Preparing the Distribution Grid to Embrace Plug-in-Electric Vehicles

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Introduction

A new era of Plug-In Electric Vehicles (PEVs) has begun. Nissan and General Motors have each launched a production plug-in electric vehicle in December, 2010. They are being followed by Ford, Mitsubishi, Toyota, Tesla, and others, all of whom have announced the introduction of plug-in vehicles to the U.S. market by 2011 or 2012. The rapidly approaching commercialization of plug-in hybrid (PHEVs) and battery electric vehicles (BEVs) has created an urgent need for utilities to support the adoption of electric vehicles by their customers, to prepare for the installation of residential, commercial, and private infrastructure in their service territories, and to manage the impact of these new loads on the electric distribution system.

In response to the overall need, EPRI initiated a multi-year project with 20 utilities to understand Plug-in Electric Vehicle (PEV) system impacts with several utilities in the United States and Europe. As part of this study, EPRI conducted a comprehensive study assessing PEV charging effects on specific circuits within a utility's distribution system - typically one or two representative feeders per utility. This effort used very detailed simulations of each distribution system, customer load characteristics, and potential electric vehicle penetration and charging profiles to assess impacts across the distribution systems (assets, overall system loading, etc.). The results of the simulations across different distribution systems were combined to develop summaries of general concerns, assets that are likely to be at most risk, conditions that could require additional monitoring to avoid problems, and the impacts of different charging profiles (including controlled charging) on these results. Since most charging is expected to occur at the residential-level, the primary focus of this initial phase was residential feeders.

This paper provides a general overview of this study and highlights some of the general conclusions that were drawn to minimize the system impacts from vehicle charging.

Charging Infrastructure

There are a number of different ways to recharge PEVs at power levels ranging from less than one kilowatt (kW) to as much as 250 kW at charging times of less than 30 minutes to more than 24 hours. Most residential and public charging will occur at power levels ranging from less than 1 kW to as much as 19.2 kW and full charge times of 3 – 8 hours. Charging is grouped into two classifications based whether the electricity delivered to the charge port on the vehicle is alternating current (AC) or direct current (DC).

AC charging is governed by SAE Recommended Practice J1772 (SAE J1772). There are currently two classifications, referred to as levels for AC charging in North America. Level 1 charging delivers 120 volts AC (VAC) and the EVSE generally consists of a self-contained cordset that terminates in a standard NEMA 5-15R plug compatible with any standard 120 volt household outlet. Level 2 charging delivers 208 – 240 VAC and requires a permanently connected EVSE. The EVSE is typically hard-mounted, either to a wall or a pedestal and supplied by a dedicated circuit. Both Level 1 and Level 2 charging utilize the same connector design at the vehicle and most vehicles can charge at either voltage through the same charge port. Level 1 AC charging is generally limited to 1.44 kW. Level 2 can reach 19.2 kW, with most vehicles and installations using a more modest 3.3 – 6.6 kW. Figure 1 compares maximum charge power for Level 1 (1.4kW) through the maximum allowed at Level 2 (19.2 kW) to average peak summer demand for households in five different U.S. cities with different climates. Likely implementations of residential Level 2 charging will likely range from a 15 amp circuit (12 amp continuous, 2.88 kW) to a 100 amp circuit (80 amp continuous, 19.2 kW). The higher capacity EVSE installations are more likely to impact the local distribution system.

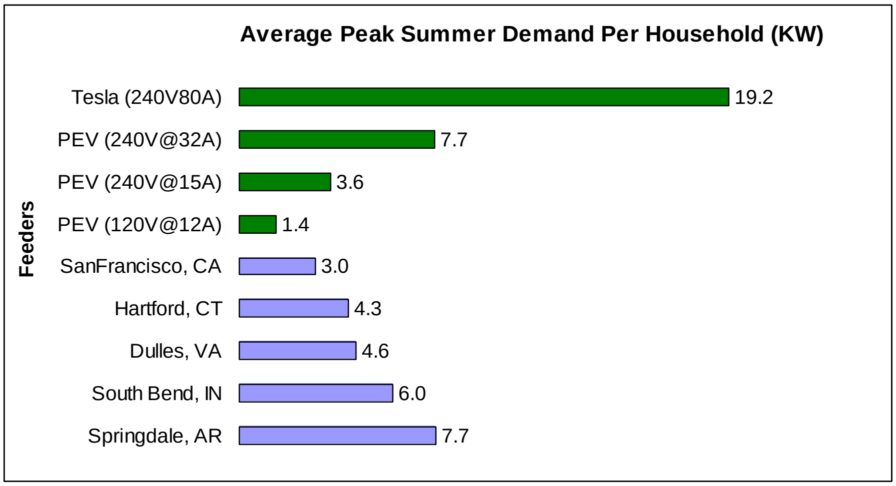

Figure 1
Relative comparison of charge power for AC Level 1 and 2 charging and average peak summer household demand

DC charging, often referred to as 'fast charging,' uses an off-board charging station to convert AC electricity to DC and directly charge the vehicle battery without the need for an onboard charger. Its primary purpose is to enable the rapid recharge of battery electric vehicles. The maximum charging power for a vehicle depends on the battery chemistry and system design. BEVs have already been designed and tested for DC charging at rates of 50 – 60 kW.

Charging Patterns

The timing of PEV charging can create either positive or negative impacts on electric generation and transmission systems. A significant amount of PEV charging coincident with the system peak would create a need for additional generation. On the other hand, charging performed consistently during off-peak hours could reduce system costs. This study used the National Personal Transportation Survey (NPTS) as a source of driving data. Vehicle home arrival is correlated with peak load, so it is often assumed that vehicle charging could create a large load coincident with the peak. However, vehicles will not all be connected at the exact same time. Figure 2 shows the distribution of home arrival times for an average American driver. Even during the peak hour of 5-6 PM, only about 12% of drivers arrive home during the hour.

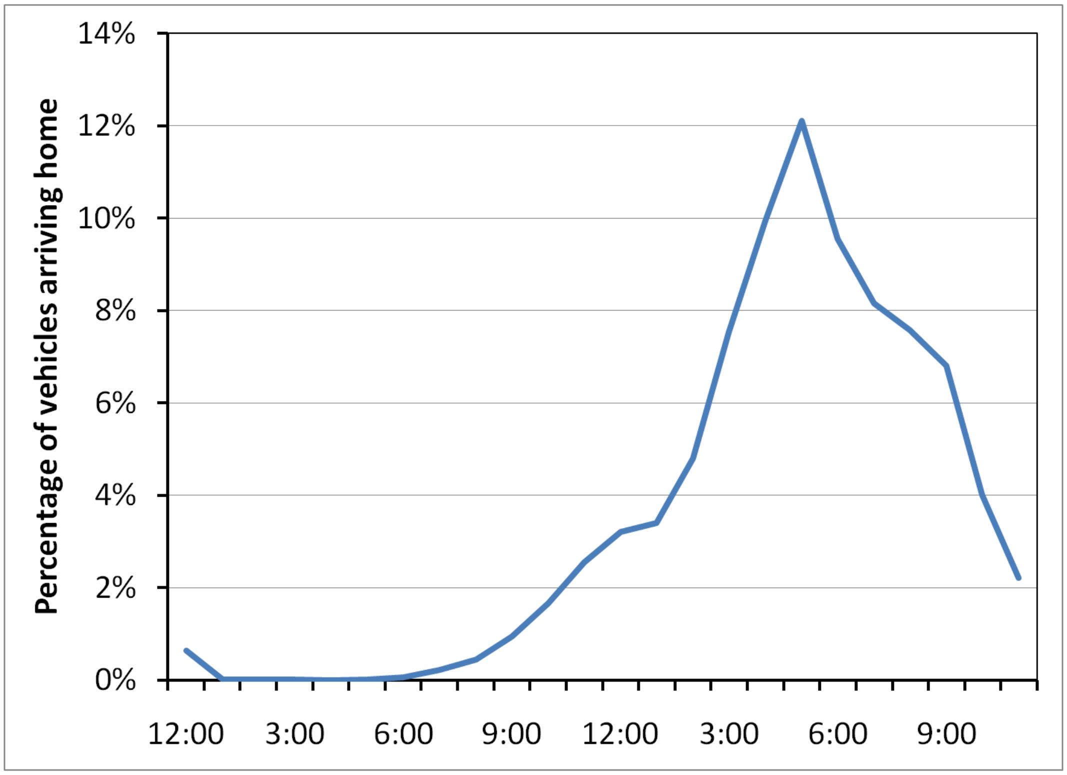

Figure 2
Home arrival time distribution

General Analysis Framework

The developed analytical framework was intended to evaluate the impacts of PEVs on distribution system thermal loading, voltage regulation, transformer loss of life, unbalance, losses, and harmonic distortion levels. These impacts are primarily determined by the assumed location of PEVs throughout the distribution network, when the PEVs are assumed to charge from the system, and the magnitude and duration of the charge cycle. In order to determine both system level impacts and individual component level impacts, the analysis framework provides for both deterministic and stochastic consideration of these key spatial and temporal variables. The study for which this analysis is conducted is based on a near-term PEV market penetration scenario representative of one to five years after PEV commercialization. Although the total PEV penetration is assumed to be small, possible high localized concentrations are possible. The study analysis framework utilized known distribution system circuit information, PEV charge characteristics, and likely customer behaviors to construct models of likely system conditions. The general analysis framework is illustrated in Figure 3.

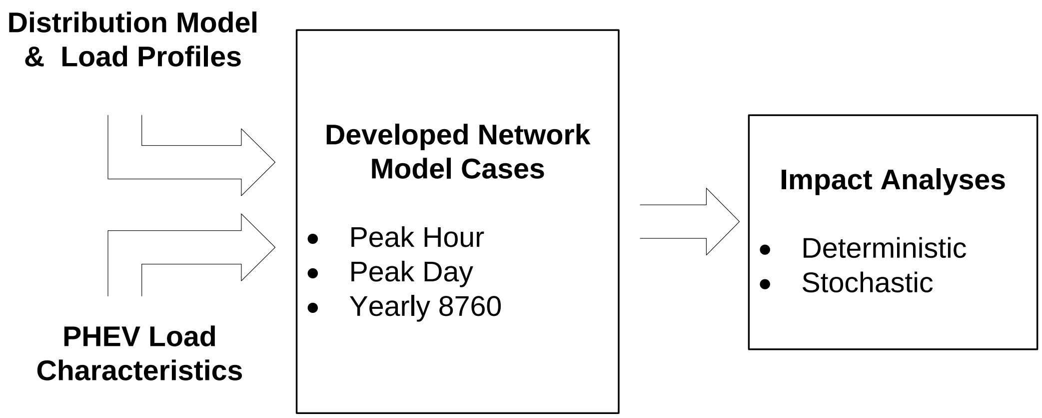

Figure 3
System Impact Analysis Framework

The developed framework considers the following principle factors that define PEV loading on distribution systems:

- Different PEV charge spectrums (battery type, charger efficiency) and profiles
- PEV market penetration levels per utility customer class (residential, commercial)
- Time profiles and likely customer charging habits
- Battery state of charge based on miles driven

The study methodology was designed to capture potential near term distribution system impacts in response to customer adoption of the new load type. Assuming a near term planning horizon, only those characteristics expected from the majority of first generations of PEVs are considered. Specifically, PEV are modeled as simple loads whose characteristics are mainly dictated by customer behavior. Controlled dispatching or vehicle-to-grid operations of PEVs are not included in this evaluation. Additionally, growth in the base load is not included as no particular planning year is being evaluated in any given scenario. Finally, only residential customers are considered as possible locations of PEV interconnections, as initial adopters are expected to most likely charge at their residence.

PEV Characteristics and Clustering

EPRI's study targets distribution system loading impacts based on near-term projections (1-5 years) of PEV market penetration. In general the projected market penetrations considered in this study of PEV penetration levels were varied from 2-25%. Given the 1-5 year projection of the study, this range is expected to provide impacts for low to extremely high levels of projected market penetration. It's important to note that even for low overall customer PEV adoption rates, PEV clusters can still occur. Based on system configuration and the assumed customer adoption probabilities, clusters will occur randomly throughout the system for each case. For example, PEV clusters are visible in the daisy plot shown in Figure 4. Each PEV is represented by the circle, and as PEVs are introduced at the same location they are spaced in a similar fashion as petals on a flower. Higher penetration rates, of course, increase the potential for larger cluster sizes and more frequent occurrences. While PEV clustering may indicate an increased risk higher than average loading levels, PEV clustering alone does not signify the likelihood of negative impact occurrence as the other PEV load characteristics, and must also be taken into account.

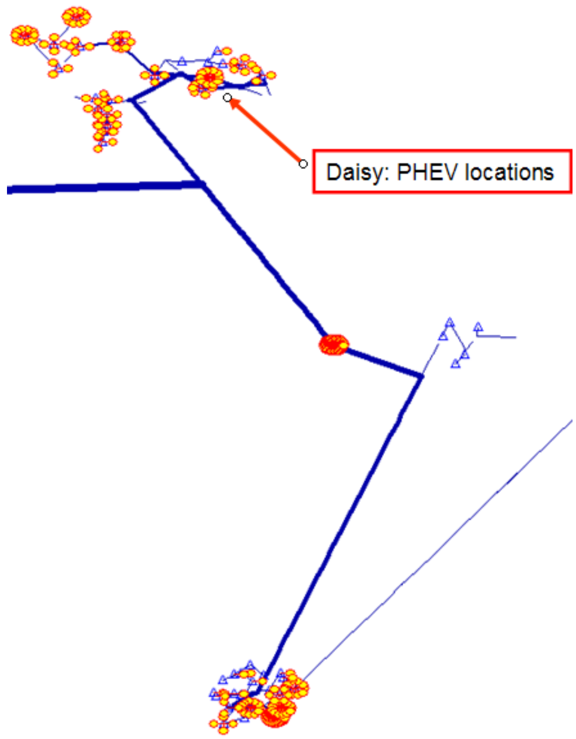

Figure 4
Example Daisy Plots Illustrating Clustering at 8% Penetration Levels

Aggregate Feeder Loading Analysis

Characterizing PEV load diversity's influence on the system is examined through the total additional loading expected to occur at the head of the feeder for each circuit. In analyzing the potential distribution impacts of electric vehicle charging a 'worst case' scenario will be needed to bind the potential negative effects; however, it is important for this worst case to be plausible. There are uncertainties in the expected makeup of PEVs, different charging patterns served off each feeder, and customer habits, but these uncertainties can be reasonably bounded at the aggregate level as seen by the substation transformer.

At this level, charging patterns correlate more closely with statistical driving patterns. Driving pattern data from the National Household Transportation Survey (NHTS)[1] is used to represent likely charge times short of smart-charging incentives. For instance, potential interconnection hours were derived from the likely residential customer home arrival times shown in Figure 2. By coupling these statistics with different customer daily driving distances patterns, known PEV types, electrical chargers characteristics, different profiles that can be used to control charging, the aggregate hourly demand as seen by the substation transformer, the aggregate hourly demand as seen by the substation transformer can be estimated.

[1] Vyas, A, Wang, M., Santini, D., and Elgowainy, A., Analysis of the 2001 National Household Transportation Survey in support of the PHEV project to evaluate impacts on electricity generation and GHG emissions, unpublished information, 2009.

Even without smart charging the load of vehicle charging is relatively well distributed. For example, Figure 5 shows a plausible high case for vehicle charging, which assumes that the fleet is made up of 30% Extended-Range Electric Vehicles (E-REVs), 50% blended PEVs, and 20% BEVs, all with 7.68 kW chargers which begin charging at full power immediately upon arriving at home. Since home arrival is coincident with other activities the load occurs on-peak, but vehicle charging has a maximum of about 0.7 kW per vehicle, and is relatively evenly distributed over about six hours. Other vehicle mixes, which include more PEVs or lower power chargers, will decrease the vehicle charging peak and shift it later. Similarly, EVs with higher power chargers will increase the vehicle charging peak, but the charging will finish sooner. Based on the study it was observed that for different vehicle mixes the aggregate on-peak load for a PEV will vary between 500-1100W per vehicle.

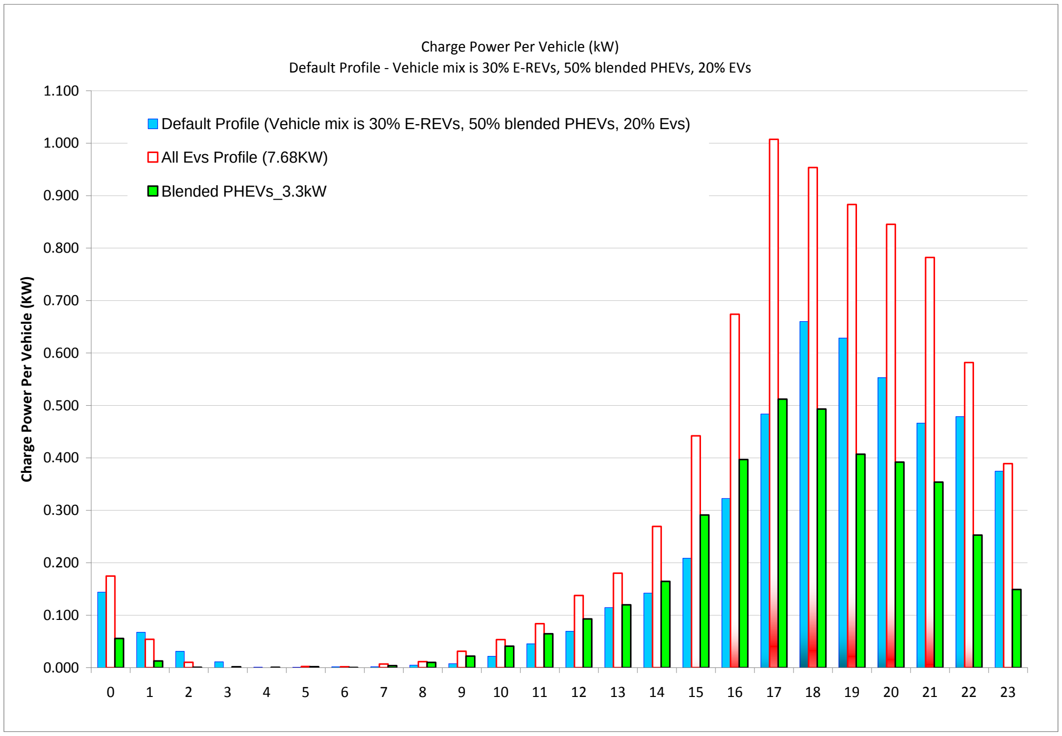

Figure 5
Aggregate Power Demand for Uncontrolled Vehicle Charging

Thermal Overloads

Identifying the extent to which particular distribution asset classes may be affected by PEV demand requires first examining how PEVs are expected to be distributed across the feeder. Correlating expected PEV demand against the remaining capacity of each asset will provide a strong indicator of the number and type of assets most at risk from PEV adoption. Assets which are potentially at risk of exceeding their thermal ratings due to PEV adoption can be then identified by comparing their existing remaining capacity to the projected PEV demand. The peak hour remaining capacity for every distribution feeder component (asset) is determined from the peak hour load flow solution and each component's specified thermal ratings.

The calculated peak hour remaining capacities for an example circuit are plotted in Figure 6 and Figure 7 as a function of the number of customers served from the component. Each asset is evaluated against projected PEV demands calculated and shown in Figure 6 and Figure 7. The remaining capacity of each asset is plotted as an individual point, and sorted based on customers served and asset class; while the projected demands are superimposed as lines for the three market penetration levels examined. Additionally, the estimated maximum PEV demand is also plotted permitting the quick identification of which assets are unlikely to be impacted and those which are at risk of impact. Each asset with a remaining capacity falling above the projected demand is unlikely to be impacted by 2%, 4%, and 20% PEV market penetration. Given the 99.99% value used for *Ptest* and the conservative construction of the maximum projected demand lines, the probability of exceeding the thermal ratings of these assets is less than 0.01%.

Intuitively, as PEV market penetration increases so does the potential for increased system impacts. As expected, the number of assets falling below the projected maximum PEV demand line increases as does the penetration level. More importantly for this system, the nature of the asset capacities in relation to the maximum PEV demand lines clearly indicate the impact from PEV adoption will most likely first appear on service transformers in particular. Not surprisingly, those transformers with the lowest kVA/customer capacity are the most susceptible. It is also interesting to note possibility of impacts from PEV clusters cannot be discounted even for penetrations as low as 2%.

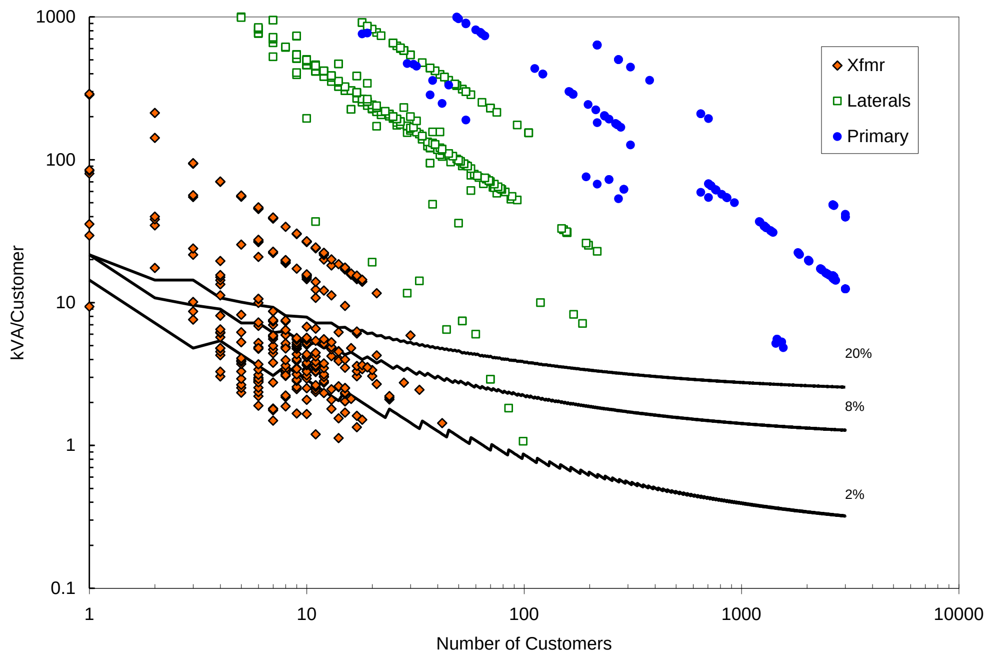

Figure 6
Feeder Asset Thermal Overload Risk Evaluation for 240V 30A PEV Charging

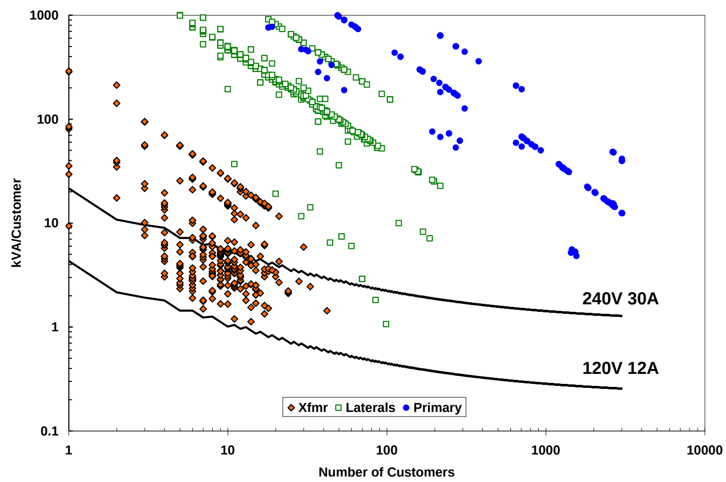

Figure 7
Service Transformer Overload Risk Evaluation 120V 12A & 240V 30A PEV Charging

It is also important to note that circuit model limitation may limit the accuracy of the projections. Specifically, circuit models based on allocation of customer load per transformer kVA do not capture innate variations in transformer loadings. As such, transformers that may be heavily loaded in the field cannot be completely discounted from being overloaded due to PEV charging. In the analysis, impact likelihood is determined through stochastic simulations of the circuit operation over a full calendar year in for projected PEV penetration levels. In each case, PEVs of specific types are randomly assigned to customer locations according to defined PDFs. For each assigned PEV, an hourly demand profile for the full year is developed from the charge time and remaining charge PDFs. This process is repeated for each penetration level. The simulated results are aggregated across assets to provide an indication of impact likelihood. While thermal overloads are the only impact presented, the analysis examines other system impacts such as steady-state voltage changes and losses. Furthermore, the stochastic analyses are designed such that the particular system and PEV conditions resulting in a negative impact to the system or a particular asset can be identified.

Conclusions

While the residential charging standard can reach power levels of 19.2 kW (80 amps at 240 volts), most vehicles are expected to charge at power levels below 7 kW. PHEVs can very comfortably recharge overnight at Level 1 (120V, 1.2 kW) or at the lower rates for Level 2 (240V, 3.3 kW). The specific impacts for any feeder will depend on the design and loading practices for various components of the feeder and assumed PEV characteristics for the area.

The results to date, however, generally show the following:

- The extent of system impacts depends upon the PEV penetration and charge behaviors of PEV adopters

- Due to diversity, the expected aggregate addition to system peak loads is 700-1000 Watt per PEV in a given utility territory. Based on typically daily driving statistics, the average energy delivered to a vehicle during a charge is 5-8 kWh for a midsize sedan.
- Recognizing, all distribution circuits will not realize the same level of PEV adoption, the extent of system impacts depends upon the PEV penetration and charge behaviors of PEV adopters
- The short-term impacts for most utilities studies should be minimal and localized. There is a possibility, however, of isolated impacts on some distribution transformers and secondary drops, particularly in neighborhoods with older distribution systems including underground systems.
- PEV Charging level is a dominant driver compared to PEV charge time (see Figure 8)
- By system design, per-capita load growth (PEV or otherwise) will first impact devices closest to the customer
- Components closer to the customer are the most likely to be impacted as they do not benefit as greatly from PEV load diversity
- Low capacity per customer ratios combined with low PEV load diversity (assets closer to the customer) are the most likely to be impacted as they do not benefit as greatly from PEV load diversity
- The remaining capacity per customer can be used as a metric for evaluating possible risk of impact due to customer adoption of PEVs
- The assets near the load are most susceptible to PEV clusters as the potential benefit of spatial diversity decreases. Older distribution systems (including underground systems), initially designed for much lower per-customer load than its current operation, it is likely that the PEV impacts are more severe and impactful than to a relatively newer infrastructure.
- Based on system configuration and customer adoption, PEV clustering will occur randomly throughout the system. While PEV clustering may indicate an increased risk higher than average loading levels, PEV clustering alone does not signify the likelihood of negative impact occurrence as the other PEV load characteristics must also be taken into account
- Transformers characterized by low capacity per customer ratios are the most likely to be impacted by PEV adoption. Furthermore, transformers lower than 25 kVA nameplates are expected to be the most susceptible to becoming overloaded as these transformers typically have lower amounts of existing capacity which can be quickly consumed by one or more PEV.
- Likelihood of a given system component becoming overloaded is a function of the remaining capacity on the element and the number of customers served from the element that are potential charging locations for PEVs. The increased loading on the substation transformer tends to be tempered by the diversity in charging times for the many PEVs that are served across the entire feeder. Conversely, a single service transformer serving 5-10 customers may become overloaded with 1 or 2 higher charge current PEVs.

- Controlled charging can defer projected impacts due to load growth to later years, but care must be taken to ensure that the control strategy does not create secondary system peaks.

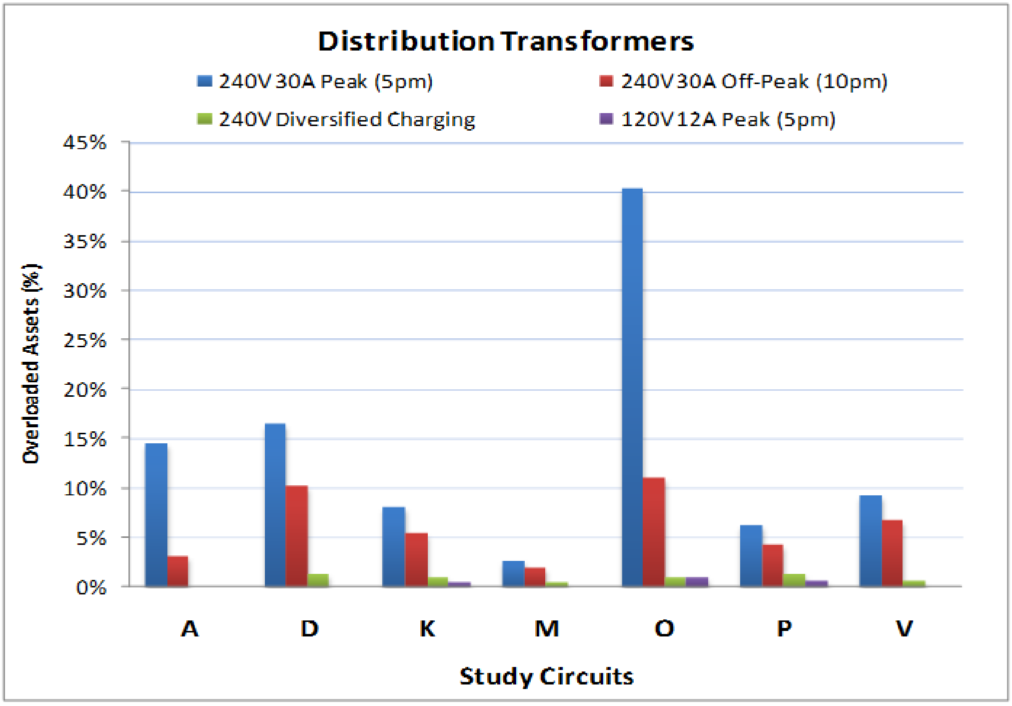

Figure 8
PEV Charge Levels Have a More Dominant Impact Compared to Charge Time

EPRI believes that potential stresses on power delivery systems can be mitigated through asset management, system design practices, controlled charging of PEV, or some combination of the three. But again, given the likely variability in customers' PEV choices, car types, varied charging patterns, varied charging speed preferences, and variable participation in utility-centric TOU charging options, we believe that the utility will not be able to manage this risk in an ex post fashion. In many cases, the utility will likely not be notified or aware of an PEV addition, or a unique charging pattern. As such, a proactive risk mitigation strategy is recommended to remove localized risk to the distribution system. Controlled charging can significantly reduce PEV loading impacts on the distribution system, but is not likely to be universally adopted. Tariffs and rates which encourage nighttime charging (e.g., load management, valley-filling, etc.) can also help to avoid or postpone upgrades. All of these factors can be taken into account in the analysis of potential risk as a function of distribution system conditions and geographic factor