UNDERSTANDING THE EFFECTS OF EV MANAGEMENT AND TOU TARIFFS ON CUSTOMERS AND DISTRIBUTION NETWORKS

Jing ZHU
The University of Melbourne
Australia
jing.zhu@ieee.org

William J. NACMANSON
The University of Melbourne
Australia
w.nacmanson@ieee.org

Luis F. OCHOA
The University of Melbourne
Australia
luis.ochoa@unimelb.edu.au

ABSTRACT

The adoption of electric vehicles (EVs) poses technical challenges for our distribution networks, which were not designed to cope with the new EV charging demand. To enable high penetrations of EVs without affecting the networks, two approaches are investigated in this paper: a direct approach that manages EV chargers, and an indirect approach that uses Time-of-Use (TOU) tariffs. To evaluate the corresponding effects on both customers and distribution networks, a real Australian MV-LV network with 1,300+ single-phase households is used in the case study. The results show that, if every house in the studied network has an EV (i.e., 100% EV penetration) with unmanaged charging, technical issues will occur mainly in the LV part. On the other hand, both direct and indirect approaches can eliminate network issues, with limited impacts on customer charging. The findings also suggest that distribution companies can hugely benefit from mixing direct and indirect approaches.

INTRODUCTION

The adoption of light-duty electric vehicles (EVs) around the world is increasing as we strive to achieve net-zero emissions. However, the unmanaged charging demand of EVs may result in significant technical problems (i.e., thermal congestions and voltage drops) in the distribution networks as they were not designed for that purpose.

To avoid large-scale network reinforcements and ensure high penetrations of EVs, many optimization algorithms for managing EVs (e.g., [1], [2]) have been proposed. However, these advanced methods require extensive real-time data from smart EV chargers (e.g., state-of-charge, battery size), which is not available for most EV customers today. Moreover, these approaches require a full understanding of the network topology, but most distribution companies around the world do not possess detailed network models of their LV feeders. Thus, more practical methods are needed that can deal with the limited measurements and network information.

Most of the literature that focuses on applying direct EV management approaches consider only the MV part of distribution networks, modelling EV demand as an aggregated load (e.g., [1]). However, thermal congestions in the LV part are usually the first bottleneck for further EV uptake [3]. Consequently, to address this and other issues, not only comprehensive solutions that consider both MV and LV parts are required but also detailed network models and EV demand profiles that can be used to assess the corresponding performance. Furthermore, from the perspective of customers, it is crucial to ensure that any direct approach does not significantly affect their charging times. Many studies consider customer impacts, but mostly from the economic perspective (e.g., charging cost [4]). Thus, the quantification of charging delays is also required to understand the potential drawbacks.

An indirect approach to reduce peak EV demand and thus eliminate network impacts is to use Time-of-Use (TOU) tariffs, which discourage customers from charging during peak hours [5], [6]. There is no requirement for additional data or infrastructure to implement a TOU tariff. However, it is critical to understand what are the most suitable TOU peak hours as well as the required TOU adoption rate of EV customers needed to effectively mitigate issues.

In this context, this paper investigates two approaches to mitigate network impacts from high EV penetrations: a direct approach that uses EV charger management based on a set of rules, and an indirect approach that considers a TOU tariff. To investigate the benefits and drawbacks of the two approaches, a real Australian MV-LV network with 1,300+ households is used in the case study, as well as real residential and EV demand data. Recommendations for each of the strategies are provided based on the results.

METHODOLOGY

This section presents the methodology of the direct approach in which EV chargers are managed, and the indirect approach that adopts a TOU tariff.

Direct Approach: EV Charger Management

As shown in the control architecture (Fig. 1), the rule-based EV charger management is achieved through the remote disconnection and reconnection of chargers in response to real-time measurements. This method is developed based on the previous work [7].

Step 1: Measurement Collection

This rule-based approach does not require detailed network modelling and only a few measurements are used. This makes the approach more practical, since most distribution companies lack comprehensive models of their LV feeders, also limited monitors are available.

At every control cycle (e.g., 10 min, required to be longer than the action time of the charger actuator), the following real-time measurements are collected from EV chargers and monitors at the head of the LV feeders:

- ✓ The powers for each LV transformer (per phase);
- ✓ The currents for each LV feeder (per phase);
- ✓ The voltages at each EV charging point; and,
- ✓ The status of each EV charger (i.e., charging, managed, non-charging).

Step 2: Corrective Disconnection

To mitigate thermal and voltage problems, the number of EVs to disconnect is calculated for each control cycle, following a bottom-up hierarchical approach. There will be two rounds of calculation: the LV feeder level and the LV transformer level.

In the first round, for each LV feeder (connected to a given LV transformer), if the phase current at the head of the feeder exceeds the safety margin α (between 0-1, e.g., 0.9 means 90% of the cable capacity), the number of EVs that must be disconnected from this phase is calculated as the ratio of the exceeding current to the EV charging current. The safety margin is important in this corrective disconnection and the following preventive reconnection as it gives allowance for the incoming EV plug-ins and avoids further congestion.

In terms of the EV charging current, a Level-1 charger of 16A is used in the calculation [8]. Nonetheless, a fast Level-2 charger of 32A is also considered in this study, thus the disconnection of one Level-2 charger will be the equivalent of two Level-1 chargers.

Moreover, to eliminate the voltage drop issues identified in this phase of the LV feeder, the number of non-compliant EV customers (i.e., customers with voltages below the statutory limit $Vmin$ which is 0.94 p.u. in Australia [9]) is recorded. Then, the larger of either the thermal cut or voltage cut is used to determine the number of EVs to disconnect from this LV feeder and phase.

In the second round, the disconnection of EVs due to the LV transformer utilisation only takes effect if the transformer is still overloaded after the first round. For each LV transformer, if the apparent power per phase exceeds the safety margin β (e.g., 0.9 means 90% of the transformer capacity), the number of critical EVs is calculated as the ratio of the exceeding power to the EV charging power (3.6kW for Level-1 charger, 230V).

The last step is to select the most suitable EVs for disconnection. To ensure fairness between EV customers, those with the longest charging duration are considered as the least affected ones, thus they should be disconnected first. Similarly, there are two rounds of selection needed, as the EVs already selected for disconnection in the first round (feeder level) need to be excluded in the second round (transformer level) to avoid overlapping.

Step 3: Preventive Reconnection

If technical issues are not presented at the start of the control cycle, several previously disconnected EVs can be reconnected. Differently from the corrective disconnection, for the reconnection process, the utilisation of LV transformers is first checked. If the transformer is still overloaded, no EVs are reconnected in any of the feeders.

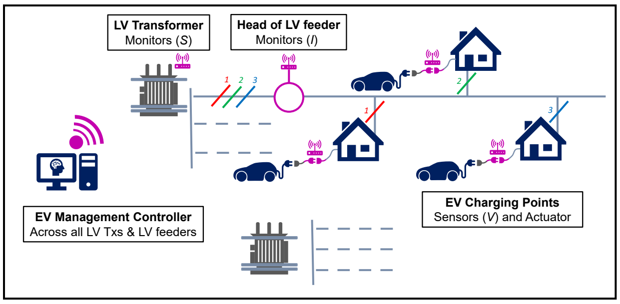

Figure 1. Control Architecture

If the phase apparent power of the given transformer is below the safety margin β of its power capacity, the number of EVs that can be reconnected to this phase is calculated as the ratio of the spare capacity to the EV charging power. A proportional gain is adopted to prevent over-control due to normal load fluctuations. A gain of 0.5 was found to be an adequate value.

Then, the spare current capacity of LV feeders is assessed. For each feeder connected to the transformer, if any of the phase currents is below the security margin α of its cable capacity, the number of EVs that can be reconnected to this phase is calculated as the ratio of the spare current to the EV charging current.

Furthermore, to avoid potential voltage drop issues caused by reconnection, EVs can only be reconnected when all the customer voltages are above the safety voltage limit $(Vmin + \gamma)$.

In terms of the selection of EVs to reconnect, those with the longest disconnection duration are considered as the most affected ones, and should be reconnected first (i.e., adopting a first-out first-in approach). There is only one round of selection at the transformer level, and the feeder spare capacity is checked once the reconnection request is made.

Indirect Approach: Time-of-Use (TOU) Tariff

The adoption of a TOU tariff profile assumes that EV customers will change their charging behaviour as they will be discouraged from charging during certain peak hours. This, in turn, can reduce coincident EV charging events and, thus, mitigate network impacts.

To create the required TOU tariff profiles for assessment, there are two key considerations. First, the TOU peak hours need to be defined as the overlap of both the original residential peak and the EV demand peak, so that the coincident EV charging demand can be shifted away. Second, the peak hours of the TOU tariff should be limited to 4-5 hours for higher customer acceptance.

Thereby, EV demand profiles are modified to not charge during the TOU peak hours and to continue charging immediately afterwards. A second charging peak is thus expected due to the elimination of diversity across the TOU window, which can lead to potential network issues. Fig. 2 presents an example of the original and the modified TOU EV demand profiles considering the peak hours of 5pm to 9pm. The same number of charging minutes occur in the new TOU EV demand profiles. However, there is now much larger EV demand after 9pm which could have a negative effect on the distribution network.

A sensitivity analysis is also carried out to study the potential benefits and drawbacks of different TOU adoption rates (percentages of EV customers changing their behaviours). Different combinations of original and TOU profiles are assessed to determine the required TOU adoption rate for the studied network.

Assessment Metrics

Several performance metrics are adopted in this study to assess the performance of the two approaches considering both distribution network aspects and customers.

- **Asset Utilisation Level (%):** Asset utilisation per phase with respect to their rated capacity. Current utilisation is assessed for feeders, and apparent power utilisation is assessed for transformers.
- **Customer Voltage Non-Compliance (%):** Percentage of customers whose voltages do not meet the local requirements (e.g., within +10%/-6% of the nominal 230V in Australia [9]).
- **EV Customer Charging Delay (hour):** Extended charging duration due to the charger management.

CASE STUDY

Australian MV-LV Network and Profiles

The methodology is demonstrated using a realistically modelled Australian MV-LV network with 1,300+ households from the distribution company Endeavour Energy, as part of the EV Integration project [10]. The topology of the network (MV parts) is illustrated in Fig. 3, and more technical details are provided in Table I.

Each household is assigned a random residential load profile from a pool of 1-min resolution profiles, which was originally created by using real Australian smart meter data from 2014. The demand data from a spring day is adopted to reflect the normal power usage.

An EV penetration of 100% is considered as a worst-case scenario (i.e., every household has an EV). To produce original EV demand profiles, real charging data from 461 EVs as part of the UK Electric Nation project is used, and more modelling details are introduced in [8]. The TOU EV demand profiles are then adopted using the methodology presented above, considering peak hours of 5pm to 9pm as shown in Fig. 2.

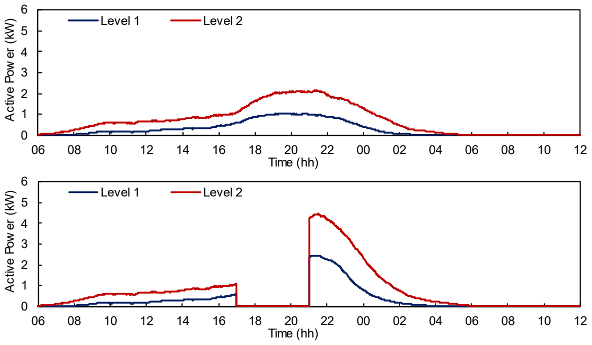

Figure 2. Diversified EV Demand Profiles: Original Profiles (top), TOU Profiles (bottom)

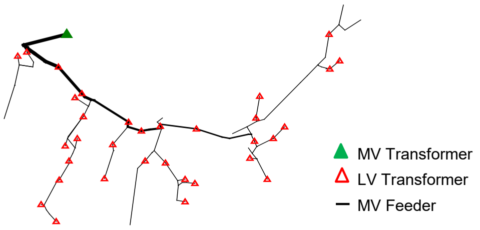

Figure 3. Network Topology (MV parts)

Table I. Network Technical Information

Feeder Region	Voltage Levels	No. of Cust	No. of LV Tx	MV Feeder Length
Rural NSW	11kV/0.4kV	1362	33	20km

Direct Approach: EV Charger Management

With EV penetration of 100%, the studied MV-LV network is problematic with unmanaged EV demand, typically in the LV part. As shown in Fig. 4 (Left), the MV conductors are capable of hosting extra EV demand, but since only 20% of headroom is left, the utilisation level can potentially breach the limit considering the residential demand growth.

The utilisation of LV transformers is assessed per phase to reflect the nature of the unbalanced EV charging demand. Therefore, certain phase of LV transformers will observe severe thermal congestions, typically for those transformers with smaller capacity. The most critical transformer, as seen in Fig. 4 (Left), can have the utilisation over 160% for more than 2 hours, which will exacerbate the asset aging. In comparison, as shown in Fig. 4 (Right), the proposed direct EV management approach significantly reduces the magnitude of thermal overloads. Note that small breaches of the technical limits can still occur but the duration of overloads is now much shorter.

LV feeders can still accommodate the extra EV demand but have already reached the thermal limit at 8pm. More headroom is available with EV management during the peak time as the load has been shifted to later hours. There is one conductor seeing a utilisation level of 100% at 10pm due to the simultaneous EV charger reconnection, which can be further improved by tuning the parameters.

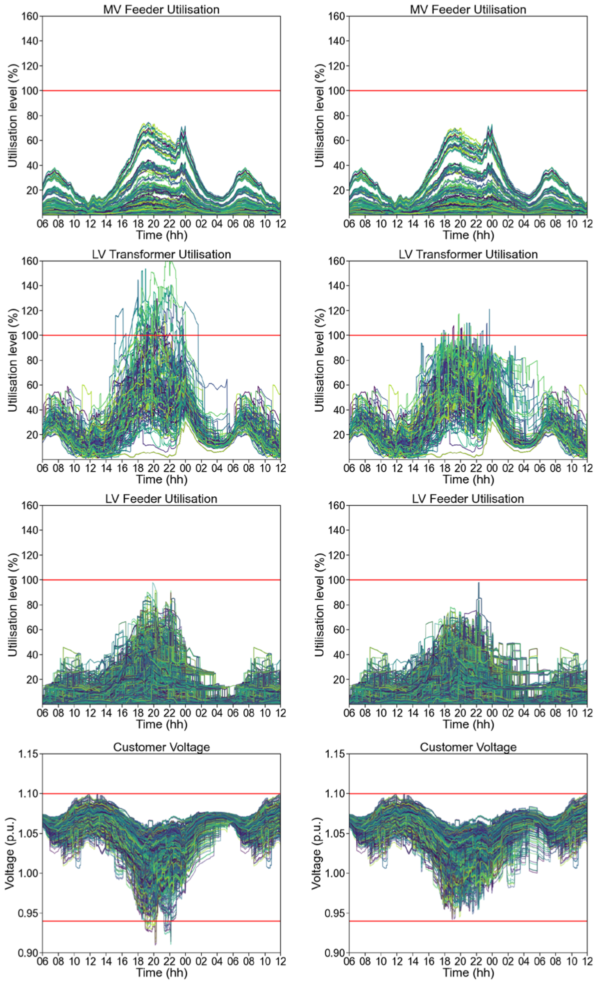

Figure. 4 Power Flow Results – EV Management: (Left) Without Management, (Right) With Management

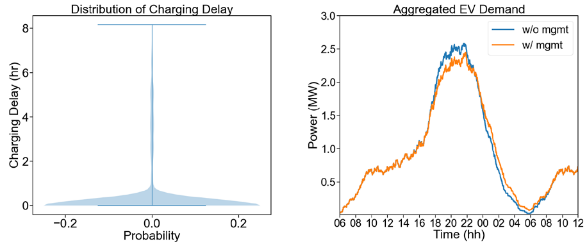

Figure. 5 Impacts on Customers – EV Management: (Left) Charging Delay, (Right) Agg. EV Demand

In terms of the voltage issues, some customers at the end of the LV feeders can experience severe voltage drops due to the coincident charging events in the neighbourhood. By directly managing EV chargers, all the customer voltages are within the statutory limit.

Besides the technical performance of the proposed EV management approach, the charging delays affecting customers need to be quantified. As shown in Fig. 5 (Left), 86% of customers are not affected by the EV charger management (i.e., with a charging delay of zero), and most managed customers experience no more than a 2-hour delay. For some critical customers connected to certain problematic feeders, they can encounter up to an 8-hour delay (which can be considered significant). However, the aggregated EV demand in Fig. 5 (Right) shows that the majority of EV chargers are disconnected during the early evening (6pm to 9pm) and reconnected at midnight. Thus, customers may not complain about this severe delay given that their EVs would have finished charging early in the morning.

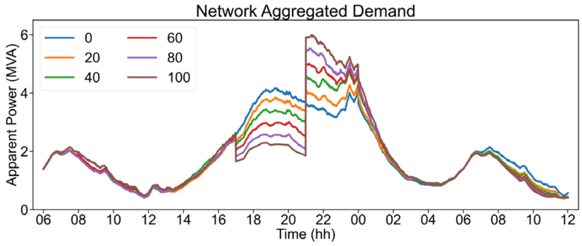

Figure. 6 Network Aggregated Demand - TOU

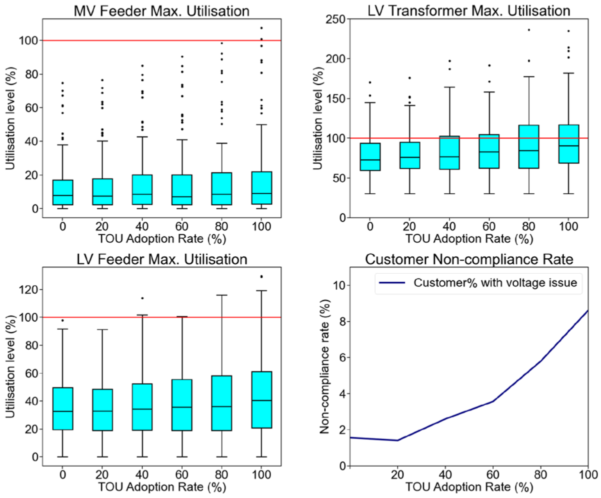

Figure. 7 Power Flow Results - TOU

Indirect Approach: Time-of-Use (TOU) Tariff

The objective of the adopted TOU tariff profile is to understand the required adoption rate of EV customers needed to adapt their behaviour to mitigate network issues. Therefore, TOU adoption rates of 0 to 100% are assessed, in steps of 20%.

By adopting a TOU tariff, the diversification of EV charging times will decrease as those using the tariff will not charge during the same window of 4 hours to then all simultaneously resume charging. This could lead to a second (new) charging peak. As shown in Fig. 6, the second peak of network demand at 9pm can be higher than the original peak, and it might cause new network issues.

The box plots in Fig. 7 present the maximum utilisation of all the assets throughout the day, also the customer voltage non-compliance rate. With 20% TOU adoption rate, the MV feeders and LV transformers maintain the similar utilisation levels compared to the business-as-usual case (0% TOU adoption), and LV feeders see a small decrease in utilisation. Also, less customers have voltage drop issues as the non-compliance rate is lower. However, the second peak becomes a significant issue beyond 40% TOU adoption, leading to worse performance on both thermal and voltage aspects, particularly on the LV parts of the network.

In general, it is found that a TOU adoption rate of 20% yields acceptable results and an improvement for the studied MV-LV network. Furthermore, a staggered TOU tariff (i.e., stages of TOU tariff that start at different times) might be highly beneficial for mitigating issues around a second peak.

Recommendations

The results suggest that the direct approach (rule-based EV charger management) can effectively eliminate the network issues with 100% EV penetration, and with most EV users seeing no or negligible charging delays. The proposed direct approach does not require detailed network models but it does need smart EV chargers. In comparison, no additional data or equipment is required to implement the indirect approach (TOU tariffs). However, since the investigated indirect approach alone cannot provide much benefit due to the occurrence of a second peak, it could be used to complement the direct EV management to achieve an even better performance.

CONCLUSIONS

To achieve net-zero emissions, people around the world are shifting towards electric vehicles (EVs). This, however, makes the adoption of EVs a clear concern for distribution companies as the additional EV charging demand could easily exceed what the infrastructure has been designed for.

To this end, this paper investigated two approaches to mitigate network impacts: a direct approach that uses EV charger management, and an indirect approach that adopts a TOU tariff. These two approaches are demonstrated on a realistically modelled Australian MV-LV network with 1,300+ households as part of the Australian EV Integration project [10]. The results show that with unmanaged EV charging, the studied MV-LV network can face thermal and voltage drop issues with 100% EV penetration, typically in the LV part. On the other hand, both direct and indirect approaches can help eliminate network issues, with limited impacts on the customer charging time. Ultimately, this paper paves the way for investigating a mix of strategies, i.e., managing EV chargers while also encouraging charging at off-peak hours with TOU tariffs. This can reduce potential delays whilst ensuring high penetrations of EVs in existing distribution networks.

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