ASSESSING THE UNMANAGED EV HOSTING CAPACITY OF AUSTRALIAN RURAL AND URBAN DISTRIBUTION NETWORKS

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ABSTRACT

This paper investigates the ability of Australian rural and urban distribution networks to host unmanaged residential electric vehicle (EV) charging, also known as EV Hosting Capacity. This study involves six fully-modelled high voltage (HV) (22kV and 11kV, known as HV in Australia) feeders and pseudo-low voltage (LV) (0.4kV) networks from the States of Victoria, New South Wales and Tasmania. The pseudo-low voltage networks make it possible to capture the effects close to end users. Highly-granular time-series analyses (1-minute resolution) using realistic demand and EV profiles are performed considering growing penetrations of EVs. Results suggest that urban feeders can have larger EV hosting capacity than rural ones (up to 80% vs up to 40%). Furthermore, the first limiting factor is asset congestion, particularly, the LV distribution transformers.

INTRODUCTION

Distribution networks were originally designed to cope with peak demand. Depending on the State or Territory in Australia, that design value can vary from 3 to 7kW per house (single phase) which accounts for diversity and demographics. Although distribution networks have been engineered to withstand demand growth, this does not include EVs (current trend is Level 2 chargers with around 7kW of demand [1]). While all EVs will not be charged at the same time, they are a concern for distribution companies as the extra demand could exceed the design limits. Therefore, we need to understand the extent to which networks can host unmanaged EVs, i.e., without any EV control strategy and/or special time-of-use tariffs.

This paper presents the modelling considerations and results of a highly-granular, detailed EV hosting capacity assessment done on six Australian urban and rural networks in Tasmania (TAS), New South Wales (NSW), and Victoria (VIC). This involves fully-modelled real high voltage (HV) (22kV and 11kV, knows as HV in Australia) feeders, provided by the distribution companies, and pseudo low voltage (LV) (0.4kV) networks to capture the effects close to end users. The network models were validated to ensure that the demand and generation profiles of residential and non-residential customers connected to the pseudo-LV feeders produce a similar aggregated behaviour at the head of the HV feeder as recorded by SCADA measurements. The validated integrated HV-LV models represent the base case of a peak demand day (worst case scenario for EV hosting capacity). EVs are modelled based on real EV data from the UK EV trial "Electric Nation" [2]. Data is used from this trial to construct realistic 1-min resolution time-series EV profiles based on real plug-in times and charging durations.

The results were part of the 2-year collaborative project "EV Integration" between Energy Networks Australia (ENA), the Australian Power Institute (API), the Centre for New Energy Technologies (C4NET), and The University of Melbourne, as part of the ENA and API's Australian Strategic Technology Program [3]. The full summary report can be found in [4]. To the authors knowledge, no such impact assessment has considered several real HV feeders with varying design features across different regions, modelled with corresponding LV feeders down to the customer connection point, thereby forming realistic HV-LV integrated models. Modelling the customer connection point is essential in an accurate EV hosting capacity assessment to assess customer voltages.

MODEL-BASED APPROACH

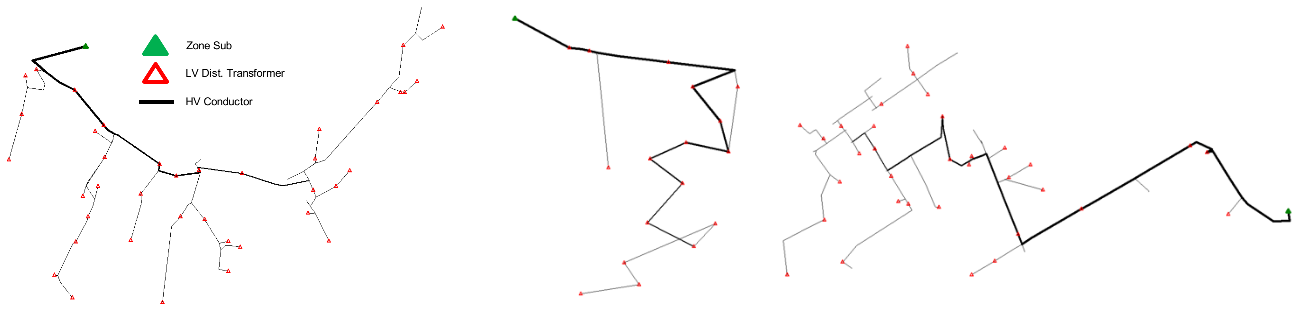
A model-based approach uses an explicit electrical model of the corresponding distribution network (including its topology, elements, parameters, etc.) that in turn allows to run power flow simulations (using specialised software packages) for different demand/generation scenarios. This is a well-known approach used routinely by distribution companies in Australia and around the world to design, plan and improve their networks. To investigate the hosting capacity of distribution networks for EVs, it is vital to perform time-series simulations to adequately capture time-dependent aspects of demand and generation allowing an accurate assessment of impacts. Furthermore three-phase unbalanced simulations should be conducted where possible and explicitly model LV feeders to fully capture voltage related limitations to EV hosting capacity.

HV Feeder Selection

The six HV feeders, shown in Fig.1 to Fig.3 and summarised in Table I, were identified and selected by the distribution companies using their know-how and expert views and considering several characteristics (rural, urban, length, number of customers, etc.) to capture an adequate spectrum across Australia within the timeframe available. The selected HV feeders are a mix of HV feeder types covering both urban and rural feeders as well as different voltage levels (11kV and 22kV). There is an inherent trade-off between the quality and availability of data (conductor information, SCADA measurements, GIS coordinates, customer information, etc.) as well as the corresponding data extraction complexity and associated time restrictions, both in finding and extracting this data as well as converting it into HV-LV network models. Some of the key characteristics to select the HV feeders provided by the distribution companies: available information related to SCADA data for validation, LV transformer

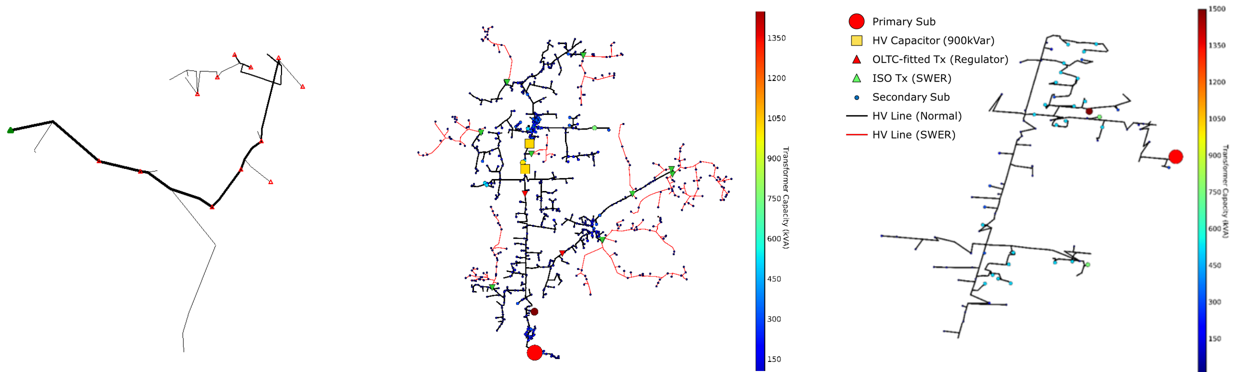
TABLE I. HV FEEDER INFORMATION SUMMARY

Feeder Name	Voltage Level	Total Number of Cust	Number of LV Dist Tx	HV Length (km)	Res LV ADMD (kW)	Avg Res Peak (kW)	Res PV Pen	Avg Res PV Size (kW)
Rural NSW	11kV	1401	39	20	6.5	2.0	24%	3.8
Urban NSW	11kV	616	17	6	6.5	2.0	30%	5.8
Rural TAS	22kV	1506	33	11	5.0	3.0	0%	-
Urban TAS	11kV	620	12	6	5.0	3.5	0%	-
Rural VIC	22kV	3669	765	486	4.0	2.0	0%	-
Urban VIC	22kV	3383	80	30	4.0	2.0	0%	-



(a) (b) (c)

Figure.1. HV Feeders: (a) Rural NSW, (b) Urban NSW, (c) Rural TAS



(a) (b) (c)

Figure.2. HV Feeders: (a) Urban TAS, (b) Rural VIC, (c) Urban VIC

information, number of customers per LV transformer, extent of PV installations, design voltages and line ratings.

HV-LV Feeder Modelling

Table I presents technical information about the HV feeders. Since LV feeder information is not readily available from most distribution companies (unlike the HV feeder models which are available), LV networks are modelled based on the number of customers per distribution transformer, planning residential after diversity maximum demand (ADMD) values used by the distribution companies and design principles (e.g., length, conductor, distribution of customers, etc.) [5]. By modelling the LV networks, even if not exactly as in reality, it is possible to have a better quantification of the impacts closer to LV customers, in particular, voltages at the customer connection points. These form so-called pseudo-LV feeder models. Data related to NSW and TAS HV feeders were supplied as part of the project, whereas the VIC HV feeders were already fully modelled in a previous project ("Advanced Planning of PV-Rich Distribution Networks" [6]).

Validation of the HV-LV networks is performed with the objective of ensuring that the demand and generation (where applicable) profiles of residential and non-residential customers connected to the pseudo-LV feeders produce a similar aggregated behaviour at the head of the HV feeder as recorded by SCADA measurements. This ensures that the integrated HV-LV models mimic the real behaviour to the extent that is possible (given the limited data availability). The validated integrated HV-LV models represent the base case to which EVs are added. Due to space limitations, further information on the HV and LV feeder creation and validation can be found in [4].

EV MODELLING

EVs are modelled based on real EV data from the UK EV trial "Electric Nation", which when launched in 2017 was the world's largest home smart charging trial with nearly 700 EV owners [2]. Having assessed its suitability for Australia, data is used from this trial to construct realistic 1-min resolution time-series EV profiles based on the real plug-in times and charging durations. The following key remarks for the EV modelling considerations are listed below:

- EV Data. Four pools of time-series 1-min resolution EV demand profiles have been created by type of day (weekday/weekend) and charger size (Level 1/Level 2), each with 1,200 profiles.
- Weekdays. From the perspective of EV impact analyses, the EV demand of interest corresponds to weekdays. Therefore, weekday profiles (from both level 1 and level 2 pools) are used to assess the effects of EVs on the integrated HV-LV feeders.
- Charger Size. 80% of EVs are assumed to be equipped with Level 2 chargers (7.36kW), 20% of EVs are assumed to be equipped with Level 1 chargers (3.68kW).
- EV Penetration. EV penetration is defined as the percentage of houses with a single EV. Since it is expected that eventually around 60% of houses will have two EVs (similar to regular cars), the maximum EV penetration to be considered is 160%, i.e., every house has one EV, and 60% of them have a second EV.
- Multiple EVs per House. To create profiles for multiple EVs per household, the charging setup for each house must be considered. Two Level 1 chargers or a single Level 1 charger and a single Level 2 charger will not cause an issue for a typical residential single-phase connection and, therefore, can be directly assigned demand profiles. For two Level 2 chargers, a dual-headed Level 2 charger is considered which results in an adapted profile in which the excess demand (above 7.36kW) is deferred, thus extending the total charging duration.
- Diversified EV Demand. Based on the individual EV profiles created, no matter the type of day, the diversified peak demand of Level 2 charging (around 2kW during weekdays and 1.5kW during weekends) is approximately twice that of Level 1. For houses with two EVs, the largest diversified peak corresponds to the use of dual-headed Level 2 charges (around 4kW during weekdays and 3kW during weekends) and is nearly twice the values of a single Level 2 charger.
- Daily Plug-in Factor. Not all the EVs in a given area will have a charging event every day. Assuming that EVs will charge up to 4 days in a week, it is estimated that 70% or less of the existing EVs will have a charging event on the same day.
- Power Factor. A power factor of 0.99 (lagging) is used for all EV demand profiles.

Further information on the creation of EV profiles and EV modelling can be found in [3].

CASE STUDY

Demand and PV Modelling

The NSW and VIC feeders used residential Victorian smart meter data is to model residential customers. In the case of the New South Wales feeders, Victorian smart meter profiles were considered as adequate. A pool of 30-min resolution, year-long (i.e., 17,520 points), anonymized smart meter demand data (i.e., P and Q), collected from 342 individual residential customers in the year of 2014 is used. Using this pool, the yearly demand profiles were broken down in daily profiles, resulting in a pool of ~30,000 profiles. Since the worst-case scenario in the context of EVs is high loading conditions, the day with the highest average demand (14th of January) is selected for residential demand. Individual load profiles from this day within the pool of load profiles are randomly assigned to residential customers.

For the TAS feeders, after discussion with the corresponding distribution company, it was decided that due to the characteristics of their residential demand which includes the widespread use of electric heating, Victorian smart meter data (with a diversified peak of 2kW per customer) would not be suitable. An aggregated residential profile based on measurements was provided by the distribution company for use in both the Rural and Urban TAS feeders. The profile was normalized for application to an appropriately sized average residential peak load value advised by the distribution company for each feeder, shown in Table I under "Avg res peak".

Non-residential demand (corresponding to commercial and industrial loads) is modelled at the secondary busbar of the LV transformers within the HV-LV feeder. After residential demand is modelled in time-series (either with smart meter data or an average residential profile), the profile for non-residential demand is tuned to match SCADA measurements at the head of the HV feeder. The result is a unique non-residential behaviour for each HV feeder, unevenly distributed, which can account for the inflexible nature of the data available for residential load modelling within the LV feeders for each HV feeder and still enable a validated HV-LV feeder.

For simplicity, for the NSW HV feeders, the PV systems are randomly assigned to residential customers across the corresponding HV feeders. For the TAS feeders, no PV information was available, thus, no PV installations are considered in the base case for these two feeders. For the VIC feeders, since they were produced by ("Advanced Planning of PV-Rich Distribution Networks" [6]), the original models without PV were also considered. Datasets of PV irradiance based on Melbourne are used in this task to model the solar PV generation for the day of interest. The clear sky irradiance is used for simplicity but also to capture the highest PV generation. The peak of PV and EV charging occur at different times, potentially leading to both voltage rise and voltage drop within the same day. The resulting voltage rise issues can trigger the need for changes in voltage regulation devices (such as the tap position of off-load tap changers) which in turn can exacerbate voltage drop issues due to EVs.

Network Considerations

Simulations are conducted considering the peak demand

TABLE II. HV FEEDER INFORMATION SUMMARY

Feeder	EV Hosting Capacity							
	20%	40%	60%	80%	100%	120%	140%	160%
Rural NSW	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond
Urban NSW	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond
Rural TAS	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond
Urban TAS	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond
Rural VIC	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond
Urban VIC	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond	V Cust LV TX LV Cond HV Cond

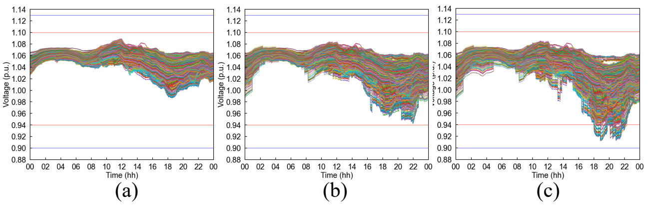


Figure. 3. Rural NSW Residential Customer Voltages for EV Penetration: (a) 0%, (b) 40%, (c) 80%

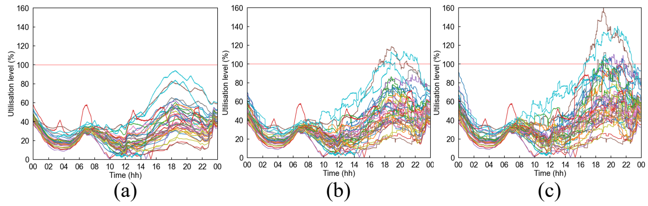


Figure. 4. Rural NSW LV Distribution Transformer Utilisation for EV Penetration: (a) 0%, (b) 40%, (c) 80%

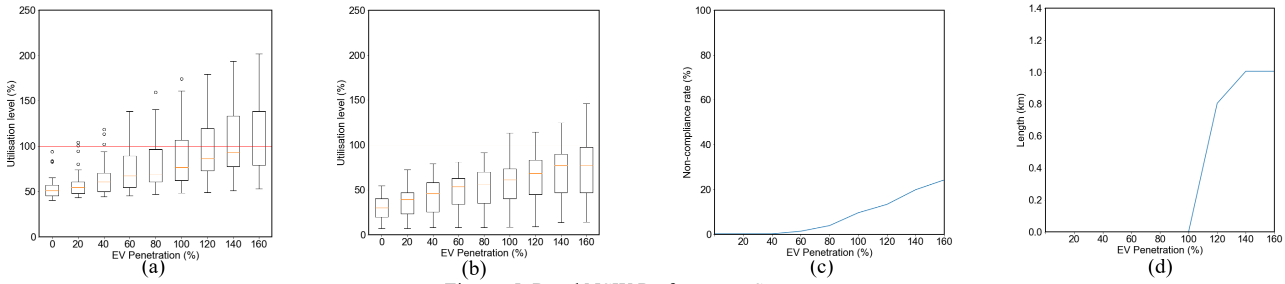


Figure. 5. Rural NSW Performance Summary:
(a) LV Transformer Util, (b) LV Conductor Util, (c) Percentage of customers with a voltage issue, (d) Total length of congested HV conductor

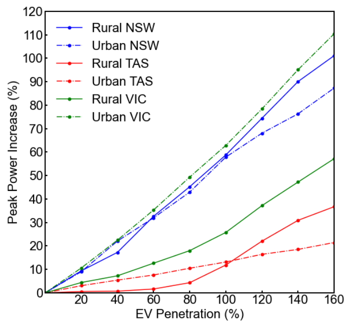


Figure. 6. Increase of Peak Apparent Power for each HV-LV Feeder from the base case at any point across a 24 hour peak demand period

day from residential demand data and validated against SCADA measurements at the head of the feeder that relates to a peak demand day.

The voltage considered for all simulations (base case and with EVs) at the head of the HV feeder is fixed and corresponds to the value used for validation. In practice, this voltage will change throughout the day depending on the upstream network, the net demand of other HV feeders connected to the same zone substation, and the characteristics of the on-load tap changer. However, given that information was limited to only the investigated HV feeder, the fixed value was deemed to be adequate.

Finally, the nominal position of the off-load tap changers used by LV distribution transformers is considered in all the six integrated HV-LV feeders. This is due to a lack of information but is also aligned with distribution companies' practices. Consequently, those distribution transformers will be effectively providing the original natural boost (approximately 8%) due to the transformation ratio used in Australia (e.g., 22kV to 433V or 11kV to 433V). Three-phase unbalanced time-series 1-min resolution simulations are performed in OpenDSS with aforementioned 1-min profiles for EV, residential and non-residential demand as well as any installed PV.

Performance Metrics

• Voltage Compliance. This metric takes the voltage profile calculated for each customer connection point from the power flow simulation to then check if the Australian standard AS 61000.3.100 (+10%/-6%) or Victorian standard (+13%/-10%) [7], depending on the HV feeder, is satisfied. If the customer's voltage does not comply with the standard, then this costumer is considered to have a voltage issue.

• Asset Congestion. To understand the impacts of residential EV charging in the adequacy (capacity to supply demand) of distribution networks, the utilisation level of all HV conductors, LV conductors and LV transformers is calculated for each of the days analysed.

EV IMPACT ASSESMENT

EV penetration is defined as the percentage of residential customers with a single EV. Thus, to assess the impacts for different EV penetrations, each of the six integrated HV-LV feeders will consider nine EV penetrations: from the base case (0%) up to a maximum of 160% in 20% steps. Houses with a second EV are only considered after all houses have one EV (i.e., 100% of EV penetration). The maximum EV penetration of 160% assumes that 60% of houses have a second EV. EV location is randomly assigned across and within the LV feeders up to the EV penetration being investigated. It is important to note that no EV management techniques or time-of-use tariffs that alter EV charging behaviour are considered. This paper focuses on the impacts of unmanaged EVs.

Table II summarises the network impacts from unmanaged residential EV charging. Green indicates the parameter (e.g., customer voltages, LV transformer utilisation, etc.) is within limits, yellow indicates marginally exceeding limits whilst red indicates the limit was greatly exceeded.

Due to space limitations the full time-series results of all six integrated HV-LV feeders across the nine EV penetrations cannot be fully presented. However, for illustration purposes, Fig 3 and 4 show time-series results for Rural NSW at the base case, 40% and 80% EV penetration. It is shown that at 80% voltages drop below the Australian standard shown in red (which is applicable for this feeder), whilst beyond the LV transformer capacities at 40 and 80% EV penetration. Fig. 5. presents a summary of Rural NSW performance across all EV penetrations, showing the transformer utilisation, LV conductor utilisation, percentage of customers with a voltage issue and finally the total length of HV conductor that is congested. For Rural NSW, the hosting capacity is 20%, first limited by LV transformer congestion at 40% followed by customer voltage issues at 60% and beyond. Full time-series and detailed summary results for each HV-LV feeder and EV penetration is found in [4].

It can be seen in Fig. 6. that the by the maximum EV penetration of 160%, the peak power for that day can increase for 80-100% for NSW, 15-40% for TAS and 50-100% for VIC. The varation in these is down to existing residential demand and existing non-residential demand, as well as the base case time peak demand time

CONCLUSION

Overall, rural feeders were found to have an EV hosting capacity of up to 40% of residential customers with an EV. LV transformer utilisation issues can appear with as little as 20% EV penetration for Rural VIC and become wider at 40% for Rural NSW and TAS, including significant customer voltage drops and LV conductor issues. The larger number and smaller size of LV transformers used in rural feeders result in many congested transformers with relatively low EV penetrations. Furthermore, the length of the rural feeders (higher impedances) lead to lower voltages with relatively low EV penetrations.

Urban feeders were found to have an EV hosting capacity of up to 80% of residential customers with an EV. The first limiting factor was asset congestion (LV and HV conductors, or LV distribution transformers). While voltage issues are not significant for urban feeders until high EV penetrations, the high density of customers inevitably leads to a much larger peak demand even with modest EV penetrations, resulting in asset congestion.

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