

## INTEGRATING PLUG-IN- ELECTRIC VEHICLES WITH THE DISTRIBUTION SYSTEM

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### ABSTRACT

*Accurate assessment of plug-in electric vehicle (PEVs) impacts on distribution system operation requires sufficient understanding and representation of PEV load variations such as daily load shape as well as network location. Traditional distribution system analysis methods cannot always address these variations and therefore not fully describe the PEV impacts on the system. EPRI has initiated a multi-year project to understand PEV system impacts with several utilities in the United States. The purpose is to identify, define, and calculate the impact to particular utility distribution system architectures considering total PEV penetration levels as well as localized concentrations. This paper provides a brief overview of the proposed process to evaluate distribution system response to PEV loading.*

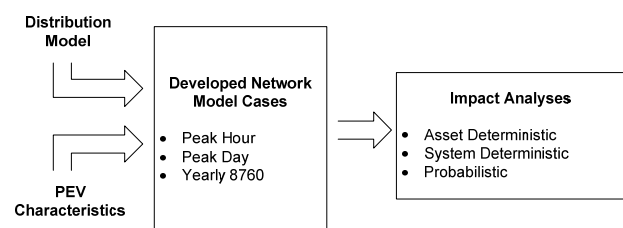
### INTRODUCTION

Interest in electric transportation, particularly plug-in electric vehicles (PEVs), has increased dramatically in recent years with some manufactures planning to introduce production models in the United States as soon as 2010. Potential utility benefits from transportation electrification include improved asset utilization, greater system efficiency, use of vehicle batteries as distributed storage, and environmental benefits stemming from the reduction of greenhouse gas emissions and criteria pollutants. The utility industry recognizes that transportation electrification will also produce considerable societal benefits from a combination of increased economic value, decreased environmental impact, and energy security by displacing imported petroleum-derived fuel with domestically produced electricity.

Understanding how the charging of increasing numbers of PEVs can influence the electrical network is key in implementing a smooth transition from an entirely petroleum based transportation system. However, current distribution planning methods may not accurately assess PEV impacts on the network due to their unidentified influence on daily load patterns and dispersal throughout the network. This paper provides overview of the multi-year collaborative research project to study Plug-in Hybrid Electric Vehicles (PHEV) and Battery Electric Vehicles (BEV) impacts and integration on utility distribution systems. PHEVs and BEVs, which have different

operational characteristics, are essentially the same when viewed as electrical loads on the distribution system and are therefore not treated differently in the study.

The overall methodology proposed for the project is presented in Figure 1. The process begins by constructing the distribution system model and identifying PEV load characteristics. These two information sets are used to construct specific cases or scenarios from which specific system impacts can be determined. Depending on the analysis, the developed cases range from single peak hour case to an 8760 model which represents each hour of the year consequentially. The impact evaluation portion is composed of three tiers consisting of a deterministic evaluation at both the device and system levels as well as a probabilistic evaluation. System impacts to be examined by the study include thermal overloads, voltage levels, system imbalance, and losses.



**Figure 1. Impact Evaluation Method**

### PEV CHARACTERISTICS CONSIDERED IN THE EVALUATIONS

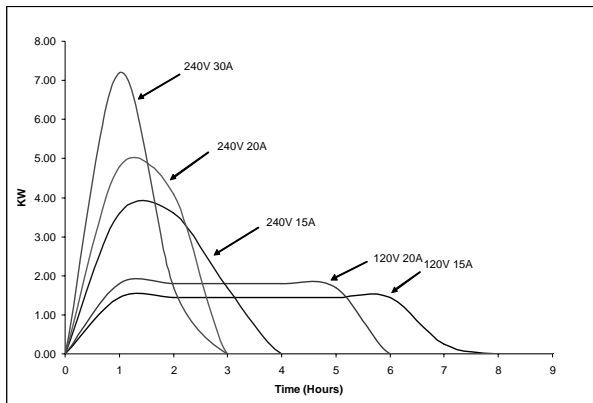
Accurate assessment of the influence corresponding to PEV usage requires understanding the mechanics of the vehicles as well as the likely user behaviors. Variables selected to represent the PEV load characteristics include:

- PEV penetration levels on the electrical network
- Vehicle types and charge profiles/power levels
- Likely customer charging habits
- Likely customer type/locations

While PEV systems are still in development, likely electrical charge characteristics have been identified. The Society of Automotive Engineers recommended practices SAE J1772 and SAE J2293 identify three levels of charging based on voltage and power levels, as presented in Table 1. The electrical demand over time, or charge profile, is then defined by the battery size and charge type, as shown in Figure 2.

**Table 1. PEV Charge Levels**

Type	Power Level
Level 1: 120 VAC	1.2 – 2.0 kW
Level 2 (low): 240 VAC	2.8 - 3.8 kW
Level 2: (high): 240 VAC	6 – 15 kW
Level 3	>15 kW

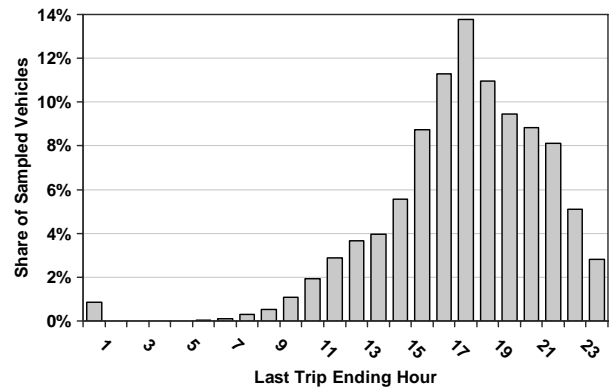


**Figure 2. Full Charge Profiles - 8 kWh Battery Pack (90% Efficiency)**

Accurately modeling PEV charge profiles is fundamental in fully capturing the influence on standard daily and yearly load shapes. Another consideration is that PEVs are large constant power loads which may alter the general dynamic behavior of the system during certain conditions. Intrinsicly, the nature of the charge has an overall influence on how the system is impacted and one aspect of the study to determine the extent to which the network is influenced by various charge profiles.

The actual time of day that a PEV is charged is influenced by a number of factors mainly associated with the end user. The study examines user driving charging habits to determine likely interconnection times. For instance, potential interconnection hours were derived from data concerning user driving habits as illustrated by the likely residential customer home arrival times shown in Figure 3. Additionally, it is recognized that off-peak charging has inherent benefits for the electrical network. To this end “Smart Charging” which utilizes communication between the utility and vehicle to control charging patterns is also being examined.

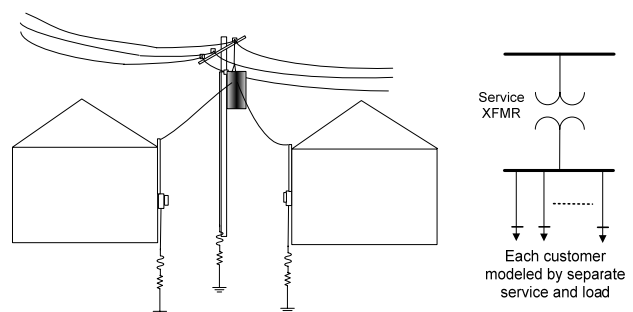
While another potential use for PEVs is as distributed electrical sources, this functionality is not expected in the first generation of PEVs. Hence, this study only considers the loading characteristics of PEVs. The potential for and impacts of PEVs utilized as distributed generation we be examined in subsequent studies.



**Figure 3. Example Profile of Home Arrival Time (Charging Profile)**

**DISTRIBUTION SYSTEM MODEL**

Electrical characteristics of PEV chargers, charge profiles, and voltage levels are all contributing factors to distribution impacts. However, distribution system design and configuration also determines the nature of system impacts. In order address adequacy on all the distribution system in terms of system components or assets, it is necessary to model the system from the substation down to the customer meter. Therefore, the scope of the study includes substation transformer, primary distribution, laterals, distribution transformer, and secondary system up to service entrance. However, for most utilities service drop information is not typically available on a per-customer basis. In these cases, typical services were modeled for each customer served, as shown in Figure 4. This allows for a better estimate of system losses as well as the voltages seen at the meter.



**Figure 4. Extend Model up to Service Entrance**

Impact assessment is performed using the Distribution Systems Simulation Model (DSS) software. DSS is a comprehensive electrical power system simulation tool for electric utility distribution systems and supports nearly all the frequency domain (sinusoidal steady state) analysis commonly performed on electric utility distribution systems. An additional functionality of DSS is the ability to perform time domain analysis on the distribution system. By simulating the network over each hour (or smaller intervals)

over a period of time, the variations of PEV load patterns combined with the daily and season variations in the normal load patterns can be used to more accurately determine the impacts PEVs will have on the system. The importance of considering daily and seasonal variations in the calculations is highlighted by examination of the yearly load shapes. An example load profile is given in Figure 5 showing both daily and seasonal load changes as seen at the substation.

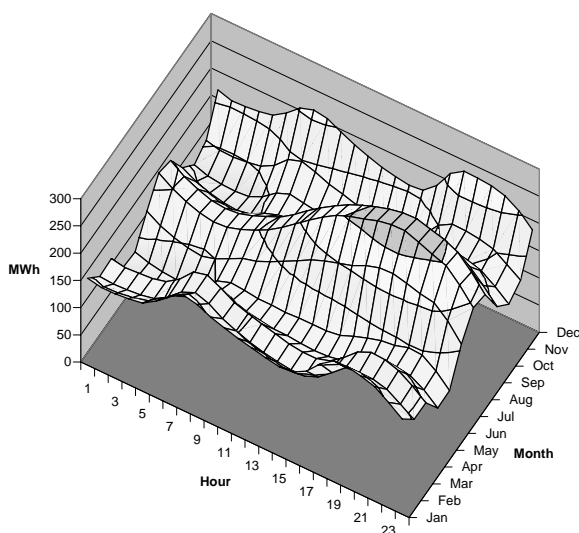


Figure 5. Base Case 8760 Feeder Demand

**IMPACT ASSESSMENT**

System impact assessment is performed through three analyses each designed to quantify various system characteristics and impacts. The Asset and System Deterministic analyses quantify system impacts given fixed increments of PEV loading for different charge types and connection times. These two analyses provide information concerning the system’s characteristics in regard to different PEV charge profiles, connection times, and customer penetration levels. For example, the total power demand at the substation for different interconnection hours is provided in Figure 6. As shown, charging during different times of the day can dramatically affect daily load shapes and subsequently distribution system impacts resulting from PEV charging.

However, deterministic analyses can not account for the variations associated with actual PEV loads. Quantification of the system response considering the spatial and temporal variations in PEV loads is addressed through the Probabilistic portion of the analyses. This portion of the study will provide empirical data towards likely system behavior in response to likely PEVs loading scenarios.

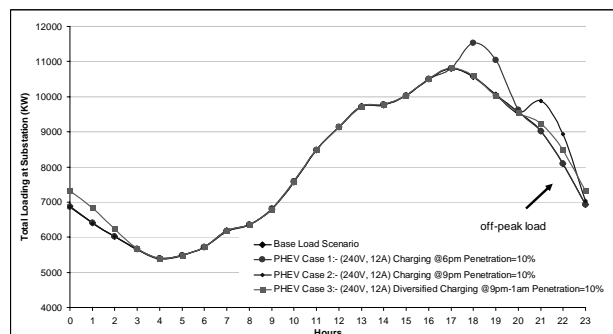


Figure 6. Substation Transformer Loading Assessment

**Asset Deterministic Analysis**

Asset deterministic analysis characterizes the network by determining the levels at which PEV loads result in overloaded conditions across different asset classes. These results will be useful in identifying which component types (secondary, distribution transformer, single-phase lateral, etc.) are potentially susceptible to overloads from PEV charging. Using the developed system model, the capacity for every component in the system is calculated during both peak and off-peak hours. Calculating capacity at two different times provides metric which to base evaluation into the influence of charge time. The capacities are first expressed in terms of the number of PEVs required to overload each device, as illustrated by Figure 7. Finally, the capacity for each device is expressed relative to the number of customers served so that comparisons between individual devices and asset classes can be better evaluated.

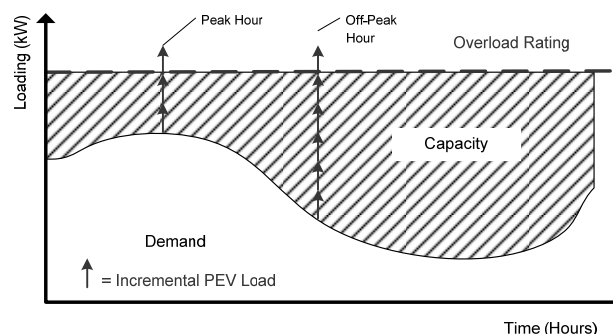
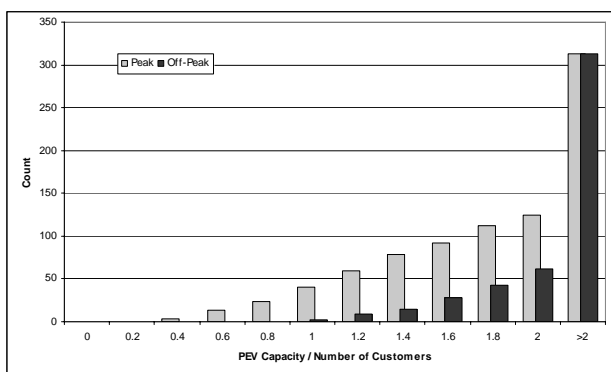
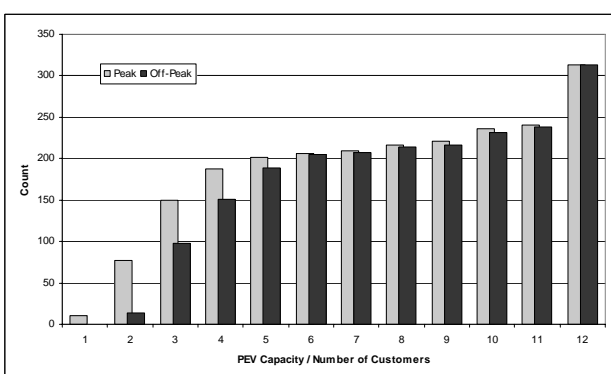


Figure 7. Defining Capacity in Terms of PEV Loading

The results for each device are aggregated across asset classes to generalize the influence on various system components. For example, a cumulative histogram of the capacity-customer ratio for service transformers is provided in Figure 8 for a 120V charge profile at both peak and off-peak hours. Comparison to the 240V results, shown in Figure 9, indicates that service transformers (for this system) to be more susceptible to overloads for the 240V PEV charge profile compared with the 120V profile. This is true regardless of whether charging at peak or off-peak hours.



**Figure 8. Cumulative Histogram of Relative 120V 12A PEV Capacity**



**Figure 9. Cumulative Histogram of Relative 240V 30A PEV Capacity**

Additional steps necessary to account for the typical loading of distribution transformers above their normal ratings during the course of the year. While exceeding normal ratings will not necessarily result in device failure, it does effectively reduce the operation lifespan of the transformer. As PEV charging will alter typical customer load profiles, additional evaluations addressing transformer “loss of life” as a function of PEV type and connection time are performed based on IEEE standard C57.91.

How PEV loading can influence transformer lifespan is illustrated by the example case shown in Table 2. The base case load shape for the 25kVA transformer is assumed to have a peak value of 90% of the transformer rating and a load factor of 44%. As additional PEVs are introduced the transformer’s equivalent load shape is altered by the PEV charge profile and connection time. The new load shape coupled with the assumed ambient temperature profile is then used to calculate the transformer insulation aging that occurs. For this example, the 120V off-peak charge represents a minimal reduction to the lifespan of the transformer. The reported percentages are based on the assumed normal insulation lifespan of 20.55 years when operating at rated load.

**Table 2. 25 kVA Transformer Yearly Aging**

# PEV	Aging per Year (% of Normal Lifespan)			
	120V 12A Peak	120V 12A Off-peak	240V 30A Peak	240V 30A Off-Peak
0	0.60 %	0.60 %	0.60 %	0.60 %
1	1.05 %	0.64 %	1.72 %	0.84 %
2	1.99 %	0.71 %	9.16 %	2.75 %
3	3.99 %	0.83 %	69.02 %	20.22 %

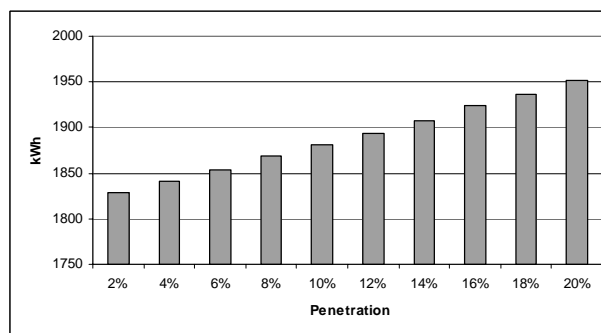
**System Level Deterministic Analysis**

The intent of system level analysis is to characterize the network’s response as a whole. While device overloads can be approached individually, other issues, such as voltage levels and imbalance, require the evaluation of the network as a whole. More importantly, these evaluations are designed to identify the boundaries for the probabilistic scenarios and provide insights into the nature of the influence of the PHEV penetration on the system.

Cases for this level of the deterministic evaluations consist of 24 hour peak day simulations based on combinations of the identified PEV characteristics and are intended to:

- Quantify specific technical impacts of the PEVs
- Quantify impacts on worst case scenarios
- Evaluate parameter sensitivities and potential levels of negative impacts

For instance, sensitivity analysis of system losses in the example system show the losses to be linearly related to the % PEV customer penetration, as shown in Figure 10.



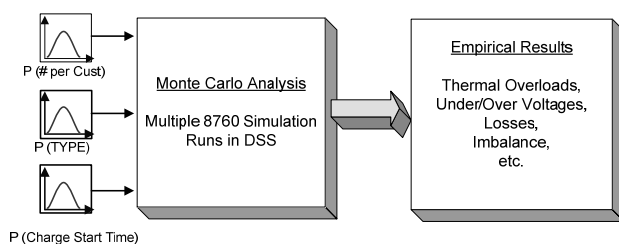
**Figure 10. Additional System Losses due to 120V Peak Hour PEV Loads**

Together the two sets of deterministic evaluations explain what factors (stemming from both PEV and system characteristics) will have a role in the impacts of PEVs on the distribution system. It should be noted, however, that the deterministic results do not indicate the likelihood of these impacts. These types of conclusions are addressed through probabilistic simulations of the distribution system and PEVs.

### Probabilistic Analysis

Monte Carlo simulations will be used to evaluate potential impacts based on probabilistic projections of certain aspects of PEV proliferation/use. The probabilistic Monte Carlo approach is intended to capture both spatial and temporal diversity of PEV integration as customers in varied locations purchase PEVs of varied types and charge them differently.

The mechanism used to implement the probabilistic simulations is illustrated in Figure 11. The Monte Carlo simulations are composed of probabilistic assignment of PEVs to the distribution base case. Each PEV is randomly assigned a location, type, and daily charge profiles based on the provided probability density functions (PDF) for each characteristic. In this manner, multiple probabilistic scenarios are generated from the system and probability density functions. Each of these cases or scenarios consists of 8760 hours representing a full year. In order to sufficiently capture the influence of the variation on the system, the number of 8760 simulations to be performed, per PDF set, is expected to consist of no fewer than 100 cases.



**Figure 11. Assessment Framework: Probabilistic Approach**

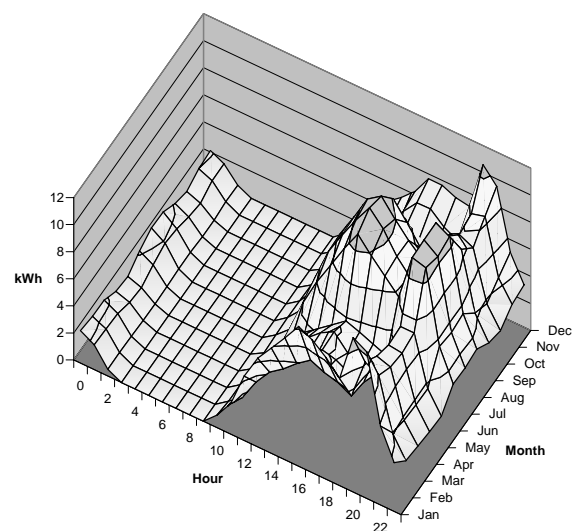
Three probabilistic sets were performed in order to capture the influence of increasing PEV penetration into the customer base. Each of these sets will require their own power density functions and are defined by low (2%), medium (5%), and high (10%) penetration levels. The empirical data gathered from the each probabilistic set will be aggregated across various asset classes and voltage levels to form general conclusions concerning likely distribution system impacts. The average hourly line losses of Figure 12, for example, indicate that additional line losses associated with the PEV charging are not only a function of daily charge patterns but vary seasonally with the base loading as well.

The probabilistic analysis results coupled with those from the asset and system level deterministic analyses provide a complete portrait of the distribution system impacts from PEV loads. Specifically, they seek to identify the general response at both the asset classes and system level to increased PEV loading as well as what impacts are likely to occur.

### SUMMARY

Wide-scale adoption of PEVs will undoubtedly influence distribution system design and operation. 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. Very high saturations or coincidental charging behaviors could result in loads beyond what current circuit design can reliably serve. To ensure that they can meet these new demands, utilities must undertake distribution feeder-level analyses to ascertain what penetration level and charging behaviors result in excess demand requiring remediation.

Traditional distribution analysis methods may not accurately capture the spatial uncertainty in PEV penetration and temporal uncertainty in charging patterns and habits of PEV adopters. EPRI has initiated a multi-year project with several utilities to understand the impact of PEV to distribution system operations. This paper describes the overall methodology along with example results.



**Figure 12. Maximum Hourly Line Losses above Base Case given High PEV Penetration**

### ACKNOWLEDGEMENT

The authors wish to acknowledge the support of Jim Browder, Paul Ireland of Dominion Resources, Angelo Giumento of Hydro Quebec for providing the circuit data, loading data, and measurement data, tuned power flow cases, and other additional information regarding the circuits and system during the course of this project. We would like to also gratefully acknowledge the co-sponsors of this research, Dominion Resources, Hydro Quebec, AEP, ConEd, TVA, Southern Company, BC Hydro, SRP, Duke, and Northeast Utilities