34 – IS2 voltage variations for medium load scenarios (3.4 kW).

The voltage variation for high load scenarios (8.4 kW) are shown in Fig. 6.35.





8.4 kW	Scenario Description			
	Battery Charging		Battery Discharging	
Scenario Number	PV (kW)	Battery (kW)	PV (kW)	Battery (kW)
Scenario 1	5	-5		
Scenario 2	1	-5		
Scenario 3			0	5
Scenario 4			1	5



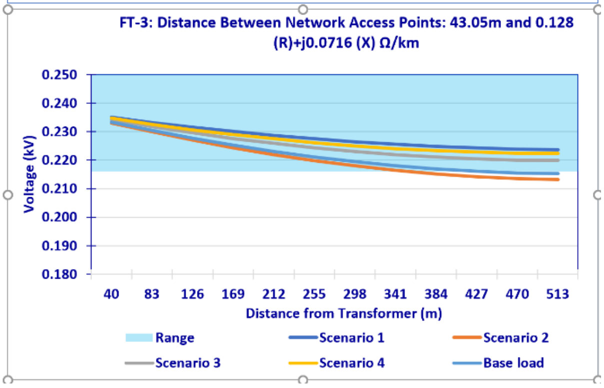


Fig. 6.35 – IS2 voltage variations for high load scenarios (8.4 kW).

End of Report