

Evaluation of the Impact of Plug-in Electric Vehicle Loading on Distribution System Operations

J. Taylor, A. Maitra, M. Alexander, D. Brooks, M. Duvall

Abstract— Electric transportation has many attractive features in today’s energy environment including decreasing greenhouse gas emissions from the transportation sector, reducing dependence on imported petroleum, and potentially providing consumers a lower cost alternative to gasoline. Plug-in hybrid Electric (PHEV) vehicles represent the most promising approach to electrification of a significant portion of the transportation sector. Electric power utilities recognize this possibility and must analyze the associated impacts to electric system operations. This paper provides details of analytical framework developed to evaluate the impact of PHEV loading on distribution system operations as part of a large, multi-utility collaborative study. This paper also summarizes partial results of the impact of PHEVs on one utility distribution feeder.

Index Terms—Plug-in Hybrid Vehicle, distribution system, measurement, deterministic models, stochastic models, spatial distribution, temporal distribution, thermal loading, charge profile

I. INTRODUCTION

A confluence is occurring between the electric power and automotive industries as the interest in plug-in hybrid vehicles advances to the point where all major U.S. automotive manufactures either have or are in the process of developing Plug-in Electric Vehicles (PEVs), including Electric Vehicles (EVs) and Plug-in Hybrid Electric Vehicles (PHEVs). For the transportation industry, electricity is a cheaper alternative to petroleum fuels, which reduces greenhouse gas emissions [1-3], and the nation’s dependence on imported petroleum.

Widespread PEV adoption by consumers requires direct utility involvement to ensure an optimal transition from purely petroleum based transportation. While electric utilities recognize the potential societal and economic benefits of PEVs, safe and reliable operation of the electrical network is still the primary utility concern. Thus, understanding and accurately predicting PEV electrical system impacts is important for automotive manufactures as well as utilities. Previous PEV integration studies [4-6] focused primarily on determining whether existing or planned generation capacity will be sufficient to supply the increased demand resulting

from PEV charging. Additionally, many of these studies have assumed the additional initial PEV load could be contained within the system off-peaks without affecting the peak demand [2,4,6]. Such system-wide assumptions do not address the potential impacts of coincident peak PEV charging at localized distribution levels where diversity benefits may be less than anticipated at system levels.

While some diversity in PEV charging and traditional demand are certain to be realized, uncertainty in PEV penetration, charging patterns, and driving habits make it difficult to accurately predict local distribution system effects. No historical data supported by comprehensive market research exists to accurately project PEV adoption along specific distribution systems. Further, a recent study, [7], concluded that PEV loads are likely to be clustered in certain areas increasing the potential for negative distribution system impacts. Additionally, while utility coordinated charging of PEVs through a two-way communication system (“smart charging”) is likely to facilitate diversified charging during low demand periods, it will not be possible to completely control customer driving and charging habits.

Evaluation of the impact of PEV loading on distribution system operation requires a micro level analysis that considers the possible variations in spatial diversity of the PEVs throughout the network and temporal diversity in PEV charging patterns relative to traditional system load. This paper describes such an analytical framework developed for a large, multi-utility study of the likely distribution system impacts due to PEV adoption into the market.

II. GENERAL ANALYSIS FRAMEWORK

The developed analytical framework is 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 PHEV commercialization, where EVs have very small market share. Although the total PEV penetration is assumed to be small, possible high localized concentrations are possible. EVs are neglected in the study since the market share for these vehicles will be small. The study analysis framework utilizes known distribution system circuit information, PHEV charge characteristics, and likely customer behaviors to construct models of likely system conditions. The general analysis framework is illustrated in Fig. 1.

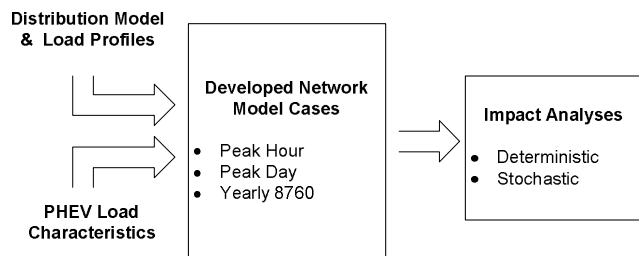


Fig. 1. System Impact Analysis Framework

III. DISTRIBUTION SYSTEM ELECTRICAL MODEL

Evaluation of PHEV loading impacts on the distribution system and specific components requires PHEV load characteristics be considered relative to specific interconnection points in the electrical system. As such, complete electrical models of individual distribution feeders are developed from the substation down to individual customer meters including the substation transformer, 3-phase primary, laterals, distribution transformers, and secondary system up to service entrance.

In order to evaluate the potential impact of PHEVs on distribution circuits of various types, multiple distribution feeders from multiple utilities are being studied. Circuits are being selected based on several factors including specific utility goals, connected customers and expected PHEV penetration levels, and basic circuit characteristics.

All circuits are modeled in EPRI’s open-source Distribution System Simulator (OpenDSS) analysis platform. OpenDSS is a comprehensive electrical power system simulation tool designed primarily for advanced analysis of distribution systems. OpenDSS is a multi-phase simulation tool that supports nearly all frequency domain analysis commonly performed on electric utility distribution systems. Additionally, OpenDSS has the ability to perform time domain analysis on the distribution system. Thus, sequential power flows can be simulated over successive time intervals (e.g., hourly) over a specified period of time with consideration of all circuit dynamic controls such as regulators and switch capacitors. This OpenDSS capability allows for direct consideration of interactions of the variations

of PHEV load patterns and daily and seasonal conventional load variations.

Generally, the basic circuit electrical model and customer load points are converted to the OpenDSS from the specific utility’s distribution system analysis software format (CYMDIST, WindMil, SYNERGEE, FeederAll, etc.) Historical annual load profiles for primary distribution points (i.e., substation) and for typical customer classes served are utilized to assign load shapes for all customers in the model. The model is also augmented with other electrical data including station and distribution transformer data, secondary/service data, and capacitor and voltage regulator and associated control settings. Finally, any additional circuit metering (additional primary metering or AMI) is utilized to validate the circuit model. The validated electrical models then serve as the base case scenario against which the impacts of various PHEV loading scenarios can be evaluated.

IV. PHEV CHARACTERISTICS

PHEVs combine operational aspects of both battery electric vehicles (BEVs) and power-assist hybrid electric vehicles (HEVs). Similar to a BEV, a PHEV can store significant energy within an onboard battery for use during daily driving and recharge the battery from the electric grid. PHEVs, however, also have internal combustion engines that are used for propulsion when the battery is depleted, which will increase the near-term marketability of PHEVs relative to EVs. From the perspective of the grid, BEVs will be the same as PHEVs but will have larger batteries and will therefore charge for longer periods.

While another potential use for PHEVs is as distributed electrical sources, this functionality is not expected in the first generation of PHEVs. Hence, this study only considers the loading characteristics of PHEVs. The developed framework considers the following principle factors that define PHEV loading on distribution systems:

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

A. Charge Profiles

PHEVs are similar to existing hybrid electric vehicles (HEV) with the primary difference being the incorporation of an “energy” battery that allows the PHEV to directly store grid electricity for propulsion. Thus, PHEVs require a method of charging the battery on a regular basis. As proposed in SAE J1772 [8], conductive charging is a method for connecting the electric power supply network to the EV for the purpose of transferring energy to charge the battery. The conductive system architecture is suitable for use with electrical ratings

as specified in Table I [8]. While PHEV systems are still in development, likely electrical charge characteristics are being identified. SAE J1772 identifies three levels of charging based on voltage and power levels, as presented in Table II.

TABLE I
ELECTRICAL RATINGS (NORTH AMERICA)

Charge Method	Nominal Voltage(Volts)	Max Current (Amps-continuous)	Circuit Breaker rating (Amps)
AC Level 1	120V, 1phase	12A/16A	15A/20A
AC Level 2	208-240V, 1phase	32A/80A	40A/100A

TABLE II
PHEV CHARGING MODEL CHARACTERISTICS

Type	Power Level
Level 1: 120 VAC	1.2 – 2.0 kW
Level 2 (low): 208-240 VAC	2.8 – 3.8 kW
Level 2: (high): 208-240 VAC	6 – 15 kW
Level 3: 208-240 VAC	>15 KW-96KW
Level 3: DC Charging: 600VDC	>15KW-240KW

The PHEV charge profile influences how the distribution system is impacted as it partially defines daily and annual PHEV load shapes. One aspect of the study is to determine the extent to which the network is influenced by various charge profiles. The electrical demand over time, or charge profile, is defined by the battery size, charger efficiency, miles driven, and charge type. An example of how charge profiles vary over time is provided in Fig. 2.

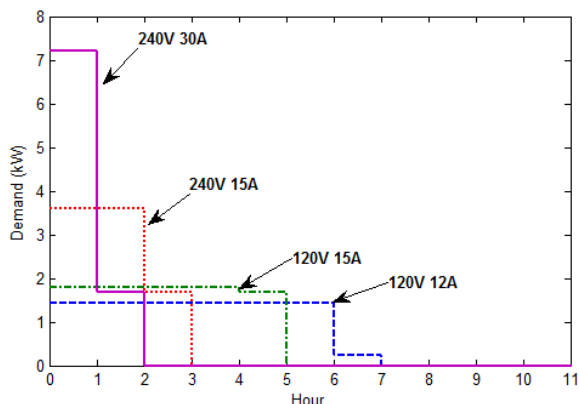


Fig. 2. Full Charge Profiles - 8 kWh Battery Pack (90% Efficiency)

B. Electric Vehicle Penetration Levels across Utility Customers

This study assumes that the entry of PHEVs into the vehicle fleet takes future market share from both conventional vehicles (CVs) and HEVs. Market penetration of CVs, HEVs, and PHEVs from 2010 to 2030 are illustrated in Fig. 3 [9-10], with HEVs representing approximately 15% of the market of new vehicle sales when PHEVs are expected to enter the market in 2010. As shown in this figure, PHEVs could reach a maximum of 10% new vehicle market share by 2015 timeframe. PHEV penetration levels in the study stochastic

analysis are based on 2010 through 2015 projections -- 2% in a low PHEV scenario, 4% in a medium PHEV scenario, and 8% in a high PHEV scenario. Penetration market levels ranging from 0 to 20% were considered for the system level deterministic evaluations.

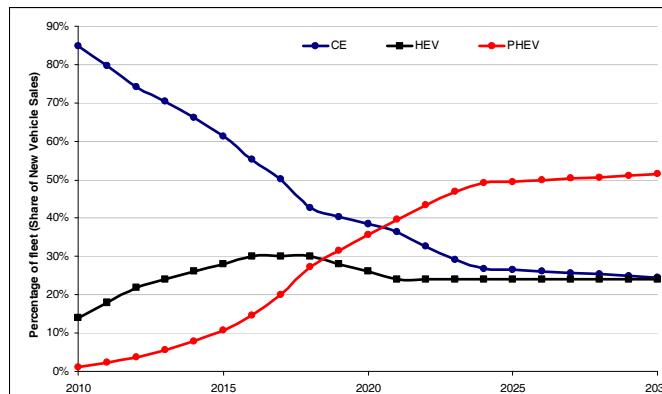


Fig. 3. Projected New Vehicle Market Share Categories

As utility customers can have multiple vehicles, PHEV market penetration levels must be translated into expected PHEV penetration across utility customers. For each utilities service territory, Department of Transportation data concerning the number of existing vehicles per household [11] are used to generate projections of the number of PHEVs per utility customer as a function of market penetration, assuming that each utility customer corresponds with a household. The probabilities of number of PHEVs per residential customer, for one example system, are provided in Table III for different market penetration levels. Note that the projected percentage of utility customers with PHEVs is higher than the specified market penetration as there is typically more than one vehicle per household.

TABLE III
RESIDENTIAL CUSTOMER PENETRATION PROJECTIONS

Market Penetration	PHEV per Customer		
	0	1	2
2%	96.9%	3.1%	0.0%
4%	93.8%	6.1%	0.1%
8%	87.8%	11.6%	0.5%

C. Charge Times & Battery State of Charge

The study uses driving pattern data from the National Household Travel Survey (NHTS 2001¹) [12] 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 Fig. 4. It is important to note that, for this dataset, approximately 14% of the time a vehicle is not driven at all during any given day. Hence, the shown cumulative density function only reaches about 86%.

¹ NHTS 2001 Unweighted Travel Day Data: Summary by Home Type, Purpose, End Time of the Last Trip, and Miles per Vehicle

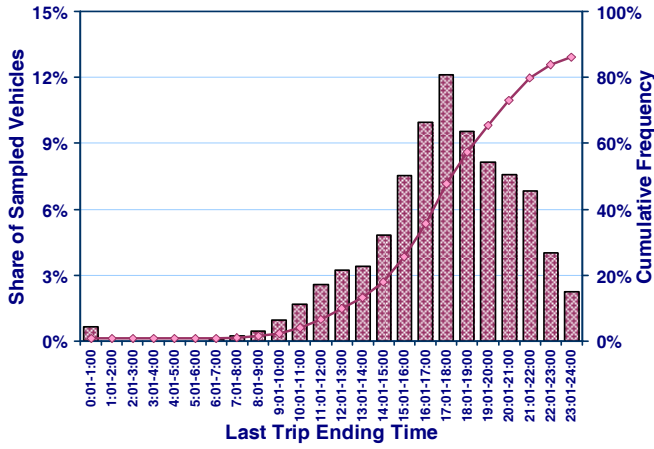


Fig. 4. Example Profile of Home Arrival Time

Remaining battery charge probabilities were also developed based on different customer daily driving distances (0.01-10 miles/day, 10.01-20 miles/day, etc.). This data is used to calculate the amount of electrical energy required to recharge the vehicle each day, based on the efficiency and battery capacity. Identified conditional relationships between projected home arrival times and miles driven are provided in Fig. 5. The majority of longer driving distances shown corresponds with early evening arrival times which reflect the commuter traffic market targeted by PHEVs.

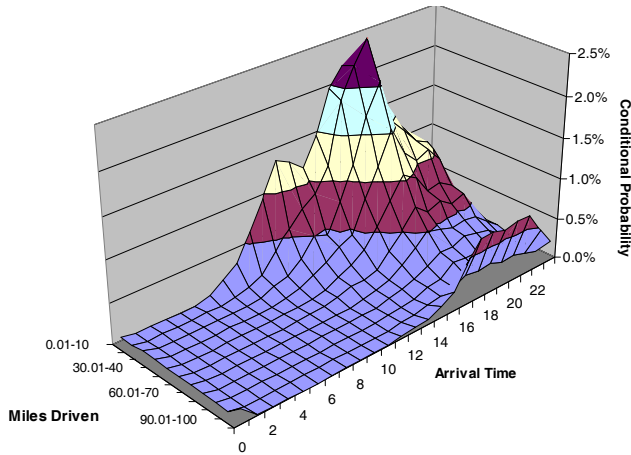


Fig. 5. Conditional Miles Driven and Arrival Time Probabilities

V. SYSTEM IMPACTS ASSESSMENT

There are numerous variables that must be considered in evaluating PHEV impacts on a given distribution system. The analysis approach utilizes both deterministic and stochastic assessments of the developed models. The deterministic analysis is designed to identify distribution system component impact sensitivities as well as general trends in network behavior for forced scenarios. The deterministic analysis does not, however, incorporate the likely temporal and spatial diversity of PHEV loads on the system. Because these

characteristics can not be known in advance with certainty, stochastic analyses are performed to evaluate system impacts in response to more realistic PHEVs loading scenarios.

A. Evaluated Impacts

The following PHEV impacts are evaluated for various PHEV characteristic combinations:

- Thermal loading → to what extent are component normal and emergency ratings exceeded (number of occurrences, typically overload asset classes, duration and magnitudes)
- Voltage → to what extent does PHEV loading adversely impact system voltage regulation. (Voltage excursions, regulator operations, cap operations, etc.)
- Unbalance → potential for disproportionate penetration on particular phase and results on system unbalance
- Losses → impact on distribution system losses

B. Deterministic Impact Analysis

The first stage of the deterministic analysis is a component level analysis that examines the impact on each distribution system asset class to increasing numbers of PHEVs served. Each component's thermal capacity is calculated at both peak and off-peak hours and used to determine the number of PHEVs which would to exceed its ratings. These loading values are normalized by the total number of customers served by the system component, as indicated in (1). Normalizing by the number of customers provides a sense of the severity of the loading as well as facilitates comparison between devices of the same class. The results do not of themselves provide an indication of likelihood of overload. The results are, however, useful in identifying PHEV penetration levels at which each distribution asset class (secondary, distribution transformer, single-phase lateral, etc.) is potentially susceptible to overloads from PHEV charging. In addition to penetration levels, the influence of various charge times and PHEV charge profiles are evaluated over different scenarios.

$$Capacity_{PHEV} = \frac{I_{rated} - I_{load}}{I_{PHEV}} * \frac{1}{\#Customers} \quad (1)$$

Fig. 6 shows the distribution transformer overload results from deterministic evaluations conducted for one feeder. This plots summarizes the number of PHEVs of a certain charge type that is required to overload each distribution transformer on the feeder for a both peak and off-peak system load hour. The results are normalized per number of customers served from each transformer. For example, the results for this one feeder shows that 12.8% of the feeders's service transformers would be overloaded if charging at the peak hour when a 1:1 ratio exists between the number of connected PHEVs and customers. In comparison, the same loading level results in 0.6% of the service transformers being overloaded when off-

peak charging is considered.

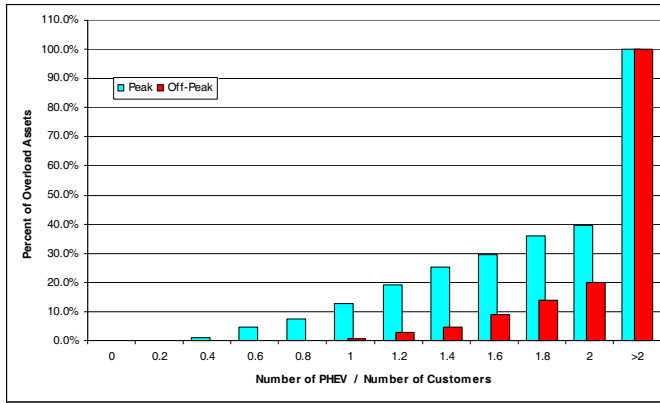


Fig. 6. Service Transformer Asset Response to PHEV Load (120V 12A)

System-level deterministic analysis is also performed to determine the extent to which individual component-level critical loadings are reached for forced system-wide PHEV penetration scenarios. These system deterministic scenarios also identify boundary cases that may not be evaluated in the stochastic scenarios. The system-level deterministic analysis consists of 24-hour peak-day simulations with increasing PHEV penetration from 0 to 20%. PHEVs are randomly sited across potential customer locations, but assigned locations are held constant over the increasing penetration scenarios. The impact results for each penetrations level provide indications of existing trends in the system’s behavior. For instance, Fig. 7 shows the results of a system-level deterministic analysis of losses for one feeder. These results show that for this circuit, losses tend to increase linearly with PHEV penetration, and are significantly affected by charge time and PHEV charge profile. As with the component-level deterministic evaluations, the system-level deterministic results do not necessarily represent realistic PHEV penetration and loading scenarios.

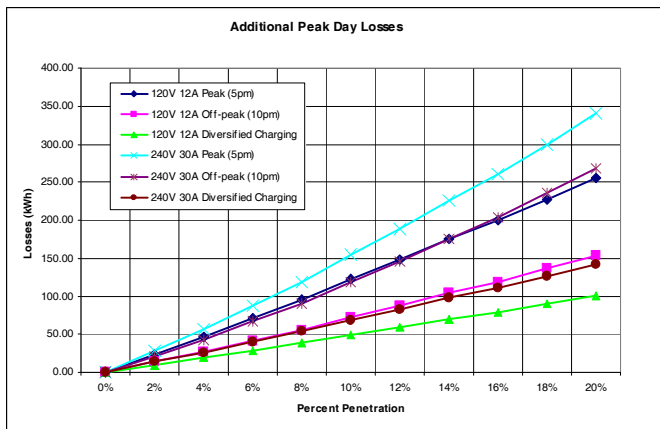


Fig. 7. System Losses for Various Deterministic PHEV Charging Scenarios

Recognizing PHEV charging will inherently alter customer daily demand profiles, deterministic transformer “loss of life”

evaluations are also performed. Changes to the insulation aging per year are shown for an example 37.5 kVA transformer in Fig. 8. Aging results in respect to increasing numbers of PHEV loads are facilitated by altering the modeled transformer hourly demand by the specified PHEV loading scenarios. The altered load shapes, coupled with a representative ambient temperature profile, are then used to calculate the transformer insulation aging over the calendar year using IEEE standard C57.91 [13].

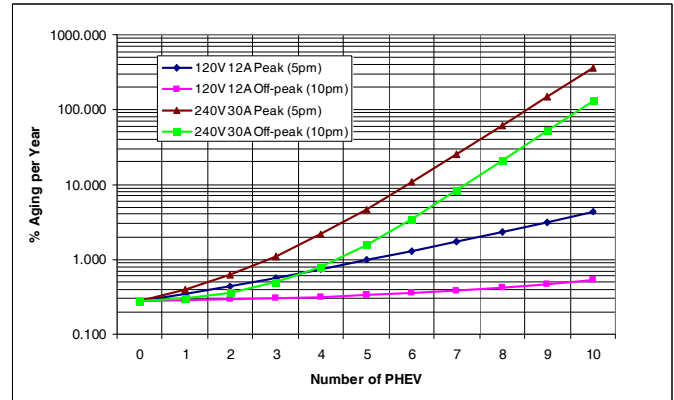


Fig. 8. Transformer Percent Aging for Various Deterministic PHEV Charging Scenarios

C. Stochastic Impact Analysis

The deterministic analysis results provide insights as to component and system impact levels for forced PHEV loading scenarios, but do not provide any indication of likely impacts. An evaluation impacts resulting from expected PHEV scenarios are performed through stochastic sequential simulations of the distribution system and PHEVs. Sequential Monte Carlo simulations are used to evaluate potential impacts based on projections of certain aspects of PHEV proliferation/use. The stochastic approach is intended to capture spatial and temporal diversity of PHEV integration.

Fig. 9 illustrates the generation stochastic analysis process. Numerous stochastic cases are derived based on random assignment of PHEV location, type, and daily charge profiles based on probability density functions described previously. Operation of the distribution system and PHEVs for each stochastic case is simulated at hourly resolution over a full calendar year (8760 hours). Three distinct sets of cases are performed to capture different levels of PHEV market penetration using the customer penetration probabilities of Table III. In order to capture sufficient variation in the modeled variables, 8760 simulations are conducted for approximately 100 stochastic cases per penetration scenario. Results gathered from each stochastic set will be aggregated across various asset classes and voltage levels to form general conclusions concerning likely distribution system impacts.

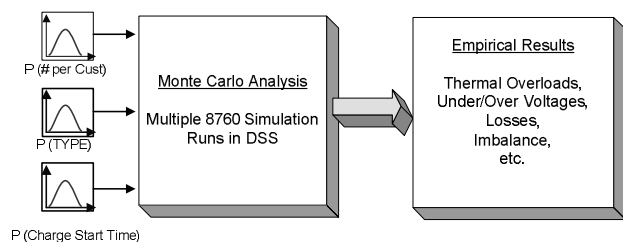


Fig. 9. Assessment Framework: Probabilistic Approach

VI. SUMMARY AND FUTURE WORK

Wide-scale adoption of PHEVs and BEVs will undoubtedly influence distribution system design and operation. Not all distribution circuits will realize the same level of PHEV adoption. The extent of system impacts depends upon the PHEV penetration and charge behaviors of PHEV adopters. Very high saturations or coincidental charging behaviors could result in loads beyond what current circuit design can reliably serve. Utilities must undertake *distribution feeder-level* analyses to ascertain what penetration level and charging behaviors result in impacts requiring remediation.

PHEV impact analysis methods must accurately capture the spatial diversity in PHEV penetration and temporal diversity in charging patterns of PHEV adaptors. This paper describes the deterministic and stochastic analytical methods being employed in a larger EPRI collaborative study of distribution impacts of PHEVs. Subsequent papers will summarize key results obtained from the study.

VII. ACKNOWLEDGEMENTS

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IX. BIOGRAPHIES

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