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Evaluation of PEV Loading Characteristics on Hydro-Quebec's Distribution System Operations

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Abstract

The utility industry recognizes electrifying a significant portion of transportation is likely to occur given current market pressures such as fuel costs, energy independence, and environmental concerns. However, successful implementation of Plug-in Electric Vehicles (PEVs) requires fully evaluating what impact the additional loading may have on distribution system operations and planning. Due to the unknown spatial and temporal variations associated with PEVs, traditional distribution system analysis methods may not accurately represent system impacts. In response, EPRI has initiated a multi-year project to understand PEV system impacts with several utilities in the United States, Canada, and Europe. The goal of the study is to identify, define, and quantify impacts on utility distribution system architectures through PEV analysis in conjunction with comprehensive system analysis. This paper presents a subset of the PEV impact results determined from the EPRI study methodology for two representative Hydro-Québec distribution feeders.

Keywords: Plug-in hybrid vehicle, distribution system, deterministic models, spatial distribution, temporal distribution, thermal loading, charge profile

1 Introduction

Plug-in Electric Vehicles (PEVs) are a transformational technology as they introduce electricity as a meaningful energy source for the transportation sector. Whether as Electric Vehicles (EVs) or Plug-in Hybrid Electric Vehicles (PHEVs), the benefits of electricity as a fuel source have motivated several major automotive manufacturers to either develop or begin the process of developing Plug-in Electric Vehicles (PEVs). As the number of PEVs served by the electrical system increase the aggregated impact on the grid could be substantial. Naturally, utilities are concerned about how this new load may affect system operation and how best to account for them in their planning structure.

While the implications of increased penetration of PEVs have been studied generally on a national energy capacity level, the impact to specific utility distribution system architectures and implications to distribution system planning and operations are not yet fully understood. Aggregated system evaluations that examine the system as a whole cannot capture all system impacts stemming from coincident peak PEV charging at localized distribution levels where diversity may be less than anticipated at system levels. Therefore, the system response considering the PEV load spatial diversity and temporal variations will need to be evaluated in terms of total PEV penetration level as well as localized PEV concentrations. Additionally, PEV charging characteristics and their correlation with system impacts must also be evaluated.

This paper provides a brief description of the PEV impact assessment methodology and selected results for two representative Hydro-Québec distribution feeders as PEV penetration levels increase.

2 Hydro-Québec's Perspective

Hydro-Québec updates its 15 year distribution planning scenarios on a yearly basis, such that the utility can plan ahead for shifting technological, economical or societal patterns which may affect the load on the distribution network. These planning scenarios include different solution scenarios onto which different control schemes, smart grid options, and infrastructure investments are studied in order to respond as effectively as possible to the growing load.

Due to Québec's particular geography and extensive use of electric space heating, Hydro-Québec is mostly a winter peaking utility. The distribution network is designed in such a way to be able to withstand a cold load pickup following a prolonged winter outage. Hydro-Québec is concerned with the possibility of a PEV clustering limiting the network's ability to withstand cold load pickup.

2.1 Energy

If we assume a PEV to have an average electric consumption of 160 Wh/km and an all electric range of 15,000 km per year; this sums to 2400 kWh per year. This consumption is the equivalent of an electric water heater, which is a very common load in Québec homes.

There are currently approximately 4 million cars in circulation in the province of Québec. Should 10% of this fleet be converted to PEVs, the total load for Hydro-Québec's network would be of 960 GWh, representing less than 0.5% of Hydro-Québec's generation capacity. Reaching a 25% penetration, it would represent 2.4 TWh per year representing less than 1.3% of Hydro-Québec generation capacity.

2.2 Power

Hydro-Québec's generation capacity is estimated at about 38 000 MW, 98% of which come from hydraulic sources. This generation capacity does not take into account new generation projects which should be operational in the next few years and energy import capabilities.

On a typical winter peak day, the system can see a demand oscillating around 36 000 MW. The below graph (Figure 1) shows the equivalent of 1 million vehicles coincidentally charging at 1.25kW; for a total additional load of 1250 MW. On the peak day, we can see that Hydro-Québec's generation capacity is sufficient to sustain this coincident load. However, it is important to note that should such a PEV penetration level be reached, more generation capacity would probably be made available.

The 1250 MW may not be an unbearable burden for the generator, however due to Québec's geography it could be expected that this load may become clustered around some critical areas hence putting additional strain on the distribution substations and the local distribution network.

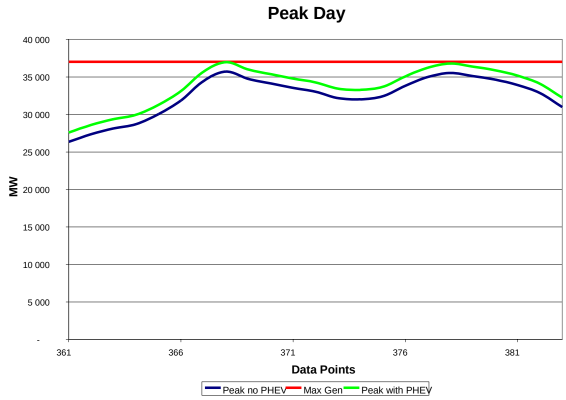

Figure 1: Hydro-Québec generation capacity

3 Methodology

Accurately assessing the impacts on distribution system operations necessitates an analytical approach which identifies component sensitivities as well as likely impacts. A full description of the assessment framework used in the analysis can be found in [1]. System impacts examined in the study include system thermal loading, voltage regulation, transformer loss of life, unbalance, losses, and harmonic distortion levels.

The process begins by selecting candidate distribution circuit, utilizing known distribution system circuit information and assumed PEV charge characteristics to construct models of likely and specific system conditions. The analysis covers the breadth of the system from the substation down to each individual utility customer and examines impacts based on timeframes ranging from a single peak hour to a full calendar year. The impact evaluation portion is composed of three tiers consisting of a component and system level evaluation under specific, selected loading conditions as well as a stochastic evaluation which examines system response under probabilistic scenarios.

The study concentrates on near-term PEV market penetration scenarios (one to five years after PEV commercialization) where PEVs are assumed to have relatively small market share. Although the total PEV penetration is assumed to be small, possible high localized concentrations are still a concern. The study does not included EVs as the market share for these vehicles is assumed to be negligible.

4 PEV Characteristics

The developed framework considers the following principle PHEV loading factors:

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

Recognizing that the implementation of PEVs as a distributed generation resource is unlikely for the first generation of vehicles, only the loading characteristics of PEVs is considered. Additionally, wide scale adoption of utility coordinated charging of PEVs through the deployment of two-way communication system ("smart charging") is also unlikely in near-term and mid-term distribution planning horizons. Therefore, controlled charging is not considered in the study and charge times are determined by predicted customer charging behavior.

4.1 Charge Profiles

SAE J1772, considered the most widely considered standard in this area, has defined two AC charging levels with a third AC level and a DC level still in development, as presented in Table 1. While PHEV systems are in development, likely electrical charge characteristics are still being identified.

Table 1: PHEV Charging Model Characteristics [2]

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 electrical demand over time, or charge profile, is defined by the battery size, charger efficiency, miles driven, and charge level. An example of how charge profiles vary over time is provided in Figure 2. As illustrated, the charge profile, for any given battery size, is a constant power load whose magnitude and duration are defined by the power level. From an analysis perspective it is important to identify the system sensitivity to different charge levels.

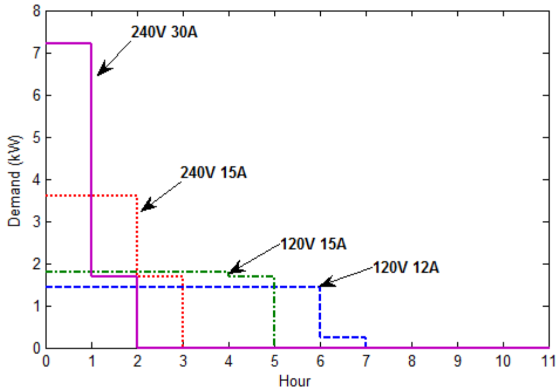

Figure 2: Full Charge Profiles - 8 kWh Battery Pack (90% Efficiency)

4.2 Customer Adoption Rates

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 Figure 3 [3-4], 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. For each utilities service territory, Department of Transportation data concerning the number of existing vehicles per household [5] are used to convert the market penetration projections into the number of PHEVs per utility customer. Therefore for a given market penetration level, a utility customer adoption rate can be identified for use in the analysis.

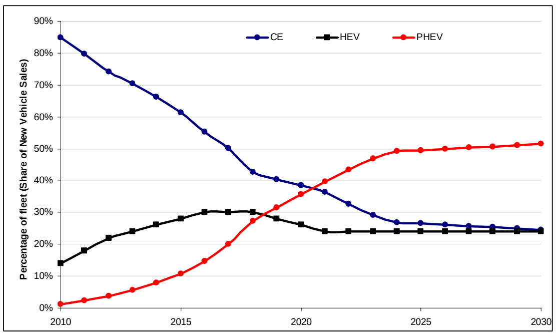

Figure 3: Projected New Vehicle Market Share Categories

4.3 Charge Times & Battery State of Charge

The study uses driving pattern data from the National Household Travel Survey (NHTS 2001[1]) [6] to

[1] NHTS 2001 Unweighted Travel Day Data

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 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%.

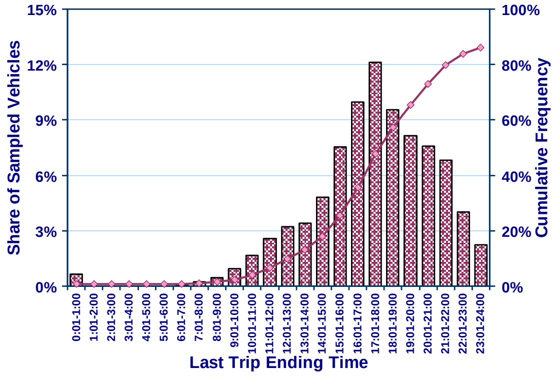

Figure 4: Example Profile of Home Arrival Time

This data is also used to calculate conditional probabilities of customer driving patterns with respect to home arrival times and miles driven shown in Figure 5. These driving patterns are used to not only set the charge start time for each day but also the energy demand required to fully recharge the vehicle's battery.

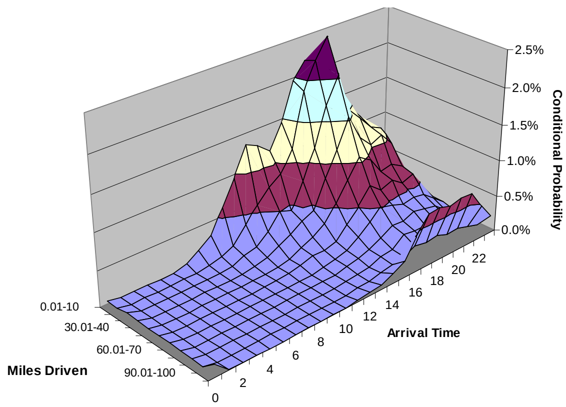

Figure 5: Conditional Miles Driven and Arrival Time Probabilities

5 Distribution System Model

In order to address overall distribution system adequacy, each distribution feeder is modeled fully from the substation transformer all the way to individual customer meters. Historical annual load profiles for primary distribution points (i.e., substation) and for typical customer classes served are utilized to assign load shapes for each customer.

Two representative Hydro-Québec distribution feeders were considered for the study. Brief summary characteristics are provided for each feeder.

5.1 Circuit Characteristics

5.1.1 Feeder A:

This feeder supplies is a highly urban circuit containing a very large population density and lots of growth. The majority of the loads represent multifamily homes or high rise condos.

- *Number of customers* – 2801, 44% (1220 customers) of which are living at high rise condos which are served out of 3-phase transformers
- *Territory* – 88% residential, 12% commercial, 95% underground.
- *Operating voltage* – 25KV.
- *Load factor* – 48%
- *Load density* – 209
- *Primary circuit length* – 13.4 miles
- *Loading* – Winter Peaking Utility. Peak occurs on 2/28/2007. The first peak occurs at 8am and the second peak occurs at 7pm.
- *Charging Scenario* – Evening and Night recharging

Base Loading for this feeder showing both daily and seasonal power demand changes are shown in Figure 6.

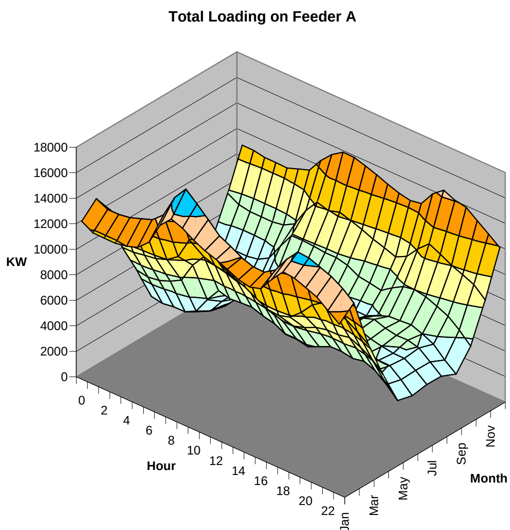

Figure 6: Base Loading Profile (Feeder A)

5.1.2 Feeder B

This feeder supplies a typical suburban neighbourhood. Mostly middle and upper middle class families travelling by car (low public transit penetration), very prone to buying a main or secondary car.

- *Number of customers* – 1132
- *Customer type*– 97% residential, 3% commercial
- *Operating voltage* – 25KV
- *Load factor* – 46%
- *Load density* – 130
- *Primary circuit length* – 8.7 miles
- *Loading* – Winter Peaking Utility. Peak occurs on 2/5/2007. The first peak occurs at 8am and the second peak occurs at 6pm

Base Loading for this feeder showing both daily and seasonal power demand changes are shown in Figure 7.

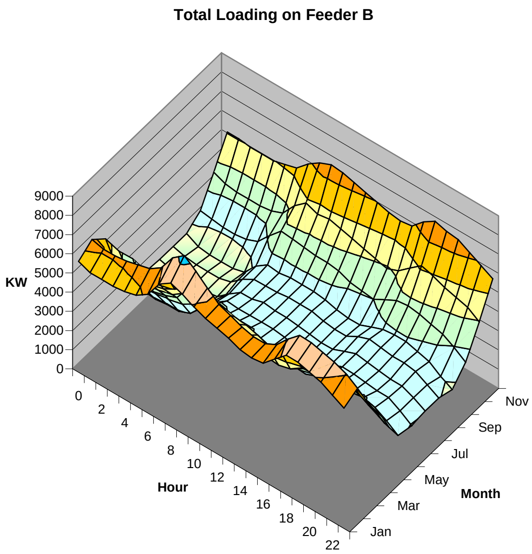

Figure 7: Base Loading Profile (Feeder B)

5.2 Circuit Modelling

Hydro Quebec uses CYMDIST for distribution system analysis. Circuit electrical model and customer load points were converted to EPRI's open-source Distribution System Simulator (OpenDSS) analysis platform. The validated electrical models then serve as the base case scenario against which the impacts of various PEV loading scenarios can be evaluated. Once the base case is developed, it is important to understand characteristics of the network.

5.2.1 Feeder A

Figure 8 and 9 shows the transformer sizes, number of customers (the box plot shows the variations of number of customers connected to this size transformer) connected to each of the transformer sizes, and base case peak hour loading levels. There are a total 68 service transformers, 17 of which are three-phase serving the high rise condos. For this feeder, 167 and 333KVA rated transformer are most common. Also, from Figure 9, it appears that the transformers are not loaded to their rated capacity. All the 333KVA transformers are operating at a loading of 80% of rated KVA and less. About 77% of the 167KVA transformers are operating at 70% of rated KVA and less. The three phase transformers (500, 750, 1000, 2000, 2500KVA) serving high rise condos are also all operating at 60% of rated KVA or less.

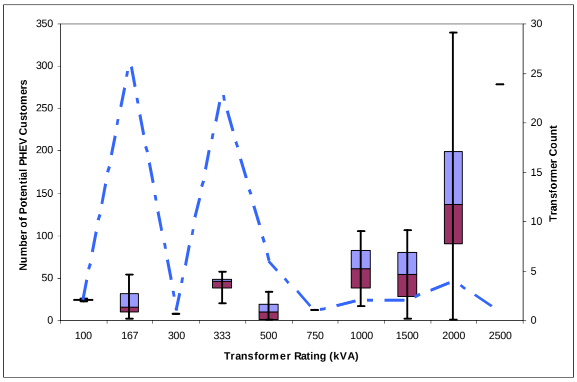

Figure 8: Transformer/Customer Network Characteristics for Feeder A

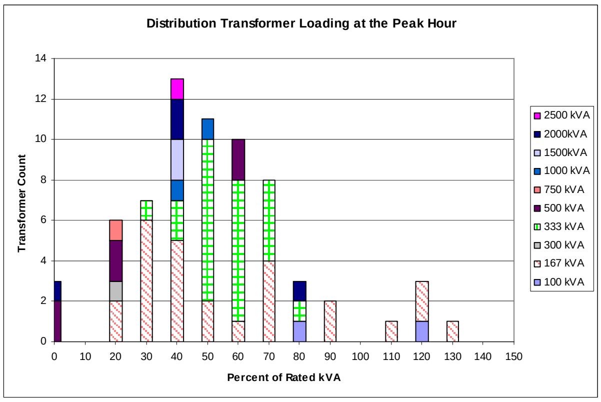

Figure 9: Transformer Loadings on Feeder A

5.2.2 Feeder B

Figure 10 and 11 shows the transformer sizes, number of customers connected to each of the transformer sizes, and base case loading levels. There are a total 101 service transformers, three of which are three-phase serving commercial customers. For this feeder, 100KVA rated transformer are most common. About 62% of the 100KVA transformers are operating at 80%of rated KVA and less.

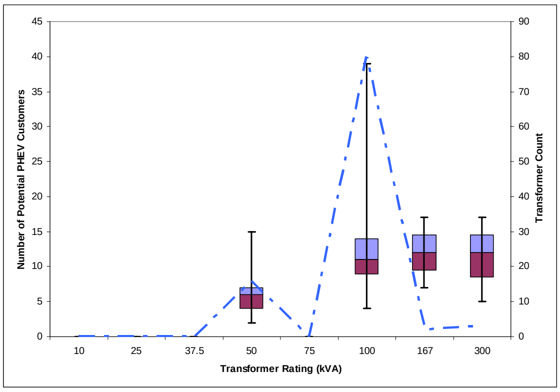

Figure 10: Transformer/Customer Network Characteristics for Feeder B

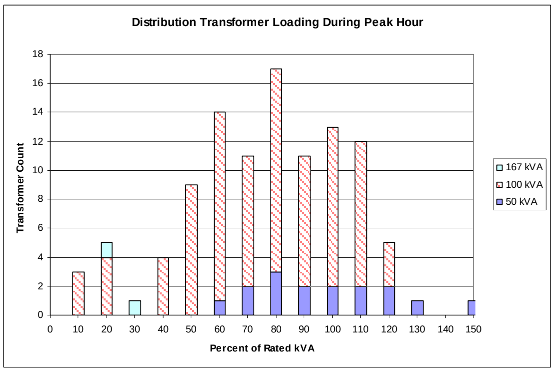

Figure 11: Transformer Loadings on Feeder B

6 Selected Impact Results

The evaluation approach utilizes both deterministic and stochastic assessments to determine the system impacts to PEV loading. The deterministic analyses are designed to identify system asset capacity limitations and identify parameters that drive potential adverse network impacts to varying PEV characteristics, with regard to the likelihood of those scenarios occurring. The evaluation of more probable impacts of PEVs is obtained through the stochastic portion of the analysis which provides for incorporation of the temporal and spatial variations associated with actual PEV loads. Only the deterministic analysis of thermal capacity and loss of life impacts are presented in this paper

6.1 Deterministic Impact Analysis

The goal of the deterministic analysis is twofold; to identify particular asset sensitivities to PEV loads and to depict the networks overall behavior to incremental PEV penetration.

6.1.1 Component Level Analysis

The first stage of the analysis capacity limitations of all circuit components in terms of the number of PEVs that can be served relative to the number of customers served. Aggregation of the components across asset classes (secondary, distribution transformer, single-phase lateral, etc.) permits the identification of which assets are potentially susceptible to overloads from increasing PEV loading and PEV charge levels.

Using the developed base case electrical models, each components' thermal capacity is calculated for both peak and off-peak hours. This provides an additional metric from which the asset sensitivity to various charge times can be gauged. These effective thermal capacities are expressed in terms of the number of PEVs of a given type that would cause the component to become overloaded. This number is normalized by the total number of customers served by each component. The resulting ratio expresses capacity in terms of number of PEVs per customer and indicates the size of the cluster required to overload each element. This metric is used to quantify the strength of the given asset class in response to PEV loading. It is important to note that these deterministic results do not indicate the actual likelihood of an overload occurring on an asset class. The results do, however, indicate which assets may be more susceptible to overloading as PEVs begin to proliferate across the system.

6.1.1.1 Feeder A

For this feeder, the deterministic asset analysis shows that service transformers and three phase primary lines (this circuit is 95% underground) are the most sensitive asset class to PEV clusters. Further, the distribution transformer results, shown in Figure 12 and 13, indicate that for this feeder the service transformer overload impact is more sensitive to the voltage charge level than to the time of charging. For example, 53% of service transformers are overloaded when serving 1.0 PHEV/Customer given a 240V coincident peak charge profile. If the same 240V charge is assumed to occur coincident at off-peak, almost 45% of the transformers remain overloaded. In comparison the same cluster size would only overload 7.8% of the transformers assuming a 120V coincident peak.

For the 17 three-phase transformers in the circuit, 1 (it serves 340 customers and was already overloaded to 70% of normal rating in the base case) out of 17 service transformers are overloaded when serving 1.0 PHEV/Customer given a 120V coincident peak charge profile. In comparison the same cluster size would overload 8 (47%) of the transformers assuming a 240V coincident peak. Similar observations were made for primarily lines as shown in Figure 14.

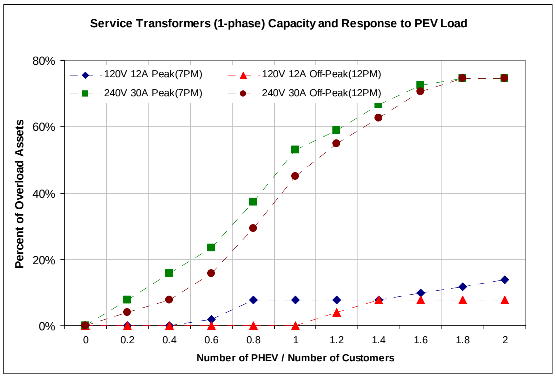

Figure 12: Single-Phase Service Transformers (Feeder A) – Asset Response

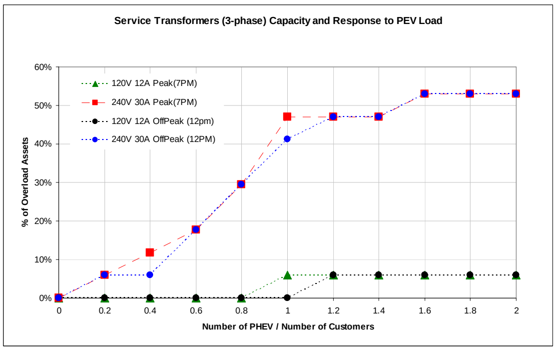

Figure 13: Three-Phase service transformers (Feeder A) serving the high rise condos – Asset Response

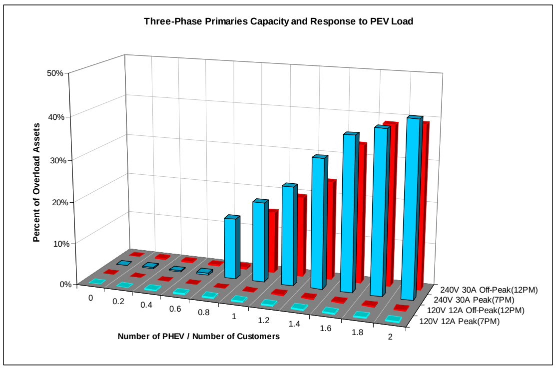

Figure 14: Primary Lines (Feeder A) – Asset Response

6.1.1.2 Feeder B

The asset response results shown in Figure 15 shows similar results to those expressed for Figure 12. This correlation between the two feeders indicates that the utilities planning practice associated with transformer loading and customers served may be influenced by PEV loads. Still, the results do not indicate the actual likelihood of overload occurring as no information concerning cluster likelihood is provided by these results.

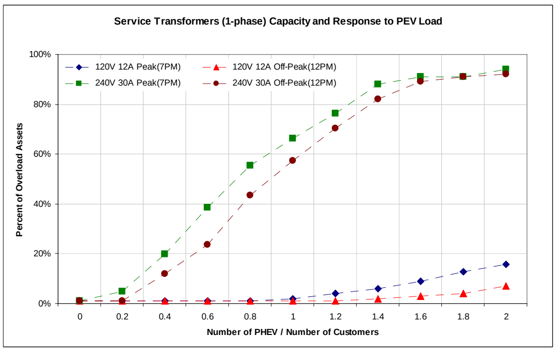

Figure 15: Single-Phase Service Transformers (Feeder B) – Asset Response

6.1.2 Transformer Loss of Life Analysis

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 [7].

6.1.2.1 Feeder A

For this feeder, 167KVA rated transformer are the most common. The influence of transformer lifespan (% insulation aging per year) hot spot temperatures on PEV loading are shown in Figure 16 and Figure 17, respectively. The reported percentages are based on the assumed normal insulation lifespan of 20.55 years when operating at rated load. For this circuit, the observed max and average peak hour demand for that transformer size of all the 167KVA transformers is 127% and 59% respectively. The base case load shape utilized for the analysis has a load factor of 44%. 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. As a whole, it appears that there is very minimal reduction to the lifespan of the transformer due to PEV loading with the 120V charging.

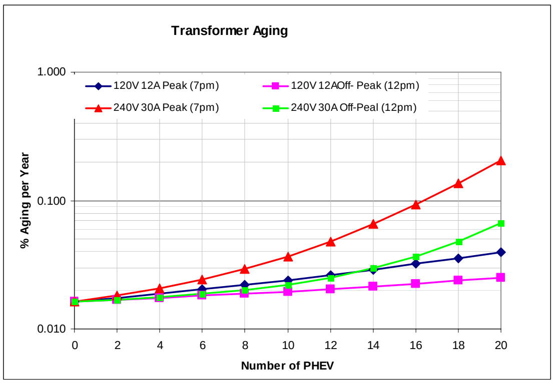

Figure 16: 167KVA Transformer Yearly Aging for Various Deterministic PEV Charging Scenarios

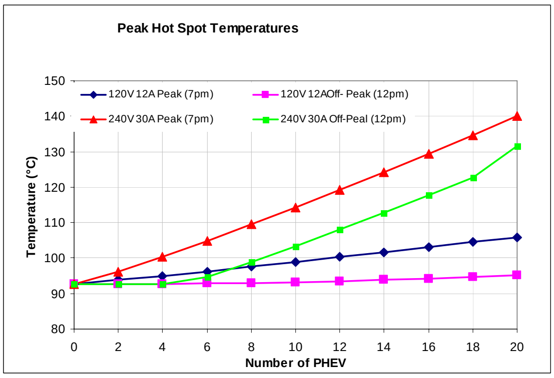

Figure 17: Hot Spot Temperature for Various Deterministic PEV Charging Scenarios

6.1.2.2 Feeder B

100kVA rated transformer are the most common in this feeder. The influence of transformer lifespan (% insulation aging per year) and hot spot temperatures on PEV loading are shown in Figure 18 and Figure 19, respectively. For this circuit, the average and maximum loading of all the 100KVA transformers is 44% and 71% respectively. The base case load shape utilized for the analysis has a load factor of 46%.

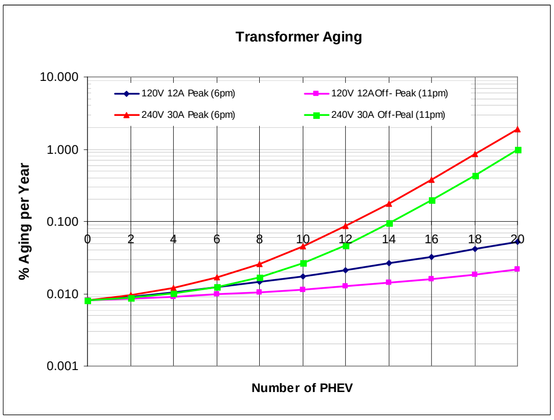

Figure 18: 100KVA Transformer Yearly Aging for Various Deterministic PEV Charging Scenarios

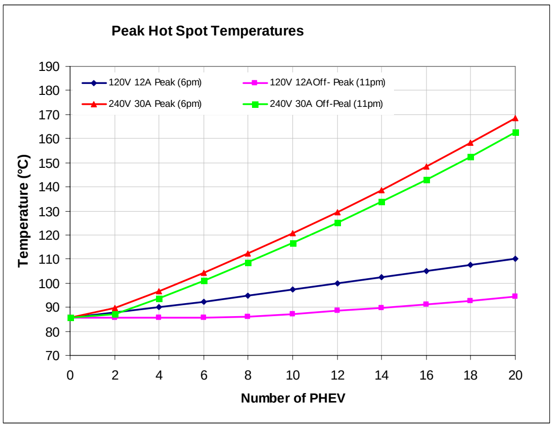

Figure 19: Hot Spot Temperature for Various Deterministic PEV Charging Scenarios

6.1.3 System Level Deterministic Analysis

The intent of the system deterministic analysis is to determine the system loading and voltage response to forced system-wide PEV penetration scenarios. While device overloads can be approached individually, other issues, such as voltage levels and imbalance, require the evaluation of the network as a whole. This analysis also provides insights concerning PEV penetration and charging boundary cases that may not be evaluated in the stochastic scenarios. The analysis is based on hourly-resolution simulations of the full electrical network across the 24-hour peak day for increasing PEV penetrations ranging from 0 to 20%. For the analysis, PEVs are randomly sited across potential customer locations to achieve each increasing penetration level with the assigned locations held constant over the increasing penetration scenarios.

6.1.3.1 Feeder A

Hydro Quebec plans for overloads of their individual assets 7 years in advance. As identified before, there is a lot of excess capacity planned into this circuit. As such, there were only 5 elements (4 transformers and one secondary service) that were overloaded in the base case (no PEVs) during the 24-hour window on the peak day that occurred on 2/28/2007. Figure 20 and Figure 21 shows the results of a system-level deterministic analysis of circuit element overloads (loading exceeding normal & emergency ratings of each individual circuit element) for various PEV charging scenarios and penetration levels. The results show that the number of overloaded elements increase with PEV penetration as expected, but that the number of additional overloads are relatively low up to 20% PEV penetration. Further, the results show that the overloads are more sensitive to PEV charge profile than charging start time.

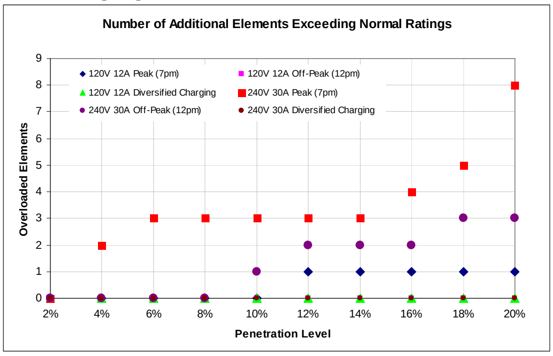

Figure 20: Number of Elements for which Normal Rating Exceeded for Deterministic PEV Penetration and Charging Scenarios

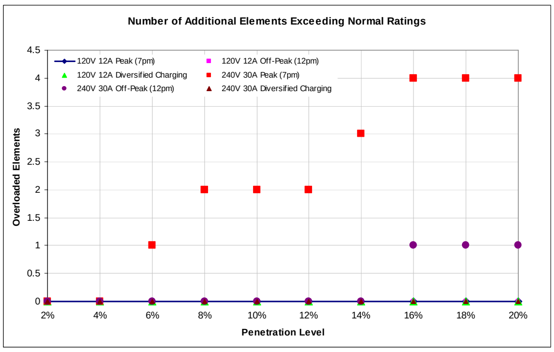

Figure 21: Number of Elements for which Emergency Rating Exceeded for Deterministic PEV Penetration and Charging Scenarios

Similar, results were obtained for the analysis of the impact on overload magnitude as shown in Figure 22. This plot shows that charge profile and coincidence of charging are the dominant factors with 240V/30A charging resulting in 150% overloads for 10% and 20% penetration levels for coincident on-peak and off-peak charge times, respectively. Whereas, the 120V/12A coincident charging and 240V/30A diversified charging never exceed 125% overvoltage regardless of charge time.

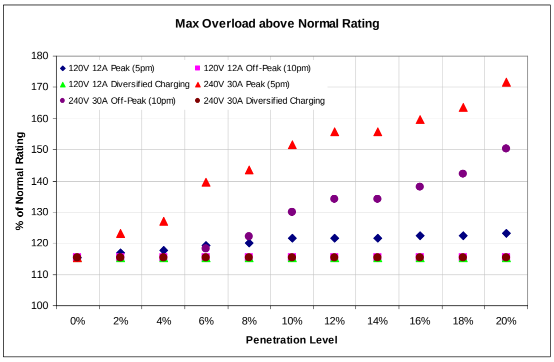

Figure 22: Overload Magnitude for Various Deterministic PEV Charging Scenarios

Like the component-level deterministic evaluations, the system-level deterministic results do not necessarily represent probable PEV penetration and loading scenarios. However, it is clear from these plots that this circuit is adequately designed to handle significant PEV penetration.

6.1.3.2 Feeder B

For the Feeder B system deterministic analysis, there were only 10 elements that were overloaded in the base case during the 24-hour window on the peak day that occurred on 2/5/2007. Figure 23 and Figure 24 shows the system-level deterministic analysis overloads (loading exceeding normal & emergency ratings of each individual circuit element) for various PEV charging scenarios and penetration levels. The numbers of overloaded elements are higher relative to the Feeder A results, but the charge profile is similarly the dominant factor in the number of overloads.

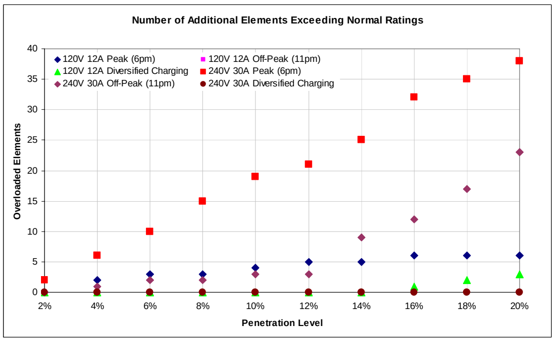

Figure 23: Number of Elements for which Normal Rating Exceeded for Deterministic PEV Penetration and Charging Scenarios

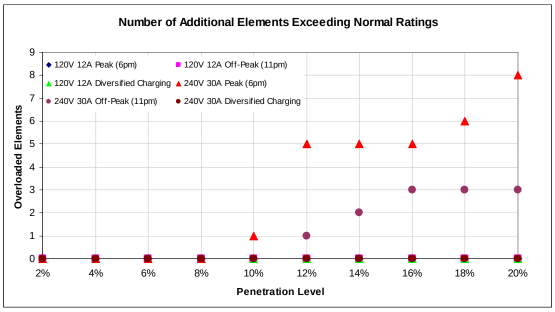

Figure 24: Number of Elements for which Emergency Rating Exceeded for Deterministic PEV Penetration and Charging Scenarios

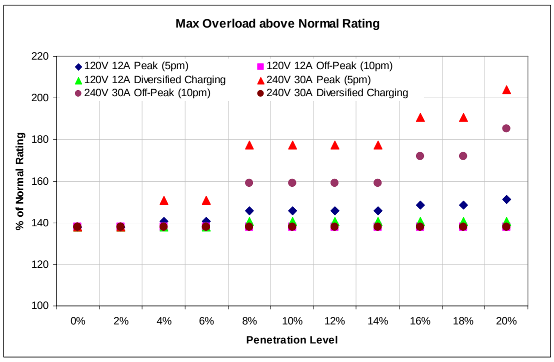

Figure 25: Overload Magnitude for Various Deterministic PEV Charging Scenarios

6.1.4 Stochastic Impact Analysis

As noted, none of the deterministic analyses provide an evaluation of probability of specific impacts. The full EPRI assessment methodology includes stochastic (sequential Monte Carlo) simulations of the distribution system and PEVs to evaluate likely impacts based on projections of certain aspects of PEV proliferation/use. The stochastic approach is intended to capture spatial and temporal diversity of PEV integration. 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 PEVs for numerous stochastic cases is simulated at hourly resolution over a full calendar year (8760 hours). The results of this portion of the analysis for the Hydro Quebec circuits is not provided here, but will be included in a future paper.

7 Summary and Future Work

EPRI has initiated a multi-year collaborative project with several utilities in the United States, Canada, and Europe to understand PEV system impacts on distribution system operations. This paper provides a brief description of the methodology used to evaluate PEV loading impacts on two representative Hydro-Québec distribution feeders. A subset of the assessment results, namely the deterministic capacity and loss of life analyses, is provided in conjunction with characteristics of the two distribution system feeders. Subsequent papers will summarize key stochastic results obtained from the study

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