Power System Level Impacts of PHEVs

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Abstract

This paper presents investigations into various aspects of how plug-in hybrid electric vehicles (PHEVs) could impact the electric power system. The investigation is focused on impacts on the power system infrastructure and impacts on the primary fuel utilizations due to PHEV charging. The investigation is presented in terms of examples of typical systems. Methodologies are presented for computing loss of life of distribution transformers, which sets the basis for needed expansion or upgrades of systems with PHEV penetration. In addition, a methodology is presented for evaluating the impact on primary fuel source utilization considering all the operating constraints of an electric power system. Examples of fuel utilization impact are presented for various levels of PHEV penetration. In general, PHEVs cause a shift of fuel utilization from petroleum to less expensive fuels utilized by electric power utilities.

1. Introduction

As of March 2008, the U.S. was importing crude oil at the rate of 9.6 Mb per day, and an additional 5.1 Mb per day was produced domestically [1]. Of the 14.7 Mb per day coming into the U.S. 9.1 Mb per day of finished motor gasoline was produced [2]. This means that 62% of crude oil used domestically is refined into gasoline. High petroleum prices, high emissions from gasoline powered vehicles, and dependence on foreign oil, all contribute to a well known national problem.

Many solutions have been suggested for this complicated problem. Some popular proposed resolutions are (a) finding more oil, (b) increasing fuel economy of conventional vehicles, (c) use of other sources of energy as transportation fuel, (d) use of hybrid electric vehicles (HEVs), and (e) use of plug-in hybrid electric vehicles (PHEVs).

This paper focuses on the last proposed solution utilizing PHEVs. Specifically, using existing technology in the form of PHEVs, the electric power industry could provide a portion of the energy needed for most transportation needs at less than one-sixth of the present cost (using present gasoline and electric energy prices). Most importantly, PHEVs provide the means to replace the use of petroleum based energy sources with a mix of energy resources (encountered in typical electric power systems) and to reduce overall emissions (pollution). In effect, the electric power system using PHEVs could replace a portion of the energy that is totally derived from gasoline in a conventional internal combustion vehicle with electric energy.

Electric energy is useful to propel a vehicle as a result of the increased efficiency of electric drive systems. On average, internal combustion vehicles operate at 12.5% efficiency; i.e., only 12.5% of the fuel energy actually drives the wheels [3]. However, electric drive systems are nearly 70% efficient. Considering that electric energy can be produced and transported with an efficiency of about 33%, in typical electric utility systems, the overall efficiency of PHEVs would be 23.1% as compared to the typical 12.5% of conventional vehicles. Two questions are addressed in this paper, related to this proposed solution: (a) can the power system handle the enormous load that PHEVs would create? And (b) what is the impact on primary energy source utilization of PHEVs?

The use of PHEVs has advantages and disadvantages compared to other proposed solutions. The deployment of PHEVs has the potential to have substantial positive impact on the electric power system from the point of view of increasing electric energy consumption, offsetting petroleum fuels with

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other energy sources, adding additional regulation capability, and assisting in emergency capacity (these last benefits will require specific additional capabilities of the grid/vehicle interface). This positive impact is mitigated with the fact that the electric power system infrastructure may not be adequate to deal with the increased demand and new patterns of consumption and power flows in the power grid.

This paper contributes to the existing body of literature by introducing two methods that quantify the potential impact that PHEVs could have on the electric utilities through realistic simulation studies using specific power system examples. Two case studies are presented: (1) the impact that PHEVs have on the infrastructure at the consumer level and in particular on the low voltage system distribution transformers (7.96 KV to 120/240 V, single phase transformer with center-tapped secondary, 15 kVA) and (2) the impact of PHEV charging on primary-energy source utilization (IEEE test system). The paper presents the methodologies used and results for the example systems.

2. Impact of PHEVs on electric distribution systems

In this section, we examined the impact of the additional load that PHEVs add in the distribution system. Distribution systems are typically designed for specific load carrying capability based on typical load consumption patterns of customers. When PHEVs are deployed (consumers acquire PHEVs and use the existing electric system in houses and commercial building for charging the PHEVs) the patterns of electric power demand change. It is possible that the electric power system may be adequate to handle the new patterns and levels of demand or it is possible that periods of overloads on this system may increase. Both circuits and transformers are vulnerable to these overloads with the transformer being more susceptible to overloads.

To evaluate the impact of this scenario on the system it is necessary to model the distribution system including the wiring in houses, service circuits, distribution transformers and the medium voltage distribution system. Since one is concerned with the adequacy of the system to handle the new loading of the system, it is expedient to use an electro-thermal model of the constituent parts of this system. The electro-thermal model allows the computation of the temperature rise of the various components of the system and subsequent evaluation of the adequacy of the system and/or the evaluation of the risk of failure. For example, in case of circuits, adequacy is expressed in terms of a maximum permissible temperature of circuit conductors. In case of transformers, one can compute the loss of life for specific temperature profiles of the transformer.

The methodology will be presented by an example test system. A test system consisting of a medium voltage distribution system, distribution transformers that feed houses and the service circuit as well as the wiring inside the house was modeled and simulated. In order to decrease the complexity of the results, we will discuss part of this system, specifically the part of the system consisting of a distribution transformer feeding three houses.

Simulations provide the temperature evolution in the transformer for specific scenarios of the operation of assumed PHEVs and typical electric loads in the system. The temperature evolution is computed from the electro-thermal model of the system components. For example, with knowledge of the currents in the transformer windings, the temperature of the windings can be calculated using a simplified first-order electro-thermal model. From the transformer windings temperature the hot spot temperature of the transformer, loss of life, and expected life can be calculated over a planning period.

Two scenarios were examined. In the first case, the homeowners did not own any PHEVs. In the second case, we assumed that each homeowner acquired one PHEV. We focused on the impact on the distribution transformer. Specifically, we compare the loss of life and expected life of the distribution transformer for these two cases (no PHEVs and three PHEVs for this part of the system).

The test system, shown in Figure 1, consists of a distribution substation (115 kV to 13.8 kV, 30 MVA) and a medium voltage distribution transformer (7.96 kV to 120/240 V, 15 kVA); feeding a residential circuit. Three-phase overhead transmission lines are delivering the power to the distribution transformer that serves three houses through mutually coupled multi-phase lines.

To charge the PHEVs the following assumptions were made. The owners of the first and second house used their 120 V, 15 A garage outlets to charge their cars, while the owner of the third house used a 240 V, 30 A outlet for charging their car. Each car needed 18 kWh to be fully charged, had a power factor of 0.92 (current lagging), had a charging efficiency of 96%, and was assumed to be fully discharged at the start of the simulation period.

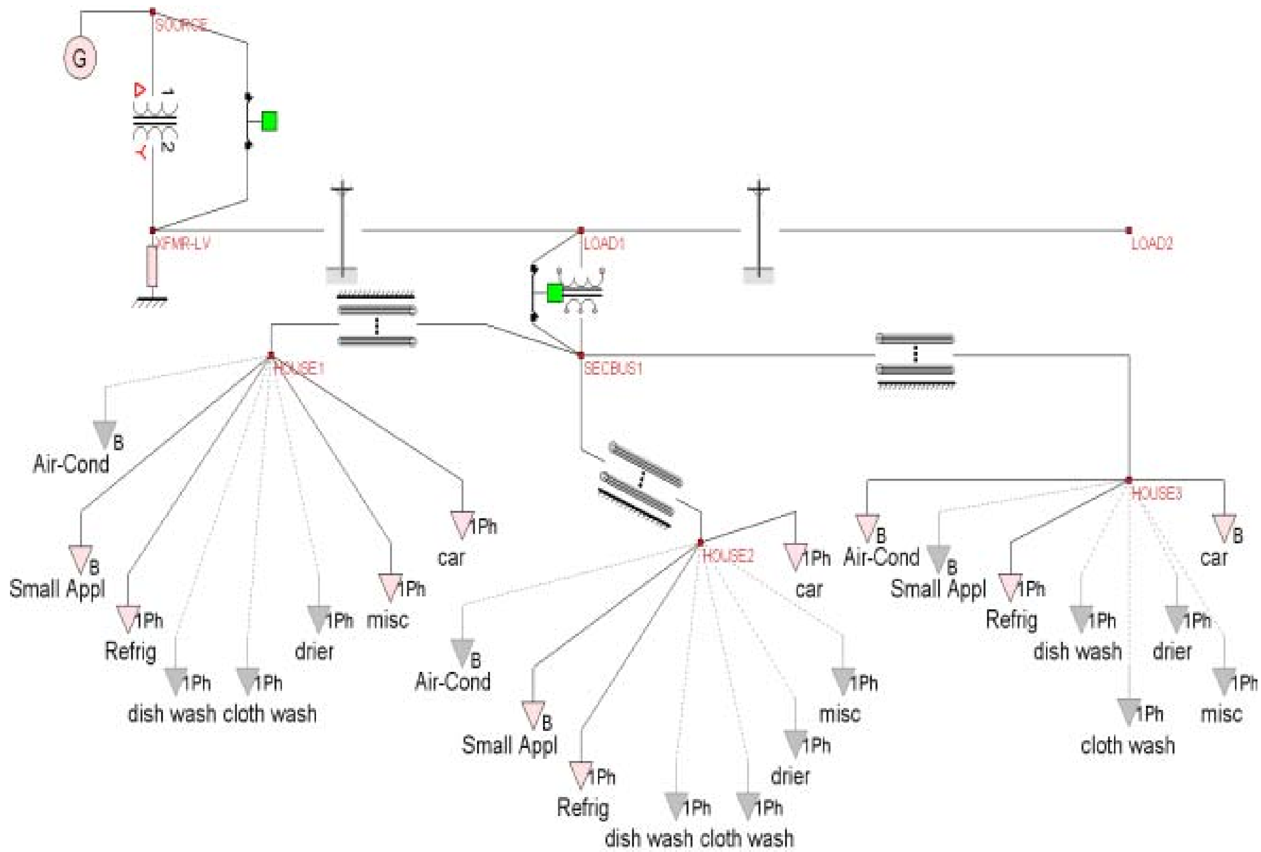

Figure 1: Single line diagram of test system

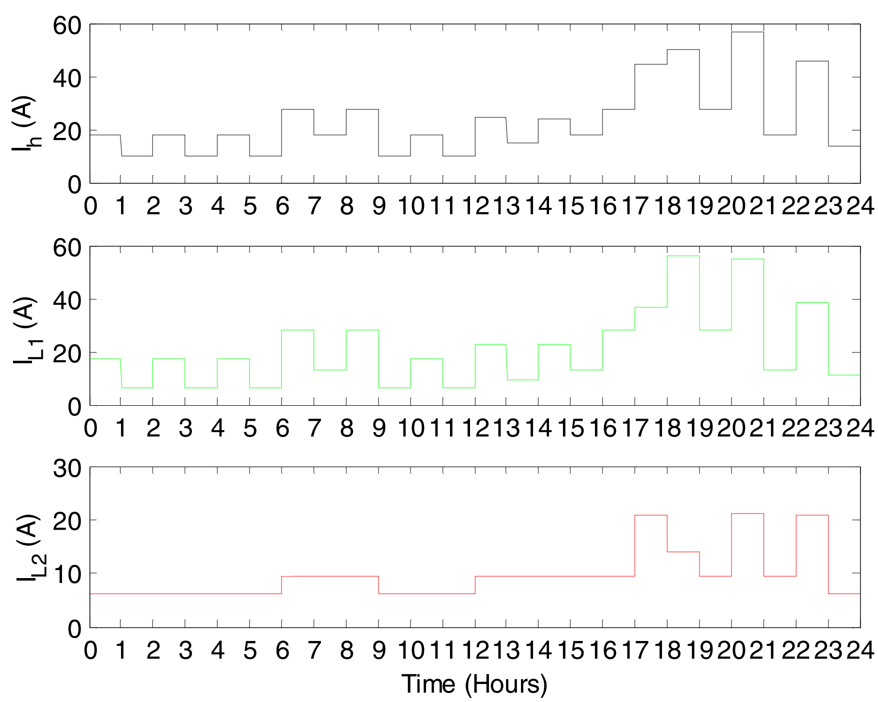

Figure 2: Transformer winding currents - without PHEVs.

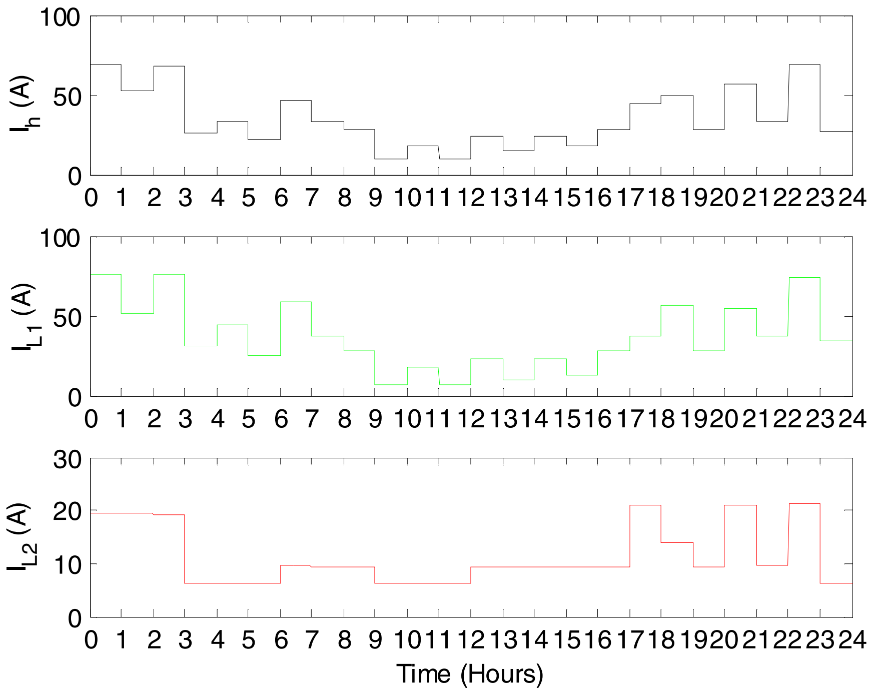

Figure 3: Transformer winding currents - with PHEVs

For each hour of the simulated day, a random daily load schedule was assumed. First, on an hourly basis, the high-voltage (I_h) and low-voltage (I_{L1} and I_{L2}) transformer winding currents were calculated for each case (with and without PHEVs). In the simulations, we assumed that the first and second cars were charged from 21:00 pm until 8:00 am of the next day (it takes almost 11 hours for the PHEVs to be fully charged with the 120 V, 15 A service). While the third car was charged from 0:00 pm to 3:00 pm (it takes 3 hours for the PHEV to be fully charged with the 240 V, 30 A service). The transformer high-voltage (I_h) and low-voltage winding (I_{L1} and I_{L2}) currents are illustrated in Figure 2 without PHEV charging and Figure 3 with PHEV charging.

To compute the temperature of the transformers windings throughout the day, a first order electro-thermal model of the transformer was utilized and is depicted in Figure 4 [4-6].

The dynamics of the transformer winding temperatures are described by the following differential equation:

$$C\frac{dT}{dt} = -G \cdot T + q,$$

where T is the temperature vector of the windings:

$$T = \begin{bmatrix} T_h & T_{L1} & T_{L2} \end{bmatrix}',$$

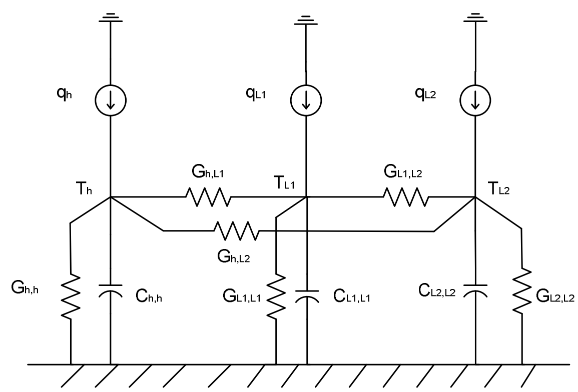

Figure 4: Electro-thermal transformer model

q is the heat source vector:

$$q = \begin{bmatrix} q_h & q_{L1} & q_{L2} \end{bmatrix}',$$

which is expressed in terms of the transformer currents as:

$$q = \begin{bmatrix} 13.8 \cdot I^2{}_h & 0.008 \cdot I^2{}_{L1} & 0.008 \cdot I^2{}_{L2} \end{bmatrix}',$$

C is the thermal capacitance matrix that represents the thermal capacity of the corresponding components:

$$C = \begin{bmatrix} C_{h,h} & 0 & 0 \\ 0 & C_{L1,L1} & 0 \\ 0 & 0 & C_{L2,L2} \end{bmatrix},$$

and G is the thermal conductance matrix, which represents the thermal conductance among the three windings:

$$G=\begin{bmatrix} \alpha & -G_{h,L1} & -G_{h,L2} \\ -G_{h,L1} & \beta & -G_{L1,L2} \\ -G_{h,L2} & -G_{L1,L2} & \gamma \end{bmatrix},$$

where:

$$\alpha = G_{h,h} + G_{h,L1} + G_{h,L2} ,$$

$$\beta = G_{L1,L1} + G_{h,L1} + G_{L1,L2} ,$$

and,

$$\gamma = G_{L2,L2} + G_{h,L2} + G_{L1,L2} .$$

A trapezoidal integration method was used to calculate the solution of the differential equation. In particular, integration within the time interval [t-h, t] was calculated to be:

$$T(t) = \left(C + G\frac{h}{2}\right)^{-1}\left(C - G\frac{h}{2}\right)\cdot T(t-h) + M ,$$

where M was evaluated to be:

$$M = \left(C + G\frac{h}{2}\right)^{-1} q\cdot h ,$$

and h was the time step of the integration.

Note that the above electro-thermal model provides the temperatures of the transformer components with respect to the ambient temperature. The absolute temperatures are affected by the ambient temperature. Therefore, knowledge of the ambient temperature is required to compute the absolute temperatures of the transformer. For these simulations, we assumed a flat ambient temperature profile for simplicity (constant ambient temperature of 20 ^{0}C).

Application of the trapezoidal integration using the heat source vectors over the simulated day, with a time step of 10 sec, gave the results for the temperatures T_h, T_{L1} and T_{L2} over the simulated days, which are illustrated in Figures 5 and 6.

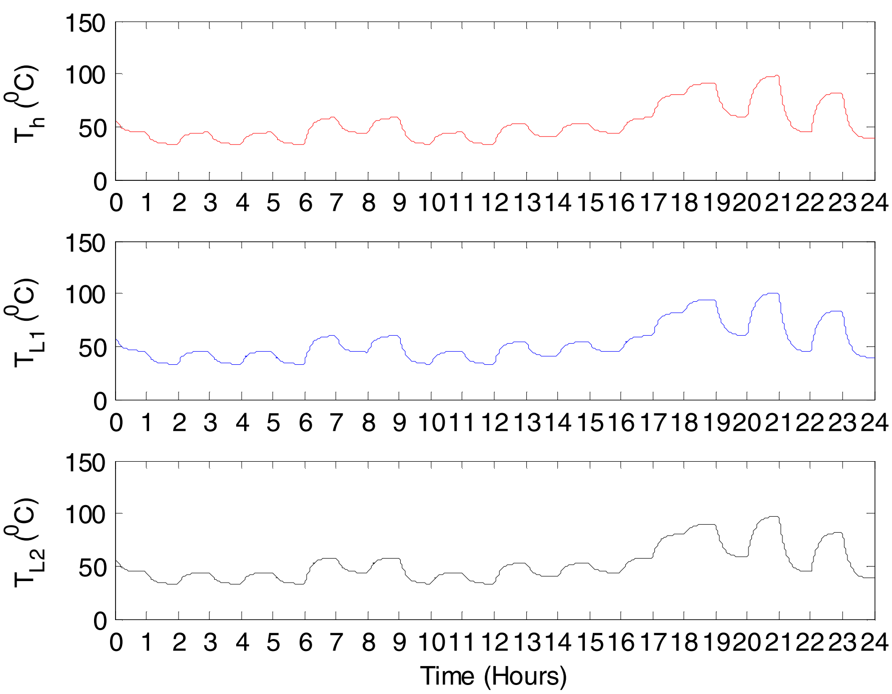

Figure 5: Transformer winding temperatures - without PHEVs

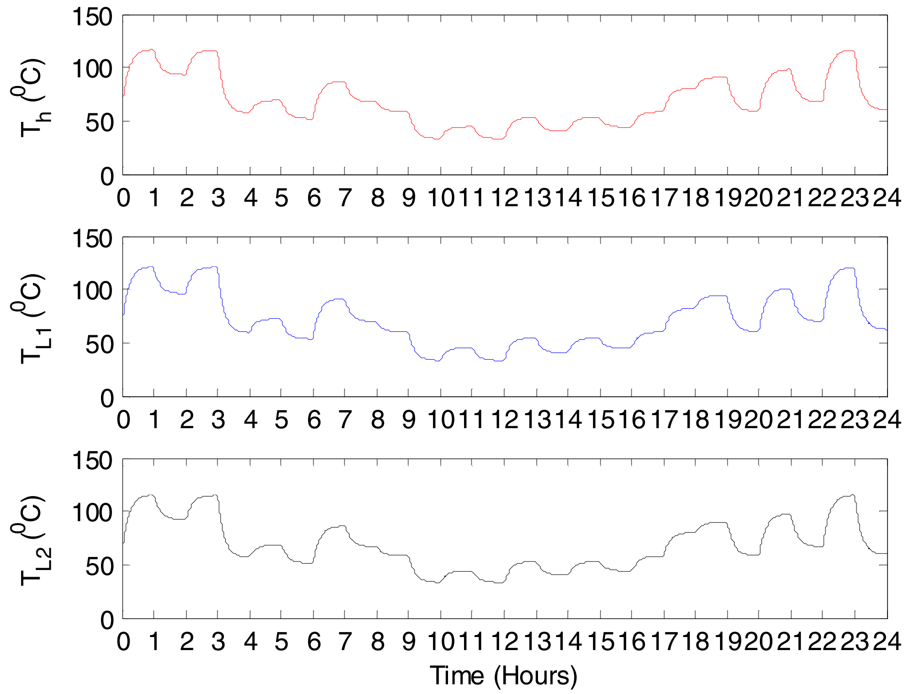

Figure 6: Transformer winding temperatures - with PHEVs

Using the calculated values of the winding temperatures throughout a day, the loss of life and the expected life of the transformer were computed using the following formulas [4-8]:

$$LOL = \sum_{h=1}^{24} \exp\left\{-(A + \frac{B}{\widetilde{T}_h})\right\},$$

$$Expected\ Life = \frac{1}{LOL \cdot 365},$$

where $\widetilde{T}_h$ is the hot spot temperature over the time interval h, in degrees Kelvin and A, B are constants depending on the design of the transformer insulation (for 55 degree transformer insulation the constants are equal to -25.9478 and 14572.6, respectively). The hot spot temperature $\widetilde{T}_h$ for each hour was considered to be the maximum value of the temperatures T_h, T_{L1} and T_{L2} within each hour. Applying the above formulas for the two cases, the results are summarized in Table 1.

Comparing the expected life values for the two examined scenarios, we concluded that in the case in which the homeowners own a PHEV, the expected life of the transformer was reduced by approximately 93%. It is also important to note that the loss of life is exponentially dependent on transformer temperatures. This means that distribution transformer failures will be very sensitive to deployment of PHEVs, ambient temperature, and any other parameter that affects transformer temperatures.

Table 1: Transformer LOL and expected life results

	LOL (normalized)	**Expected Life (years)**
Without PHEVs, 20 ^{0}C	$7.7588 \cdot 10^{-6}$	353.11
With PHEVs, 20 ^{0}C	$10.6 \cdot 10^{-5}$	25.85
Without PHEVs, 30 ^{0}C	$2.2 \cdot 10^{-5}$	124.3
With PHEVs, 30 ^{0}C	$2.67 \cdot 10^{-4}$	10.25

As an example of the effect of the ambient temperature, the last two rows of Table 1 show results of the simulations using a higher ambient temperature (30°C). The expected life of the distribution transformer decreased 65% with no effects of the PHEV charging. Further, the effect of charging PHEVs with a higher ambient temperature reduced the expected life of the transformer by 92%.

In general these results are extremely system specific. This potential problem can be corrected with a variety of approaches including replacing distribution transformers with higher rating units, implementing smart chargers that may coordinate with the transformer loading, etc. These approaches are beyond the scope of this paper.

3. Primary energy source utilization

Another important impact of PHEVs is their ability to blend electric and gasoline energy for transportation. The relative amount of the two energy sources depends on design parameters of the PHEV, driving distances, and driving patterns of the owner. The electric energy usage of PHEVs comes from the mix of the electric utility generation system and therefore PHEVs play an important role in replacing energy needs from petroleum based to electric utility mix (nuclear, hydro, coal, gas, petroleum, wind, etc.). It is important to determine the shift in primary energy source utilization due to this process to determine where the added electricity will be derived.

This analysis is quite complex since the determination of the primary source utilization for electric energy production is influenced by optimization procedures of the electric power system as well as availability of the generating equipment that are subject to random and planned maintenance outages. In general this procedure requires detailed simulation of the operating conditions of the electric power system taking into consideration random events that determine the status of the transmission system as well as the generating system. In this paper we utilize a probabilistic simulation of the power system operations [9]. These methodologies were developed in the 1970s and have been utilized for a variety of reliability and planning studies. Details of this method can be found in [9].

The probabilistic simulation method has been applied to an example system under various scenarios of PHEV penetration. The base example power system is the IEEE 1979 reliability test system (RTS) described in [10]. Subsequent paragraphs describe the procedure and scenarios used in the study.

3.1. PHEV simulation methodology

To study the effects of PHEV charging on primary energy source utilization, three scenarios were developed. The first scenario was the case without any PHEVs in the system (therefore no additional electric load due to PHEVs). We refer to this case as 'Base Case'. The next two scenarios represent specific penetration levels of PHEVs. Here we define penetration as the number of PHEVs with respect to the total population of light duty vehicles. Scenario two will be referred to as '10% PHEV'. For this scenario the added required power capacity due to PHEVs was 275 MW. Similarly the third scenario represents 20% penetration of PHEVs and we will refer to this scenario as '20% PHEV'. For this scenario the added required power capacity due to PHEVs was 550 MW. It is important to note that the peak electric load due to the charging PHEVs does not coincide with the peak load of the system.

3.2. PHEV model

In order to determine the pattern of the additional load due to the charging of the PHEVs, an analysis of the energy requirements of PHEVs was formulated. First, the number of cars in the power system area was derived.

The number of vehicles in the RTS area was estimated based on a number of assumptions, as follows. The number of customers was calculated from an electric monthly demand of 1500 kWh. Based on an average month of 30 days the average power demand per customer was 2.083 kW. The RTS peak power capacity was 2850 MW, thus the number of customers in the RTS area was calculated to be 1.368 million. Further, the number of vehicles per electric customer was assumed to be two, which resulted in a total number of vehicles in the RTS area of 2.736 million (N_T). Thus the 10% PHEV scenario added 0.2736 million PHEVs on to the RTS system, and the 20% PHEV scenario added 0.5472 million PHEVs.

Next, we estimated how many miles each vehicle drove each day. A simple approach for this was to assume 12,000 miles driven per car per year (*mpy*) and divide by the number of days in a year to have an average number of miles driven per day per car equal to 32.9 miles.

Finally, to calculate the total additional load due to PHEVs a number of vehicle parameters were assumed. The efficiency of a conventional powertrain, i.e. the amount of fuel energy transferred to the driven wheels, was 12.5% (η_{conv}). The efficiency of the power electronic controller, inverter, was 92% ($\eta_{control}$). The efficiency of the drive motor was 90% (η_{motor}). The fraction of conventional fuel input energy per mile supplied by the electric drive was 70% (k_{PHEV}). The turn-around efficiency of the battery was 85% (η_{bat}). The efficiency of the battery charger was 90% ($\eta_{charger}$), and finally an energy density of gasoline of 36.65 kWh per gallon (ρ_{fuel}). The last two parameters were taken from the EPA rating of miles per gallon average for each vehicle class (mpg_i) and the percentage each vehicle class would represent in the total population of light duty vehicles (p_i). These parameters are shown in Table 2.

Table 2: Average EPA mpg for each vehicle class and percentage of vehicle class in each scenario

Vehicle Class	1	2	3	4
Vehicle Description	Compact	Full Size	Medium SUV & Pickup Truck	Large SUV & Pickup Truck
EPA mpg [miles/U.S. Gal]	29.72	24.84	17.11	16.70
10% PHEV p_i	2%	3%	3%	2%
20% PHEV p_i	4%	6%	6%	4%

Based on the above definitions the energy input per mile driven from the fuel tank for a conventional vehicle, in class-*i* was calculated:

$$E_{input-i} = \frac{\rho_{fuel}}{mpg_i} \left[\frac{\text{kWh}}{\text{mile}} \right].$$

Next, the recharging energy per mile that would be required from the grid for each vehicle, in class-*i* was calculated:

$$E_{grid-i} = \frac{k_{PHEV} \cdot \eta_{conv} \cdot E_{input-i}}{\eta_{charger} \cdot \eta_{bat} \cdot \eta_{control} \cdot \eta_{motor}} \left[\frac{\text{kWh}}{\text{mile}} \right].$$

Finally, the total recharge energy required per day for the entire system was calculated:

$$E_{grid} = N_T \cdot \frac{mpy}{365} \sum_{i=1}^{4} p_i \cdot E_{grid-i} \left[\frac{\text{kWh}}{\text{day}} \right].$$

The last step was to convert energy to power by dividing the average length of time needed to charge each PHEV. The described method calculated a peak level of 275 MW per day and 550 MW per day for the 10% and 20% PHEV penetration scenarios, respectively.

3.3. Simulation data

The probabilistic simulation method requires a number of parameters that describe the system in terms of generating cost, fuel utilization, variability of electric load, etc. This section presents the data for the RTS example system and the scenarios used. Generator data including fuel utilized, max generating capacity and forced outage rate for each generating unit type is shown in Table 3. Additionally, Table 4 shows the heat rate data for each generating unit type. The heat rate coefficients a_h, b_h, and c_h in Table 4 are defined as follows:

$$h(P) = a_h + b_h \cdot P + c_h \cdot P^2 \left[\frac{\text{kcal}}{\text{h}} \right],$$

where P is the generated power in MW. Table 5 shows the fuel data for the fuel types used by this system.

Table 3: Generator size and forced outage rate

Fuel	Size [MW]	FOR
#6 Oil	12	0.02
#2 Oil	20	0.1
Hydro	50	0.01
Coal	76	0.02
#6 Oil	100	0.04
Coal	155	0.04
#6 Oil	197	0.05
Coal	350	0.08
Nuclear	400	0.12

Table 4: Generator heat rate coefficients

Size [MW]	a_h	b_h	c_h
12	3330369	2550425	15047.24
20	10080000	3150000	0
76	21092334	2550425	2375.881
100	31362044	1963834	2413.314
155	43407948	1946828	1401.447
197	33003505	2193793	328.5092
350	81532894	1873123	822.2852
400	90962133	2244962	116.0031

Table 5: Fuel data

Fuel Type	Fuel Costs [$/kg]	Fuel Energy Density [kcal/kg]
#6 Oil	0.6	11200
#2 Oil	0.65	12000
Coal	0.05	6000
Nuclear	60000	$200 \cdot 10^{19}$

The charging of PHEV was modeled as a probabilistic event. Considering the model of PHEVs the probability distribution function of PHEV charging was obtained and shown in Figure 7 (chronological curve over a period of one day). The total electric load on the system is the addition of the

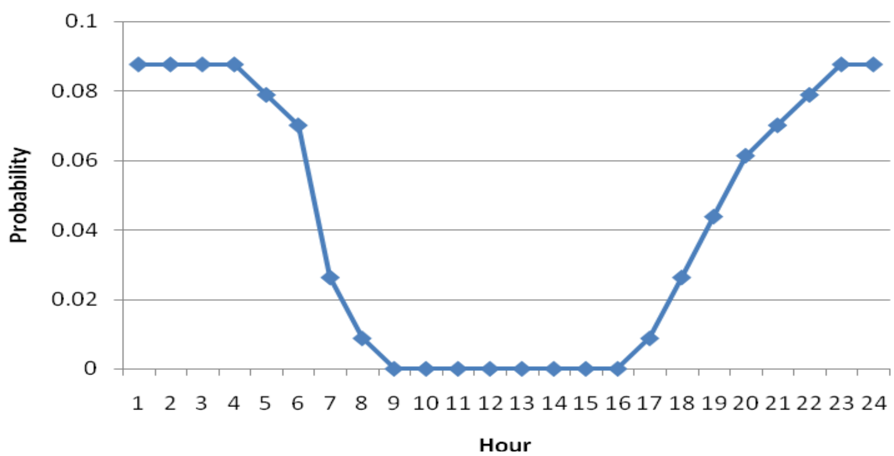

Figure 7: PHEV charging distribution

chronological PHEV loads (a scaled and repeated version of Figure 7) and the chronological base case electric load of the system. The chronological electric load model is converted into a probability distribution function (inverted) of the load for the purposes of the probabilistic simulation method. In general, a normalized inverted load duration curve describes the length of time for which the load was greater than a specified value, which ranges from the system minimum load to the maximum load [9].

One of the effects of the PHEV charging distribution used was that the additional load due to PHEVs significantly weighted the time of day where typically the power system load was lowest, the early morning hours and the late evening hours. This caused a much greater increase in the system minimum load then the maximum load. The minimum increased 22.10% and 30.66% for the 10% and 20% PHEV penetration scenarios, respectively. And the maximum load increased only 1.75% and 10.78% increase for the 10% and 20% PHEV penetration, respectively. This load leveling is a potential benefit of the semi-controllable load that PHEVs present.

3.5. Simulation results

The results of the probabilistic power system simulations calculated the amount of primary energy source utilization to meet the energy demand. The amount of the energy produced per fuel type showed the greatest increase in coal consumption, a smaller increase in #6 oil, and a very small increase in both #2 oil and nuclear fuel usage. The numerical values are provided in Table 6. The percent change was calculated normalized by the total energy generated in the Base Case equal to 12.995 GWh.

It is important to note that these results are system specific and also depend on the specific costs of the various fuels. Specifically, the probabilistic simulation dispatches units on the basis of their costs and availability. As a result a lower cost unit and fuel will be preferred and it will show as an increased utilization of that specific fuel. In addition, the generation mix varies quite a lot from one utility to another and therefore the fuels utilized are quite different for different utilities.

Table 6. Effects of PHEV charging on primary energy source utilization

Primary Energy Source:		#6 Oil	#2 Oil	Coal	Nuclear
Total Energy [GWh/year]	Base Case	542.9	2.873	6369	6080
	10% PHEV	720.1	4.572	7267	6150
	20% PHEV	1021	9.020	8094	6158
Percent Change	10% PHEV	1.36	0.01	6.91	0.54
	20% PHEV	3.68	0.05	13.28	0.61

4. Conclusion

Various economic studies have concluded that the entering of PHEVs into the power system would be beneficial in terms of financial and environmental issues; however, whether the current infrastructure could withstand the increased load that the PHEVs would require remains as a question. In the initial investigation presented, we focused on the effects that PHEVs can have on distribution systems. A test system consisting of a distribution substation, distribution circuit and transformer feeding three houses was examined. When PHEVs were included in the simulation, a 93% reduction of the expected life of the distribution transformer was calculated for a specific scenario. The impact on the infrastructure can be substantial and methodologies must be developed to solve these issues. It is important to note that these issues are not different from the usual issues encountered when traditional electric loads increase in parts of the electric power system.

We have also investigated the impacts of PHEV charging on primary energy-source utilization by means of an example. Additional PHEV based load affects the generation of electric energy and the primary fuel used for this generation. Scenarios of different levels of PHEV penetration were considered. The results indicate the increase of the various fuel utilizations depend on their cost and the availability of the generating unit burning this fuel. Certainly, PHEVs cause a shift from petroleum utilization to other fuels depending on the generation mix of the electric utility.

The primary energy source utilization methodology, presented in this paper, can be extended to determine the impact of PHEVs on pollutants. Specifically, the simulation method can be augmented to compute power plant emissions as well as the PHEV pollutants providing the total emissions. These emissions then can be compared to pollutants from scenarios without PHEVs. The goal is to develop a comparison of the operational air pollution impact. Comparing two scenarios, where scenario (1) is the system operating with no PHEVs, and scenario (2) is the system operating with PHEV penetration. Scenario (1) will have pollution from the power system with the base-case load and the full population of conventional vehicles. Scenario (2) will have an increase in pollution from the power system and less pollution from the PHEVs. Comparing the total emissions under these scenarios will provide a comprehensive comparison method of potential PHEV charging methodologies.

5. Acknowledgments

The work reported in this paper has been partially supported by the PSERC project T-34, “Power System Level Impacts of Plug-In Hybrid Vehicles”. This support is gratefully acknowledged.

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