



## **Impacts of High EV Penetration on Distribution Networks and Its Mitigation: A Study Framework**

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### **SUMMARY**

The transportation sector is beginning a great shift away from fossil fuels and toward electric batteries. Because transportation accounts for roughly one-quarter of all energy used on earth, the transition toward electric vehicles (EVs) is expected to significantly increase electric energy demand. This transition is likely to be slow enough that the world's bulk power systems should be able to handle the new load in terms of having enough capacity and without much impact on power quality. However, the impacts of EV-charging on the distribution system can be significant given the system's original basis-of-design for capacity and power quality. Because EV-chargers will be connected to the distribution networks, distribution companies are performing planning studies to understand the potential impacts on their systems and to evaluate the effectiveness of proposed mitigation solutions.

This paper presents a study framework for the evaluation of the impacts of anticipated EV-charging levels on distribution networks and an assessment of the effectiveness of proposed mitigation solutions. The framework is flexible in terms of the granularity of available data because typically data availability for such studies is limited. By defining a number of possible future scenarios, this methodology allows the planning engineer to perform a high-level analysis to evaluate potential impacts of different EV-charging scenarios on a given distribution system and the effectiveness of proposed mitigation solutions. The impacts of loading, voltage regulation, and harmonic injections from EV-charging stations on power quality of distribution networks is evaluated.

### **KEYWORDS**

Electric Vehicles, time-series power flow analysis, managed charging, harmonic emission.

## INTRODUCTION

The combined factors of decarbonization policy, government incentives, electric vehicles approaching price parity with fossil fuel-based vehicles, and increasing EV-model options have driven EV adoption among certain vehicle types [1]. There are also major EV fleet commitments from groups such as the U.S. Postal Service, Amazon, FedEx, and electric utilities that include both light-commercial and passenger vehicles [2]. This increased rate of EV adoption translates into a potentially significant amount of new load on the distribution network. Moreover, the peak of this new load has the potential to coincide with the existing peak load, which will exacerbate the impacts on a distribution system.

Awareness of the transportation-electrification trend is increasing among electric utilities, and many utilities are in the process of preparing their infrastructures to accommodate the projected EV-charging load on their systems. It is likely that there will be areas of near- and mid-term challenges, though primarily on the distribution networks and mostly coming from clustered charging of fleet and non-fleet vehicles.

The effects of increased EV penetration have been studied for bulk power systems [3-4]. The overall results of the analyses based on historical growth rates suggest sufficient generation and transmission capacity will be available to support the forecasted EV fleet over time. However, these studies caution that factors such as policy, regulatory framework, and economic constraints may change the results of such analyses over time.

The negative impacts of high EV penetration will first affect distribution systems. This is because the increased system load caused by high EV-charging is unlikely to be spread out evenly across an entire distribution network. Rather, it is likely to be concentrated on distribution feeders that serve EV-charging locations. For example, fleet-charging can concentrate in areas near distribution hubs (airports and harbors) or near commercial centers (in urban areas where large parking lots tend to cluster), resulting in multiple fleet-charging enterprises clustered along a single feeder. Thus, negative impacts of EV-charging will be more pronounced in some locations than others, leading to increased risk of degraded grid performance and lower reliability.

Addressing the impacts of aggregate EV-charging, whether for commercial, fleet, or residential, will become increasingly important to grid performance and reliability. This requires that the impacts of different scenarios of clustered EV-charging on distribution networks be evaluated and mitigation solutions be tested in a systematic and flexible analysis framework.

This paper presents a study framework for the evaluation of the impacts of anticipated EV-charging levels on distribution networks and an assessment of the effectiveness of proposed mitigation solutions. The framework is flexible in terms of granularity of the available data because typically data from distribution utilities for such studies are limited. The major impacts of increased EV-charging on distribution networks include thermal loading, voltage regulation, transformer loss of life, phase unbalance, and harmonic distortion [8]. This paper will focus on thermal loading, voltage regulation, and harmonic distortion impacts to present the study framework. Distribution network data from several distribution utilities were used as test feeders in the analyses.

## STUDY FRAMEWORK

The study framework is depicted in Figure 1. There are two main modeling tasks when determining the impact of EV-charging on a distribution system: modeling the distribution feeder as a host and modeling the EV-charging as a load. The first task requires an as-built network model of a distribution feeder, including load levels and load types as well as seasonal load profiles. The second task requires a spatiotemporal (i.e., when and where) quantification of EV-charging on the network that can be synthesized by estimating EV-charger quantities, types, locations, ratings, battery capacities, on/off statuses, and power-level settings at any given time.

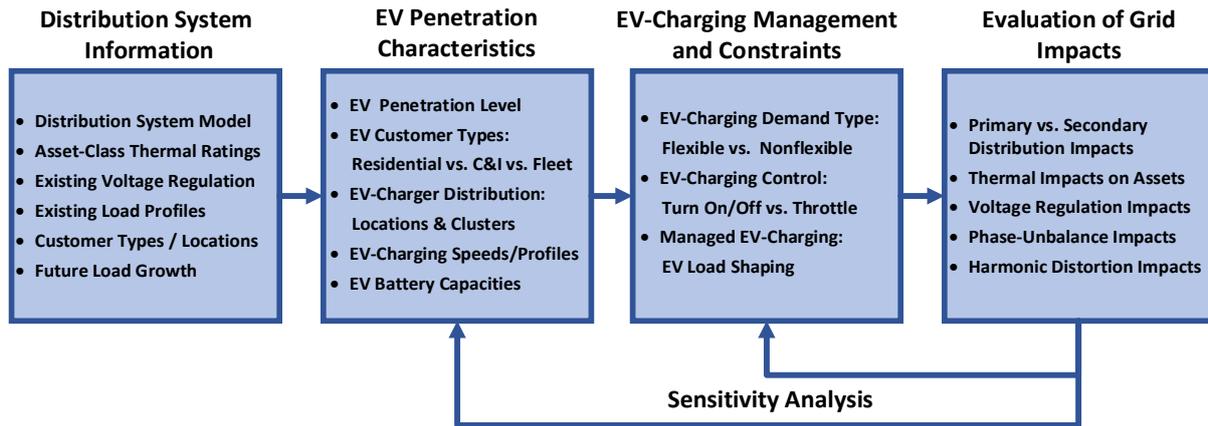


Figure 1: A study framework for evaluation of grid impacts and testing of mitigation solutions for large-scale EV penetration on distribution networks.

The first task, which is building a software model of the feeder, is quite straightforward because most distribution utilities have a working model of their system in a commercially available power system simulation software. To gather the required information for the analysis, collaboration with the utility owner is necessary to acquire localized knowledge of its network, operational constraints, customer types, planning, and scheduled work. For this analysis, the network model must contain the following information:

- **A distribution system structure:** This aspect of the model defines how the network is built and thus is shared between all scenarios of the study because it is invariant. Data that constitute this portion of the model includes existing and planned equipment and the connectivity between equipment.
- **A steady-state hypothesis:** This aspect of the model specifies the steady-state condition of the network and thus defines study cases or scenarios. Data that constitute this portion of the model includes switch status, load levels, and seasonal load profiles.
- **A timeline:** This aspect of the model defines the time dimension of the study, such as point-in-time or time-series, based on daily, monthly, and yearly information.

The objective of the second modeling task is to capture the location, timing, and energy demand of EVs on the feeder. Thus, this modeling task consists of synthesizing load profiles across the feeder to represent EV-charging. Key considerations in assembling the required data for

synthesizing the EV-load profiles to be assigned at each EV-charger (or group of chargers as a lumped element) location is discussed below.

The timing of EV-charging encompasses the start of EV-charging until its completion. Thus, it is dependent on the EV-customer type, with some being more flexible in terms of when their vehicles can be charged than others. Here, the difference between charging during peak versus off-peak hours will be significant in terms of the grid impacts. EV-load profiles were modeled based on literature review of the charging behavior of different types of EV customers [6-7] and the characteristics of the feeder and customer composition. Each EV-customer type was assigned an EV-charger power rating based on the standard, SAE J1772 - Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler.

Several key considerations for synthesizing EV-charging profiles based on test feeder characteristics and customer types were defined as follows:

- Centralized fleet-charging is most likely to happen outside of business hours and with high-power chargers clustered in locations where EVs park.
- For non-fleet EVs, mostly passenger cars, the charging is expected to happen with low-power chargers distributed throughout residential neighborhoods. Even distributed residential charging can become problematic if a large number of EVs charge during peak hours.
- There will be a propagation of public charging stations. These locations (most likely gas stations and parking lots) likely will not have the megawatt scale of electrical service needed to supply the high-power fast chargers that would be required for fleet EVs. Also, the on-demand charging associated with commercial locations cannot be scheduled to support flatter load curves and nighttime charging.

The next step in the study framework is testing different solutions to mitigate the negative grid impacts and assessing their effectiveness. Many stakeholders of EV infrastructure are considering managed or smart charging as a potentially effective method to mitigate the negative effects of high-penetration EV-charging on distribution networks. A real-world case study from California demonstrates the potential values of managed charging to the grid [12].

In this method, the EV load is shifted in time so the power demand in congested areas on the grid is decreased and thus the demand profile is flattened. A simplified example of a managed charging scheme is shown in Figure 2. In performing managed charging, the constraints of EV-charging times for each customer type discussed above must be satisfied. In this example, residential EV-charging was shifted to early-morning hours, fleet-charging was stretched overnight, and commercial charging was left unchanged because of its inflexibility as a load. There are different ways of implementing EV managed charging, but they fall into three general categories: Time-of-use (TOU) pricing, demand response, and energy management systems. The limitation of each method can be accounted for by placing constraints on the EV load-shifting strategy.

Unmanaged EV Charging		Hours Peak Day																								
Profile Type	Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
Existing Load	A	48	45	43	43	43	43	44	48	58	74	81	87	91	89	93	90	86	85	79	72	68	63	61	57	
Existing Load	B	48	46	43	42	43	43	43	47	59	75	85	91	96	95	100	96	93	90	82	73	68	62	59	55	
Existing Load	C	52	49	47	47	46	46	46	50	61	77	85	89	96	94	100	98	95	94	88	80	74	71	68	64	
Residential	A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	0	0	0	0
Residential	B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	0	0	0	0
Residential	C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	0	0	0	0
Commercial	A	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	0	0	0	0
Commercial	B	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	0	0	0	0
Commercial	C	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	0	0	0	0
Fleet	A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100
Fleet	B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100
Fleet	C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100

Managed EV Charging		Hours Peak Day																								
Profile Type	Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
Existing Load	A	48	45	43	43	43	43	44	48	58	74	81	87	91	89	93	90	86	85	79	72	68	63	61	57	
Existing Load	B	48	46	43	42	43	43	43	47	59	75	85	91	96	95	100	96	93	90	82	73	68	62	59	55	
Existing Load	C	52	49	47	47	46	46	46	50	61	77	85	89	96	94	100	98	95	94	88	80	74	71	68	64	
Residential	A	0	0	0	0	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Residential	B	0	0	0	0	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Residential	C	0	0	0	0	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Commercial	A	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	0	0	0	0
Commercial	B	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	0	0	0	0
Commercial	C	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	0	0	0	0
Fleet	A	50	50	50	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	50	50	50
Fleet	B	50	50	50	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	50	50	50
Fleet	C	50	50	50	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	50	50	50

Figure 2: Example of load shifting to implement managed EV-charging.

The charging profiles of the three different EV types (i.e., residential, commercial, and fleet) are combined to create the total EV-demand profile of a distribution network. Three different charging scenarios are considered in the study framework. These include unmanaged EV-charging, partially managed EV-charging, and fully managed EV-charging.

Figure 3 shows the load profiles of the three scenarios. In each case, the EV-load profiles were added to the existing load profile at each location corresponding to the EV-load types. After assigning the combined EV-charging and existing load profiles at each location, a time-series power-flow analysis was performed to assess the impacts of the EV load on system loading and voltage regulation.

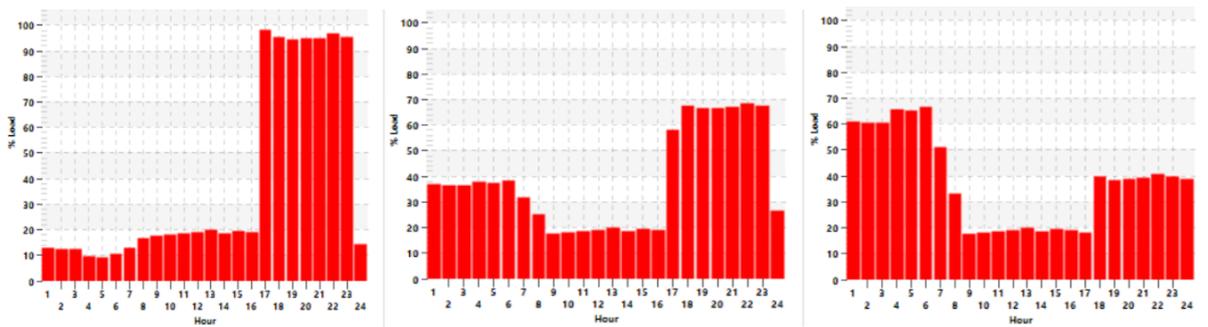


Figure 3: Examples of the load profiles of the three scenarios of, from left to right, unmanaged, partially managed, and fully managed EV-charging.

By using this methodology, the grid impacts of EV-charging can be evaluated under different scenarios, such as minimum/maximum existing loading conditions, EV-charging levels for fleet and non-fleet EVs, distributed versus clustered charging, charging location, and other relevant considerations [8-11].

## EVALUATION OF GRID IMPACTS OF EV-CHARGING ON TEST FEEDERS

Using the study framework described in the previous section, test feeders from several distribution utilities were evaluated under various EV-charging penetration levels considering unmanaged, partially managed, and fully managed charging. The primary findings of the study indicate high but realistic levels of unmanaged EV-charging on the test feeders would likely require upgrades to the feeders loaded close to 50 percent or more of their maximum capacity if no other mitigations were applied. Furthermore, the study found managed charging schemes can eliminate or postpone the need for system upgrades on the primary distribution system.

The results of a time-series power-flow analysis for one of the test feeders are shown in Figure 4 as an example. The figure shows feeder-loading and worst-case voltage profiles caused by high levels of EV-charging. Various levels of EV-charging were considered in the study, including high levels by different EV-customer types (i.e., residential, commercial, and fleet).

A key takeaway from the results is that unmanaged charging can significantly increase the demand on the network, close to doubling the peak in this case. In addition to increasing the peak load magnitude, EV-charging can cause significant changes to the shape of the existing load profile and introduce peaks at new time intervals. The highest peak seen in the plots shown in Figure 4 is caused by the evening peak coinciding with the residential EV-charging peak.

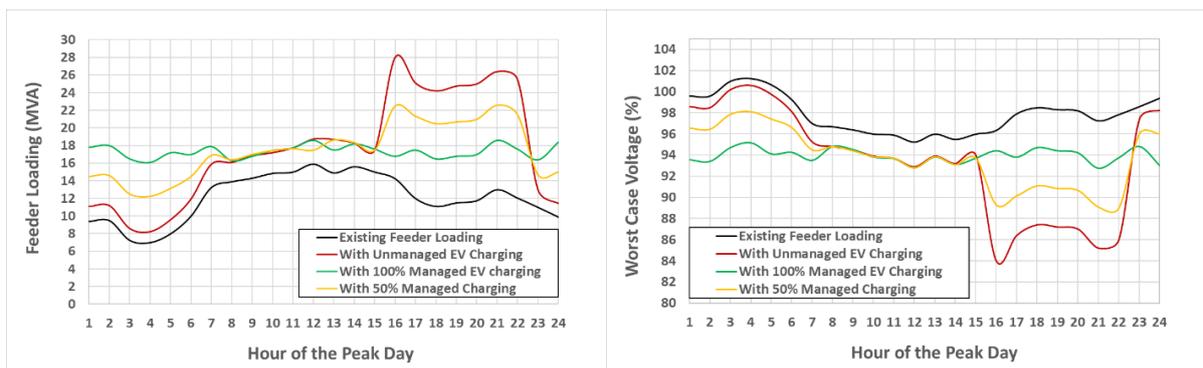


Figure 4: Effectiveness of managed charging to mitigate feeder-loading and voltage regulation.

A sensitivity analysis was also performed by applying varying levels of EV-charging management to evaluate their effectiveness. To achieve this, load-shifting was performed with the objective of flattening the demand curve by leveraging the flexibility of residential and fleet EV-charging times. The EV-charging management using 100 percent (fully managed) and 50 percent (partially managed) controllable EV-chargers are shown in the plots in Figure 4. The results indicate the load-profile peaks can be significantly alleviated, thus mitigating the observed negative impacts in terms of thermal overloads and voltage excursions on the distribution network.

At each stage of the analysis, feeder heat maps were produced to help identify geographic locations of overloads and voltage excursions on a feeder caused by different levels of EV-charging penetration as well as the effectiveness of the mitigation measures. For example, Figure 5 shows a significant section of the feeder would be overloaded if EV-charging was performed during peak demand hours (late afternoon and early night hours in this case). However, the excessive overload condition could be eliminated by shifting most of the EV-charging load to overnight hours when other electricity demand is significantly reduced. Similar

feeder heat maps were produced to help identify sections of the feeders that experienced voltage excursions.

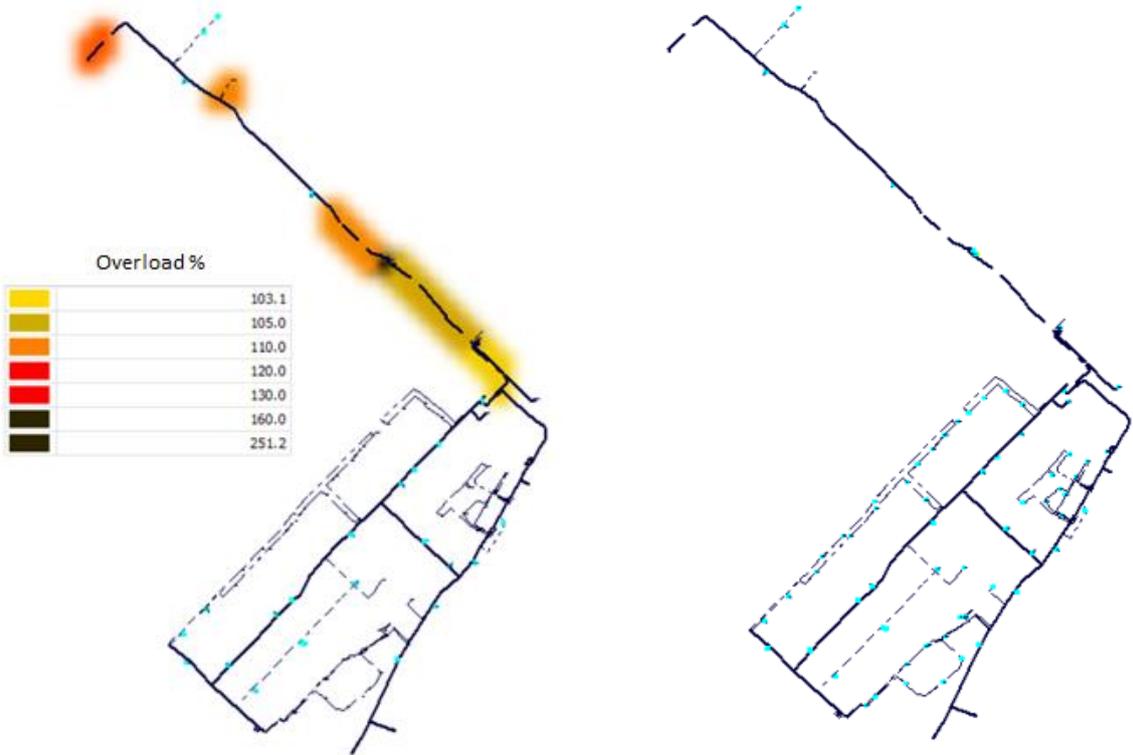


Figure 5: Feeder heat map comparing feeder overload caused by EV-charging during peak hours (left) to off-peak hours (right).

**IMPACTS OF EV-CHARGING ON SECONDARY DISTRIBUTION NETWORKS**

Depending on the characteristics of the distribution network, managed EV-charging schemes may not be as effective in preventing negative impacts of high EV-charging penetration on the secondary distribution network (including service transformers) as they would on the primary distribution network. This is because, when moving downstream from the feeder head, the benefits of load diversity diminish, and the local distribution network is greatly influenced by the local loads.

For example, when clustered fast-charging occurs, especially during a peak-usage period of the secondary distribution network, that section of the feeder would likely experience unacceptable voltage drops and line overloads while the rest of the distribution system operates normally. Under such circumstances, only the local sections of the distribution network may require upgrades to mitigate the observed problems.

**HARMONIC ANALYSIS OF INTEGRATED EV CLUSTERS**

EV-chargers are a new type of nonlinear load expected to increase in number on the distribution networks in the coming years. As such, it is important to study their effects on power quality of the system. In [13], authors have made a comparative study on the harmonic injection effect of a single fast-charger versus two fast-chargers operating simultaneously. Also, in [14], Western Power Distribution has investigated the harmonic emission effect of EV-chargers on the power grid.

In this study, the effects of EV-chargers on the power quality of a test distribution feeder were explored. Specifically, the effects of charging location and charging rate were evaluated. EV-charging penetration was set at 20% of maximum load (approximately 1 MW) in the understudied feeder. Both slow and fast chargers were evaluated by exploiting data reported by Idaho national lab [15],[16] for slower chargers (level 2) and Hydro Quebec [17] for dc fast-chargers respectively. These chargers generated harmonic currents at the specified levels shown in Figure 6.

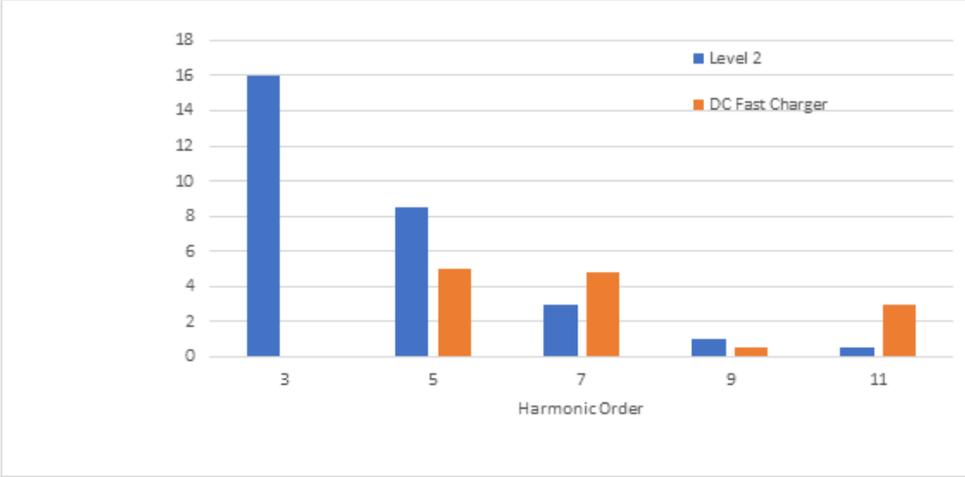


Figure 6: Harmonic components of level 2 and dc fast-chargers.

The data indicate the harmonic distortion associated with level 2 chargers is higher than the dc fast-chargers. To model the harmonic distortion impact of EV-fleet charging, such as light trucks or community charging facilities, level 2 and dc fast-chargers were clustered in three different locations along the feeder, as detailed in Table 1. The considered locations include close to the substation, middle of the feeder, and toward the end of the feeder.

The evaluation of the test feeder indicated the total harmonic distortion (THD) of the voltage on the medium-voltage side of the point of common coupling (PCC) in all scenarios was below the limits of IEEE Std 519-2014, whereas the total demand distortion (TDD) exceeded the limits in cases where the chargers are toward the end of feeder. On the other hand, on the low-voltage side of the PCC, the TDD exceeded the limits in most of the studied cases.

Table 1: Harmonic distortion analysis of EV-chargers on a distribution feeder.

Charger Type	Location on the feeder	Distortion measured on the MV feeder	
		THD <sub>v</sub> %	TDD <sub>I</sub> %
Level 2	Close to substation	1.35	2.35
	Middle of feeder	1.45	6.02
	Toward the end of feeder	1.6	14.81 (Violation)
DC fast charger	Close to substation	0.66	0.08
	Middle of feeder	0.58	2.09
	Toward the end of feeder	0.60	4.05

These harmonic currents can potentially affect distribution equipment, including shortening their service life through overheating, as well as causing annoyance to customers. Distribution utilities can benefit from working closely with EV site developers to understand the impact and may need to consider additional monitoring of charging stations that might be appropriate at a feeder level to ensure compliance.

## **DISTRIBUTION UTILITY CHALLENGES IDENTIFIED**

The analysis of the test feeders indicated high penetration of EV-charging is likely to create negative impacts on distribution networks loaded close to 50 percent or more of their maximum capacity. Results from the time-series power-flow simulations indicate power utilities can expect two major impacts:

- Overloading of distribution system equipment (e.g., transformers and power lines) and/or an excessive voltage drop on distribution feeders, leading to undervoltage issues
- Voltage variations caused by fluctuating EV-charging profiles on the feeder that may cause an increase in cycling of voltage-regulation devices, leading to decreased times between their maintenance and reduced service life

The impacts to the distribution system depend on several factors, including the level of EV penetration, feeder characteristics (e.g., robustness, topology, and length), proportion and location of different EV-customer types, and the clustering patterns of EV-charging locations. As previously indicated, these impacts can affect the primary distribution system differently from the secondary distribution system (in this context, the secondary distribution system includes distribution transformers and the low-voltage network supplied by these transformers).

The impact on primary distribution networks becomes more pronounced as we move farther downstream from the substation. This is because the voltage drop increases in proportion to distance from the substation and the system becomes less robust. Increased EV penetration toward the end of a feeder will increase the power demand (current flow), which will further increase the voltage drop across a feeder, causing undervoltage problems toward the end of feeder. Furthermore, the conductor size (and ampacity) tapers off toward the end of a feeder leading to potential system-overload problems.

EV clusters will have a more severe impact on distribution networks if clusters of charging stations are located farther away from the substation, especially where the system is less robust for the previously discussed reasons. If the primary distribution system is already robust, upgrading the secondary distribution network, where EV-charging stations are located, may be sufficient to mitigate any negative impacts on power quality. Usually, upgrading the secondary distribution network is much simpler and less expensive.

Grid reliability can also be negatively impacted by the increased likelihood of protection-induced outages, a decrease in transformer service life caused by overloads, and frequent operation of voltage-regulation devices leading to decreased times between maintenance cycles and reduced service life. With the increase in EV penetration, clustered charging in certain locations on the network is more likely to occur. As a result, the negative impacts of EV-charging will be more pronounced, and the risks to grid performance and reliability will be higher. Therefore, addressing the impacts of aggregate EV-charging, whether they are caused by residential, commercial, or fleet EVs, will become increasingly important to grid performance and reliability.

## IMPLEMENTATION OF MITIGATION SOLUTIONS FOR UTILITIES

The study framework presented was used to evaluate the effectiveness of managed charging in mitigating the negative impacts of charging from high EV penetration. Effectiveness of other mitigation methods can be evaluated in a similar manner by modeling the mitigation methodology in a time-series power flow simulation. This section briefly discusses several mitigation methods that are currently used by some utilities, either fully adopted or in pilot stage.

As discussed in previous sections, load management will have significant impact on reducing overloads and power quality problems on primary distribution lines. Even managing a portion of the EV load, which is easier to achieve, can significantly reduce the risks associated with high EV-charging loads. Managing EV-charging may be a more cost-effective solution than major grid investments. The methods of load management generally fall into two general categories: active and passive [18]. An example of a passive managed charging is Time-of-Use (TOU) pricing which can be either fixed or dynamic rates set by utilities to provide incentive to EV users to charge during periods of lower demand on the grid (off-peak hours) [19]. Passive solutions may be a good intermediary solution. However, as the complexity of the distribution grid increases due to the ever-increasing penetration of distributed energy resources (DERs) and smart loads, a more holistic and systematic solution will be needed. Such methods will deploy systems that have observability and controllability over the grid as well as its resources and smart loads. These methods include distributed energy management systems (DERMS) and advanced distribution management systems (ADMS). In this control architecture, a utility's ADMS interacts with a third-party DERMS and its connected EV chargers and DERs as one entity to negotiate an agreed outcome [20]. This outcome would aim to meet the needs of both the grid and the EV customers. Achievable levels of managed charging (i.e., partially or fully managed) depend on the charging management strategy adopted by the utility.

In cases where load management can't be achieved to a sufficient degree or the benefits are not significant, there are several other options that can be used to counteract excessive EV loads. A brief description of some of these options follows.

The use of non-wires alternatives (NWAs) can potentially mitigate overload and undervoltage issues if applied strategically. NWA refers to localized DERs that can be installed in distribution networks. By strategically co-locating DERs with high EV clusters, energy demand of EV charging stations from the grid can be reduced, alleviating network overloads and power quality problems at these locations [21].

Another option for utilities is the use of distribution automation (DA) to increase grid flexibility for the purpose of accommodating excessive EV charging demands during peak times [22]. Distribution networks can be automatically reconfigured through the actions of electronically controlled switching devices to spread demand peaks away from heavily loaded feeders and towards feeders with lower loads. This allows utilities to operate their grid infrastructure more flexibly and would offer the added benefits of conventional DA applications such as increased system reliability, better control, and equipment protection.

## CONCLUSIONS AND RECOMMENDATIONS

The increased penetration of EVs is likely to present challenges for the electric grid. Although the bulk power system is expected to accommodate the increased demand without much impact, distribution networks are expected to experience several challenges. This paper presented a study framework for the evaluation of the impacts of anticipated EV-charging levels on distribution networks and an assessment of the effectiveness of proposed mitigation solutions. The study framework is flexible in terms of the granularity of available data because such studies typically have a limited amount of data available. The study framework was used on several test feeders from distribution utilities to identify the potential negative impacts of EV-charging on the grid and demonstrated the effectiveness of managed charging in alleviating the impacts. Specifically, the negative impacts of EV-charging on thermal loading, voltage regulation, and harmonic distortion were analyzed.

The results of the analysis indicate increased EV penetration is likely to create some challenges to distribution networks. The main challenges observed in the study include system overloads and voltage excursions. High EV penetration will have greater impact on distribution networks that are less robust. Furthermore, the challenges will be especially pronounced in areas with clusters of EV-charging stations, especially if these clusters are located toward the end of feeders where the system is usually less robust.

One way to mitigate the negative impacts of high EV penetration is through managed EV-charging. In this method, EV loads can be shifted in time so distribution networks will have smoother load profiles with lower peaks and higher valleys. The study framework developed different levels of load-management scenarios to demonstrate the effectiveness of managed charging on mitigating the negative effects of high EV-charging loads. The results indicate the load-profile peaks can be significantly alleviated, thus mitigating the thermal and voltage violations on the distribution network. Even partially managing the EV load, which is easier to achieve, can significantly reduce the risks associated with high EV-charging loads.

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