Method to Assess the Power-Quality Impact of Plug-in Electric Vehicles

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***Abstract*—This paper presents a probabilistic harmonic simulation method to study the power-quality impact of electric vehicles (EVs). The proposed method takes into account the random operating characteristics of the vehicles, such as random charging time, charging duration, and vehicle locations. A multiphase model of the primary and secondary systems is used to represent the study system. Extensive case studies have been conducted using the method and the measured EV data. The results reveal that the current versions of plug-in hybrid EVs have no significant harmonic impact on power systems. However, the Level 1 charger can increase the neutral-to-earth voltage at homes which could lead to increased stray voltage incidents.**

***Index Terms*—Electric vehicles, harmonics, power quality (PQ).**

I. Introduction

TRANSPORTATION makes up a substantial portion of global air pollution and oil consumption. In recent years, the desire to reduce air pollution and reliance on oil has resulted in increased reception of electric vehicles (EV) [1]–[3]. Among them, pure battery electric vehicles (BEV) and plug-in hybrid vehicles (PHEV) that can be charged from an external source are becoming a new type of loads in power systems.

As BEVs and PHEVs draw power through power electronic circuits from the grid when being charged, utility companies are concerned with the potential power-quality (PQ) impact of the mass adoption of these vehicles [4], [5]. For example, they may inject harmonics into utility systems. The high level of unbalanced Level 1 charging load may cause problems such as neutral current rise. Therefore, there is an urgent need for techniques that can model and assess the collective impact of the EVs.

As will be shown later, the above problem cannot be analyzed using some form of deterministic approaches based on "average" or "typical" deterministic model and data. A Monte Carlo simulation-based method is proposed. This is because the car chargers can be plugged into utility system at any time. A utility feeder sees a set of randomly connected plug-in EVs with diverse harmonic characteristics and charging duration. The locations of the EVs being charged are also random. A main challenge, therefore, is to model the random charging behavior of the EVs. This behavior is in turn affected by the driving habits of the vehicle owners. In addition, the PQ impact of the vehicles cannot be assessed in isolation, as other home appliances can also produce PQ disturbances, whose operating pattern has some correlations with that of the EVs.

Based on the Monte Carlo simulation method developed in [6], this paper presents techniques to model the random operation of PHEV chargers and to integrate the models into the simulation method of [6] for system wide PQ impact assessment. With this approach, PHEVs are treated as one of the (large) "home appliances". As a result, the combined and relative impact of various residential harmonic producers can be determined.

It is worthwhile to point out that the sales of PHEV grow much faster than the BEV due to longer driving range, lower battery costs and faster recharging times [3], [7]. The models and results presented in this paper are related to the PHEV. Many of the concepts and models proposed can be modified for BEVs once their mass-market versions mature and are accepted by consumers. In addition, the study assumes that PHEV owners charge their cars at homes. The proposed method can be extended to charging-station-based refueling systems.

The remainder of the paper is organized as follows: Section II explains the overall strategy of Monte Carlo simulation. Section III presents a set of models to characterize the random behaviors of PHEVs. Section IV shows a model of PHEV consumer adoption trends, which is needed to predict the PQ impact of PHEVs in the future. The electric model of PHEV, and utility system are provided in Section V. Sample case study results are presented in Section VI.

II. General Simulation Scheme

A. Overview of Published Works

Over the years, various works have investigated the PQ impact of plug-in EVs, which greatly contributed to our understanding on the subject. Reference [8], one of the pioneer works on the subject, identified the harmonic currents produced by electric vehicle chargers. However, it considers all chargers clustered on a single bus. The methods and results cannot be applied to the more realistic, disperse charging scenario. Harmonic impacts produced by five different types of chargers are assessed on [9], without considering the vehicle plug-in behavior and penetration characteristics. The authors further

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expanded their work on [10] to include EV random plug-in time and charging duration. But the proposed method only addresses EV connection impact on HV/MV substation, limiting penetration level to, at most, one EV per MV/LV transformer.

References [11], [12] derive EV random impact on system voltage and current harmonics using an analytical approach. This approach presents some limitations, such as: (a) to provide reliable results (converged average and standard deviation), at least 6 vehicles must be connected to network; (b) the impact of chargers with different characteristics (e.g., power demand and harmonic spectrum) simultaneously connected to the network is not considered. On [13], a more detailed EV model is proposed, but random characteristics of plug-in instant, charging time and EV location are not taken into account. Vehicle penetration level, for instance, is regarded as equally distributed within all LV consumers. In addition, many of the above studies have not modeled the secondary, "two-phase" networks. So the impact of the EVs on the secondary network cannot be evaluated properly.

B. Proposed Monte-Carlo Simulation Methodology

Build on the above works and the Monte-Carlo simulation concept of [6], this paper analyzes the various factors that must be considered for the PQ impact assessment of PHEVs and proposes methods to include such factors.

In a realistic scenario, a PHEV can connect to a power system for charging up at any time. As a result, a utility feeder will supply a set of randomly connected EVs at any given time. Furthermore, these vehicles will go off the grid at different time as each of them has different charging duration. The locations of the EV being charged in a feeder are also random. In order to determine the power quality impact of these vehicles, a methodology that can model these random factors must be developed.

The methodology proposed by this paper is the Monte Carlo simulation technique. The basic idea is to create numerous plausible scenarios of PHEV activities in a feeder for a given instant of time, say at 12:04 pm. One of the scenarios, for example, represents the case where PHEV-A is connected to location X and PHEV-B to location Y etc. At the instant of 12:04 pm, PHEV-A battery is charged to m% and PHEV-B is at n%. Once such a scenario is created, all load activities become known and are deterministic. Harmonic power flow studies can then be conducted to determine the harmonic levels associated with this particular scenario. A Monte Carlo simulation involves the creation of thousands of plausible scenarios for 12:04 pm. Therefore, thousands of harmonic studies are performed. The average of the harmonic results among all scenarios should represent the most likely results expected at 12:04 pm.

The remaining problem becomes how to create the multiple plausible scenarios for the instant of 12:04 pm. This is done by considering the probability of occurrence of the various factors. For example, if 10% houses are found to have a PHEV based on consumer trend, 10% of the randomly selected houses in the feeder model will be flagged as the candidate locations for PHEV connection. For each house, the time of PHEV connection and its charging duration depend on the driving habit. There is also a probability curve for the habit. For example, if the probability curve shows that there is a 10% chance that the car will be charged at 12:04 pm, 10% the scenarios created will have a car being charged at that particular house location. By considering various probabilistic factors, multiple scenarios can be created. Naturally, these scenarios will satisfy or have included the probabilistic characteristics of the various factors.

The above multiscenario simulations can be conducted for every minute (or other resolution) over a 24 hour period. A total of 1440 snapshots are produced for one day. In order to provide more succinct indices to characterize the PHEV impact, the results over a 24 hour period can be further condensed by using some statistical indices. In this paper, the 95% probability value commonly used by industry to process measured harmonic data over an extended period is adopted. This value is the threshold that will not be exceeded for the 95% of the time over a 24 hour period. With this approach, the impact of PHEV can be understood from one value for each PQ index of concern.

C. Key Factors for Inclusion in Simulation Studies

To achieve the above simulation goal, three groups of factors must be modeled. The 1st group is the charging behavior of PHEV. This behavior is affected by the following factors:

- charging strategy—deterministic and random;
- charging start time—random;
- PHEV charging duration—random.

The 2nd group is the locations and density of the PHEV in a feeder. It is affected by the following factors:

- PHEV penetration level—deterministic;
- PHEV location in a residential system—random;
- type of chargers—semi-deterministic.

The third group is the electric characteristics of the PHEV and power systems. Important factors are:

- the harmonic model for PHEV chargers;
- the multiphase model of the supply network;
- the impact of other home appliances.

The following three sections will present specific solutions to deal with the above factors.

III. Charging Behavior of PHEVs

This section will present methods to model the three factors affecting the charging behavior of PHEVs.

A. PHEV Charging Start Time

The charging start time determines when vehicles will start being charged during the day. Since all PHEVs will not begin charging simultaneously, it is more suitable to treat this variable as a random variable based upon daily charge strategy. Charging strategy is the way PHEV owners plan (or forced to plan) to charge their batteries every day. There are three types of charging strategies that need to be modeled.

1) Uncontrolled Charging: Uncontrolled charging means that PHEVs could start charging any time during the day. In this strategy, most people will immediately charge their vehicles to prepare them for the next trip just when they arrive home from work. Obviously, uncontrolled charging tendency is strongly associated with people's travelling behavior. In this case, most PHEVs are plugged in and start charging around 6:00 p.m. when people usually come back home. However, a uniformly distributed probability density function (pdf) with a narrow

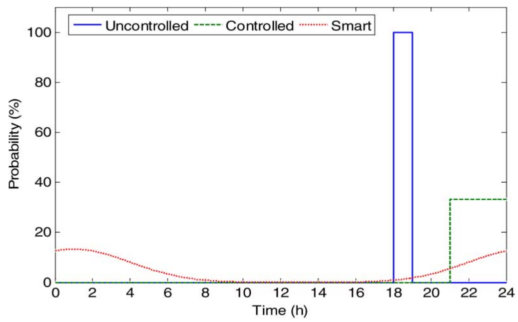


Fig. 1. Charging start time pattern for each charging strategy.

range around 6:00 p.m. is more close to reality, as shown in Fig. 1. It may be mathematically described by (1) [14], where x represents the random charging start time in hour; while a and b are the lower and upper limits of hours of charging, respectively

$$f(x) = \frac{1}{b-a}, \quad \mathrm{a} \leq \mathrm{x} \leq \mathrm{b}, \quad \mathrm{a} = 18, \quad \mathrm{b} = 19. \quad (1)$$

2) Controlled Charging: Once PHEV adoption rate reaches a certain level, because of the coincidence with early evening system peak, uncontrolled charging plan could significantly increase this peak. Therefore, it is likely that utilities would use either Time-Of-Use (TOU) pricing or direct control methods such as in-home delay devices to shift PHEV charging load to off-peak time. TOU pricing is used in most regions, which leads people to postpone charging after 9:00 p.m. in order to minimize their electricity bills. As a result, the model described in (2) is used to simulate controlled charging

$$f(x) = \frac{1}{b-a}, \quad \mathrm{a} \leq \mathrm{x} \leq \mathrm{b}, \quad \mathrm{a} = 21, \quad \mathrm{b} = 24. \quad (2)$$

3) Smart Charging: The last strategy is smart charging. This strategy not only maintains the evening peak constant but also can be advantageous to utilities. For example, [15] uses Advanced Metering Infrastructure (AMI) together with PHEV control unit and remote switches to imply stagger charging which limits the charging based upon pre-determined power levels communicated through the grid. This method will help smooth the PHEV charging load seen by service transformer, especially for high PHEV penetration. As a result, no additional peaks due to PHEV will be created on transformer load, either in the early evening or midnight. Considering the complexity of employing various smart charging optimization algorithms, a normal distribution of start time to represent all smart charging strategies is adopted in this paper, as illustrated in Fig. 1 [16]. In this case, the charging start time is described by (3), where x is the random plug-in instant; μ and σ are the average and standard deviation of x, respectively

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \mathrm{e}^{\left(-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right)}, \quad \mu = 1, \quad \sigma = 3. \quad (3)$$

B. *PHEV Charging Duration*

When a driver arrives at home, the PHEV battery has remaining energy, which is quantified here by the factor called state of charge (SOC). The SOC is the equivalent of a fuel gauge for the battery pack in an electric vehicle and the units of SOC are percentage points ($0\% = \text{empty}$; $100\% = \text{full}$). SOC is random and its associated pdf is based upon daily charge and travel pattern, as explained below.

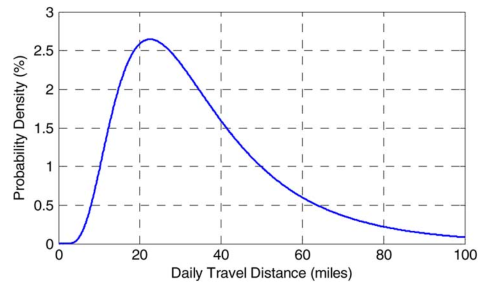


Fig. 2. Probability density function of PHEV daily distance driven.

To determine the SOC of each PHEV, it is essential to know how deep it was discharged during the day, which is directly related to the distance it traveled. From general vehicles driving pattern, a probability distribution of daily distance driven has been derived in [8]. The distribution is found to be log-normal type, but with zero probability at all negative distances. The mean of the distribution is 34.2 miles and the standard deviation is 21.1 miles, at the year of 1983. The probability function is as follows:

$$d(m) = \frac{1}{m\sigma\sqrt{2\pi}} e^{\frac{-(\ln(m)-\mu)^2}{2\sigma^2}}, \quad m > 0 \quad (4)$$

where

$$\mu = \ln(E[M]) - \frac{1}{2}\ln\left(1 + \frac{Var[M]}{E[M]^2}\right) \quad (5)$$

$$\sigma^2 = \ln\left(1 + \frac{Var[M]}{E[M]^2}\right) \quad (6)$$

where the random variable m is the daily distance travelled in miles, and $E[M]$ and $Var[M]$ stand for the mean value and variance of m. According to updated information provided by [17], daily average vehicle miles travelled is 33 miles. To update our estimation, the standard deviation is scaled to 20.4 miles with constant ratio. Fig. 2 shows the probability density function of daily distance driven.

Using the traveled distance (in meters), the battery state of charge (SOC) at the beginning of charging can be determined by

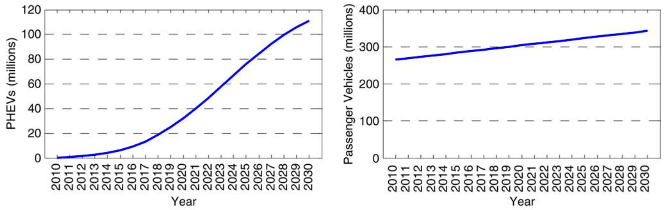
$$\mathrm{SOC} = \begin{cases} \frac{R-m}{R} \times 100\%, & 0 \leq m \leq R \\ 0, & m > R \end{cases} \quad (7)$$

where R is the all-electric range of the PHEV in miles.

The next step is to find the charging duration (D) from the SOC value determined before. This can be calculated from the PHEV battery nameplate parameters, which includes battery capacity, charger level and initial SOC, as follows:

$$D = \frac{C \times (1 - \mathrm{SOC}) \times \mathrm{DOD}}{P \times \eta} \quad (8)$$

where C is battery capacity (kwh); P is the power rating of charger (kW), which is determined by charger level; and η is the efficiency of charger (%). In many types of batteries, the



(a) (b)

Fig. 3. PHEV market trend data for 2010 to 2030. (a) Total estimated number of PHEVs. (b) Total estimated number of passenger vehicles.

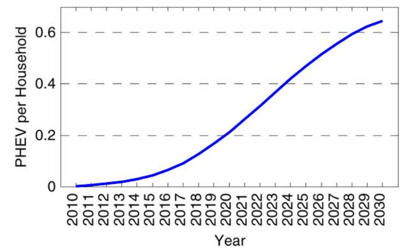


Fig. 4. Total estimated number of PHEVs per household for 2010 to 2030.

full energy stored in the battery cannot be withdrawn (i.e., the battery cannot be fully discharged) without causing serious, and often irreparable damage to the battery. The depth of discharge (DOD) of a battery determines the fraction of power that can be withdrawn from the battery. For example, if the DOD of a battery is given by the manufacturer as 60%, then only 60% of the battery capacity can be used by the load.

IV. Consumer Adoption of PHEVs

In order to model charger loads in a network and anticipate their impact in the future, the penetration level of chargers should be estimated. In other words, the number of PHEVs per household in the network should be predicted. Several organizations have provided estimations for PHEV penetration level for the near future. As a case in point, a report by Oak Ridge National Laboratory in 2006 [18] estimates that PHEV-20 vehicles (which have 20-mile all electric range) will have a base case market potential of over 25% of sales for the entire car and light-truck market in 2018. EPRI reports [19], [20] have similar analysis results for 2010 to 2030 PHEV market share.

The number of cars sold every year in the US is about 20 million. So, considering the PHEV market share level for year 2010 to 2030 as well as the assumption of average 12 years vehicle lifespan, the total number of PHEV for 2010 to 2030 is shown in Fig. 3(a) [18], [21]. According to the linear regression analysis over the data from 1990 to 2008 available in [21], the total projected number of passenger vehicles for 2010 to 2030 is calculated and plotted in Fig. 3(b).

Assuming that the average number of vehicles per household is 2, the penetration level across households can be calculated as follows:

$$\mathrm{PHEVH}(i) = \frac{N_{\mathrm{PHEV}}(i)}{N_{\mathrm{PV}}(i)} \times \mathrm{PVH} \tag{9}$$

where $\mathrm{PHEVH}(i)$ is the number of PHEVs per household at year i, N_{PHEV} is the total number of PHEVs shown in Fig. 3(a), N_{PV} is the total number of passenger vehicles shown in Fig. 3(b) and PVH is the average number of vehicles per household, which is assumed equal to 2. From (9), the final expected number of PHEVs per household can be estimated and it is shown in Fig. 4. From this figure, the average number of PHEVs per household in 2020 is 0.2, which shows good consistency with the estimation in [15]. Given the number of houses connected to each transformer, the number of PHEVs fed by each transformer can be simply calculated using Fig. 4.

Fig. 4 is essential to determine PHEVs locations for a 24-h Monte Carlo simulation. The following procedure is used: for each residential customer (x), a randomly generated number $(\mathrm{r_x})$, uniformly distributed between 0 and 1 is compared to the corresponding PHEVs penetration rate. If $\mathrm{r_x}$ is less than the penetration rate, then a PHEV is assigned to that house. Once a house is selected as the PHEV owner, it will stay as the PHEV location throughout the simulation.

TABLE I
PHEV Charger Types Defined in SAE J1772 [22]

Charger Type	Input Voltage	Maximum Power (kW)
Level 1	120 VAC	1.440
Level 2	208-240 VAC	11.50
Level 3	208-240 VAC	96.00
Level 3 (DC)	208-600 VDC	240.0

According to the Society of Automotive Engineers (SAE) all PHEVs produced by automakers in North America must follow SAE J1772 standard [22]. Based on voltage and power levels, three levels of charging are identified in SAE J1772, which are shown in Table I.

Level 1 and 2 chargers are for consumer PHEVs. Their distribution among the PHEV owners is treated as a sensitivity study factor. Namely, PQ impact of different types of chargers and their combinations are determined. Level 3 chargers are mainly intended for commercial and public transportations and, therefore, are not considered in this paper. However, the proposed model can be extended to include these chargers.

V. Electrical Models

There are three factors to consider for the electrical models, which are addressed in this section.

A. Harmonic Model for PHEV Charger

The common method to model the harmonic characteristics of a power electronic device such as the PHEV charger is the harmonic current source model, which is adopted here. This model is deterministic, that is, once a PHEV charger is turned on, its harmonic current output follows a typical harmonic current spectrum (with reference to its supply voltage) regardless its location in the system. The harmonic model is as follows [23], where *spectrum* refers to charger typical harmonic current spectrum, and $I_1\angle\theta_1$ is the fundamental current injected by the charger on the network. This current is determined from the 60 Hz power flow results.

$$\begin{aligned} I_h &= I_1 \times \frac{I_{h-\mathrm{spectrum}}}{I_{1-\mathrm{spectrum}}} \\ \theta_h &= \theta_{h-\mathrm{spectrum}} + h \times (\theta_1 - \theta_{1-\mathrm{spectrum}}). \end{aligned} \tag{10}$$

TABLE II
HARMONIC SPECTRA OF MEASURED PHEV CHARGERS

Charger	Level 1		Level 2	
Voltage	120V		240V	
Harmonic Order	Mag. (%)	Angle (deg.)	Mag. (%)	Angle (deg.)
H1	100.0	15.1	100.0	15.5
H3	9.125	144.9	8.864	111.8
H5	3.230	30.9	2.452	-73.4
H7	0.947	-126.2	0.891	38.6
H9	1.520	76.5	0.911	-114.5
H11	1.329	-85.1	0.870	-69.5

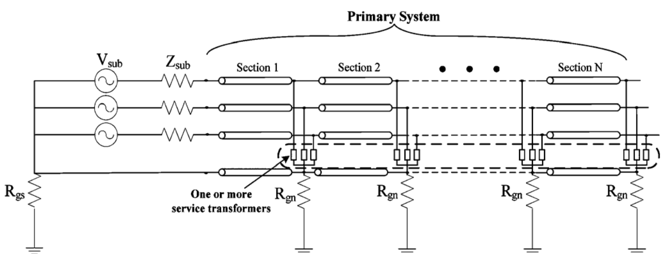


Fig. 5. Schematic model to study primary distribution systems.

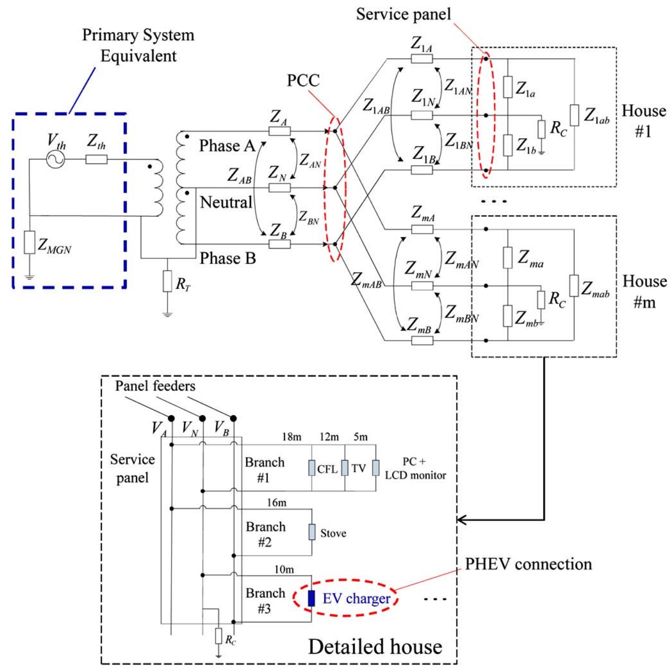


Fig. 6. Schematic model to study secondary distribution systems.

The current phase-angle correction shown above is important since charger harmonic currents may cancel out currents from other nonlinear appliances. Furthermore, it is important to note that the current phase angle is not treated as a random variable in the above equation. This is because the PHEV chargers always draw harmonic currents at approximately the same phase angle with respect to the supply voltage. This angle is therefore deterministic.

This research has obtained harmonic current spectrum data from several PHEVs. A sample results are shown in Table II. At the fundamental frequency, PHEVs are treated as a constant power load.

B. Network Model

In North America, the most common primary power distribution system is the multigrounded neutral (MGN) system. This system contains three phase conductors and one neutral conductor grounded at regular intervals (Fig. 5). The primary system delivers the electrical power from the source at the substation $(V_{\rm sub}, Z_{\rm sub})$ to the service transformers (Fig. 5). A service transformer delivers power to several houses through the secondary system (Fig. 6).

It is clear that a single-phase or a three-phase equivalent network model is not adequate for studying harmonics in such a system. An equivalent model will make it impossible to investigate harmonic impacts such as neutral voltage rise. Consequently, a multiphase model of the network which includes every conductor of the system shall be used. Fortunately, [24] has developed a method to model and calculate multiphase systems. It is adopted here.

With the multiphase network model, harmonic cancellation effect caused by voltage phase differences at different points of a feeder because of the branch impedances are included. This is realized through (10) where the impedance will change 60 Hz current angle θ_1.

If the study target is the primary system, an equivalent circuit for the secondary system must be calculated and attached to the multiphase primary network, as shown on Fig. 5. The portion of the network inside the dashed rectangle represents one or more single-phase service transformers connected between each phase of the primary conductor and neutral conductor, and each service transformer could be represented by the secondary system configuration shown in Fig. 6. Table III presents the system parameters of the primary and secondary test systems.

When studying the PHEV impact on the secondary system shown in Fig. 6, the primary system is modeled as an equivalent circuit ($\rm V_{th}$, $\rm Z_{th}$ and $\rm Z_{MGN}$), whose parameters are established by performing frequency scans at the location of the service transformer. For the results presented in this paper, the equivalent voltage source $\rm V_{th}$ is assumed to contain 60 Hz voltage only. This is because the interest here is to understand the impact of PHEV on the secondary system. If harmonic voltages are included, it becomes the study of the impact of harmonic voltages on the secondary system in addition to the impact of the PHEVs. Depending on the assumed phase angle and magnitudes of the harmonic voltages, the results can be quite different and are difficult to generalize. As a result, 60 Hz voltage is assumed. However, the impact of harmonic voltages on the secondary system was investigated as a separate issue. It can be found from [25].

C. Modeling of Other Household Loads

The third factor that must be considered is the impact of other household loads such as personal computers and washers. Harmonics produced from such appliances may add or cancel the harmonics produced by PHEV. The household loads also operate randomly. They are modeled according to the method described in [6].

TABLE III
SYSTEM PARAMETERS

Base Case System Parameters		Values
Primary System	Supply system voltage (V_{sub})	14400 V (@ 60 Hz)
	Substation pos. sequence impedance	0.688 + j2.470 Ω
	Substation zero sequence impedance	0.065 + j2.814 Ω
	Substation grounding (R_{gs})	0.15 ohms
	MGN grounding resistance (R_{gn})	15 ohms
	Grounding span of MGN neutral	75 m
	Feeder length	15 km
	Feeder conductor type	4 - 336.4 ACSR
Service Transformer	Voltage (V_H/V_L) rating	14400/120 V
	KVA rating	37.5 kVA
	Impedance	2 %
	Resistance	1.293 %
	Grounding resistance (R_T)	12 ohms
Secondary System	Primary system Thévenin equivalent voltage (V_{th})	14400 V (@ 60 Hz)
	Primary system impedance (Z_{th})	0.48 + j2.58 Ω
	Grounding impedance (Z_{MGN})	0.885 + j0.580 Ω
	Customer grounding resistance (R_C)	1 ohm
	Neutral impedance (Z_N)	0.55 + j0.365 Ω/km
	Phase impedance (Z_A and Z_B)	0.21 + j0.094 Ω/km
	Num. of houses for each transformer	10
	Distance between PCC and house	40-70 m

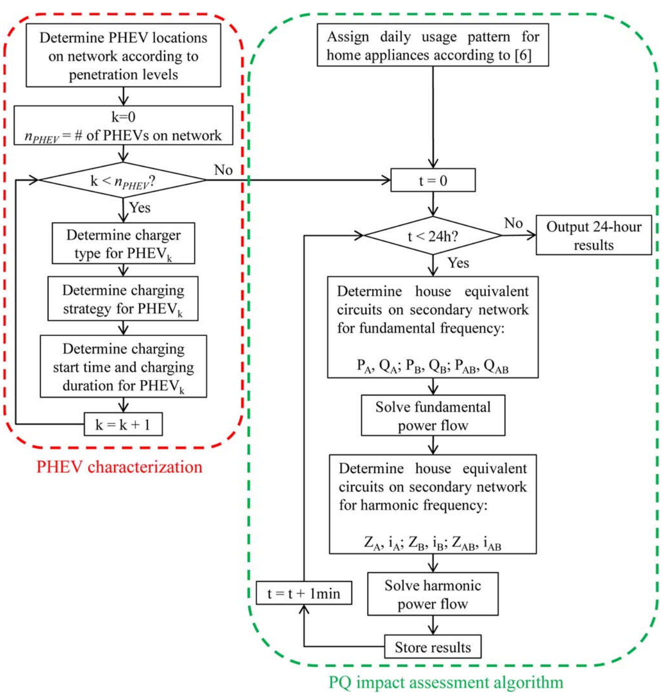


Fig. 7. Flowchart for the PHEV PQ impact analysis on secondary networks.

D. Summary

The detailed procedure to simulate PHEV activities in the secondary system is presented on Fig. 7. In order to simplify the flowchart, only 1 day simulation is presented. The overall Monte Carlo simulation method consists on repeating this algorithm multiple times until converged results are achieved.

Primary system assessment can be performed using the same flowchart with an additional step. Before performing power flow solution, once house circuit parameters have been determined, the equivalent circuit seen from primary network must be calculated for each MV/LV transformer [6].

VI. CASE STUDIES

A number of case studies have been conducted to quantify the impact of PHEV. Due to space limitation, this section illustrates two important findings. One is the harmonic impact of PHEV and the other is the neutral voltage impact. Both are related to the secondary network. The impact of PHEV on the primary network including increased harmonic voltages is small. They are not reported here.

A. Case Study 1: Harmonic Impact

For this study, the base case scenario is defined as mixed charger types under uncontrolled charging strategy with 30% PHEV penetration level. Mixed chargers include Level 1 and Level 2 chargers at a ratio of 1:1. This case represents the worst charging strategy and most common charger composition. The impact of PHEV is also compared with those of other nonlinear home appliances. This "30% PHEV" case is compared to three other scenarios:

1) "*Base Load*": This scenario considers only home appliances and the respective penetration rates refer to year 2011 market data. There are no PHEVs in the system;
2) "*CFL 2015*": All home appliances loads remain the same as the "*Base Load*" scenario, except that the penetration of CFL (Compact Fluorescent Lamp) appliances refers to year 2015 market data [6].
3) "*PC 2015*": All home appliances loads remain the same as the "*Base Load*" scenario, except that the penetration of personal computer appliances refers to year 2015 market data [6].

Once the simulation scenarios have been established, thousands of Monte Carlo runs were performed for each scenario, obtaining the 95% probability values over the harmonic voltage profile for the entrance point (service panel) of each home connected to the sample secondary system. Fig. 8 summarizes such results by presenting the average of the 95% probability values of all homes connected to the network. This figure indicates that even with 30% penetration level, the harmonic distortion caused by PHEV is not significant since both phase and neutral harmonic voltage levels are comparable to those of "*Base Load*" case study. Moreover, the "*CFL 2015*" and "*PC 2015*" cases show that CFL and PC loads should be of more concern to utilities in terms of harmonic distortion. The significant increase on fundamental and RMS neutral voltage is mainly caused by load imbalance between the two phases due to Level 1 chargers.

B. Further Analysis on the PHEV Harmonic Impact

The finding that the PHEV has little harmonic impact on power system is not surprising if we compare the harmonic current characteristics of PHEV with those of other home appliances. For this comparison, the equivalent CFL index proposed in [26] is used. This index quantifies the harmonic current injection level of each appliance expressed as the number of CFLs it is equivalent to.

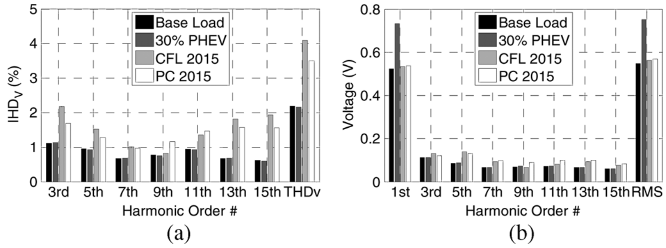


Fig. 8. Comparison between harmonic voltages produced by PHEVs, CFLs, and PCs: (a) 95% index for phase voltage and (b) 95% index for neutral voltage.

TABLE IV
COMPARING THE HARMONIC EFFECT OF PHEVS

Appliance type	Operating Power [W]	Power Ratio	Equivalent CFL
CFL	15	1	1.00
Dryer	4500	300	2.13
LCD monitor	40	3	2.35
Furnace	500	33	3.49
Fridge	1200	80	4.34
Desktop PC	100	7	6.53
Microwave oven	1200	80	24.30
PHEV Charger	1355	90	9.77

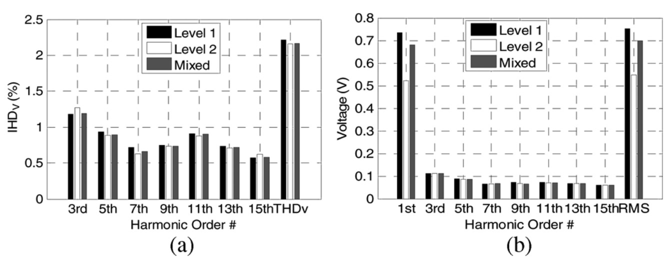


Fig. 9. PQ impact of different charger types: (a) 95% index for phase voltage and (b) 95% index for neutral voltage.

Table IV shows the values of the total equivalent CFL index for one PHEV charger and other key home appliances.

One can observe that, in terms of harmonic effects to the system, one PHEV is equivalent to approximately 10 CFLs or 1.5 desktop PCs. Since most homes will have CFLs and PCs while the PHEV penetration level is only 0.2 per home by year 2020, one can conclude that the PHEV's harmonic impact will be significantly less than that of the CFLs or PCs. It is worthwhile to point out the reason that a PHEV generates fewer harmonics: the PHEV manufacturers have voluntarily adopted the IEC 1000-3-2 [27] and SAE J2894/1 [4] in its harmonic limits.

C. Case Study 2: Neutral Voltage Rise

The charger types are changed in this study to identify their impact on the secondary system. All system parameters remain the same as base case described on Case Study 1 (30% PHEV penetration), except charger types. Fig. 9(a) shows the 95% index associated to the average phase harmonic voltages, for different chargers types. Fig. 9(b) shows the 95% index of the average neutral to ground voltage.

The results show that the harmonic impact of different chargers is comparable. However, Level 1 charger causes noticeable rise of the neutral voltage at the fundamental frequency. This is due to the fact that Level 1 charger draws current from just one phase. Level 2 chargers cause no neutral voltage rise, since they are phase-to-phase connected. This finding is important since it implies a potential concern to utility companies when PHEVs become mass adopted. Note that the results are based on models with adequate grounding conditions. If poor grounding condition is modeled, the neutral voltage could increase by 2 to 4 V. It implies that, statistically, more homes may experience high neutral-to-earth voltages and associated stray voltage problems. In addition, some utilities do have concerns when neutral voltage rises above 1.0 V [28], [29]. Unfortunately, most homes don't have a 240 V supply in the garage so adopting a level 2 charger involves the cost of re-wiring home circuits.

This research has studied other PQ impact of PHEV such as metering error, losses and transformer overloading etc. Beside the neutral voltage rise issue, no other significant impact was found. It is also understandable that the harmonic impact of PHEV on the primary system is small. In theory, the PHEV may cause 60 Hz overloading on the service transformers. Our study shows that this is not a major issue if the PHEV penetration level up to 30% (i.e., year 2022 based on this paper market data) is considered.

VII. CONCLUSIONS

This paper presented a PQ impact assessment methodology for distributed plug-in EVs. Methods to model various deterministic and random factors that influence the charging activities of PHEV are proposed. The factors include charging strategies, charging start time, charging duration, market penetration, vehicle connection point and charger electrical data. A Monte Carlo simulation method has been employed to identify PHEV impacts at both fundamental and harmonic frequencies. The usefulness of the method has been demonstrated through case studies. The results show that PHEV chargers have negligible harmonic impact on power systems in the near future (up to 2022). However, Level 1 charger may cause the rise of neutral to earth voltage, which could lead to more stray voltage incidents. The proposed method can be used to study the impact of other types of EVs, such as BEV, different PHEV market penetration scenarios, and vehicle to grid operation modes.

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