



Power System Level Impacts of Plug-In Hybrid Vehicles

Final Project Report

Power Systems Engineering Research Center

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Power Systems Engineering Research Center

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Executive Summary

Plug-in hybrid electric vehicles (PHEVs) offer an attractive solution to a growing dependence on imported foreign oil with potential benefits and issues to the electric power industry. The impact of PHEVs on the power grid is investigated. The methodology for this investigation is based on three procedures: (a) typical utilization of PHEVs that capture human habits and terrain on which cars are driven for the purpose of evaluating the energy consumption and split between electric and gas, (b) simulation of the electric infrastructure (distribution systems) and the loading patterns that results from PHEV deployment and the effects on the equipment and in particular the expected life of transformers, (c) impact of PHEV deployment on energy resource utilization in the power grid, and (d) impact of PHEV deployment on the operations and the security of the power grid. Proper models are utilized that capture all the interactions of the complex system that comprises the power grid, the distribution system and the PHEVs. The report consists of two volumes.

Volume I

First, four hybrid-electric vehicle (HEV) powertrain architectures are described. These architectures are commonly termed series, parallel, single-mode split-power, and dual-mode split-power. Conclusions suggest that either a parallel architecture or the GM 2-MT is the best choice.

Second, calculations of the electric energy consumed by PHEVs under typical scenarios are performed using both an analytic approach and computer simulation. The analytic approach utilizes estimates for the efficiency of PHEV components. Simulations are run using the *Powertrain System Analysis Toolkit (PSAT) v.6.2* program developed by DOE's Argonne National Lab. A comparison of results from both methods is provided. Sample results show that if 10% of the entire US vehicle fleet is replaced by PHEVs, and vehicles travel an average of 12,000 miles per year the added electric load due to PHEVs would be 3.3% of the installed 950 GW generation capacity in the US; a small increase in the added electric demand.

Third, the vehicle emissions including nitrogen oxides (NO_x) and the greenhouse gas carbon dioxide (CO_2) are described. It is found that if a PHEV control algorithm can operate a vehicle such that, on average, 62% of the energy supplied to the powertrain comes from the battery, then, with a standard spark-ignited IC engine the regulated emissions meet the latest standard (Tier2-Bin5).

Fourth, two infrastructure implications are described (1) the impact of typical household infrastructure on PHEV recharging, and (2) the vehicle to grid interface. The household circuit capacity (120V / 20A) is capable of recharging the required battery capacity needed to drive 40 miles in charge sustaining mode (70% of the required energy per mile is derived from onboard electric energy over the entire 40 miles) in 6 hours; further, the size of this battery pack is feasible in terms of weight and volume using battery technology available today. Additionally, four levels of vehicle to grid interface are defined, increasing in functionality and complexity.

Fifth, the impact of PHEV charging on distribution transformers is described. This impact is quantified through a loss-of-life (LOL) calculation. The LOL calculation is based on distribution transformer hot-spot temperature. This temperature is estimated using an electro-thermal distribution transformer model and is a function of the transformer winding currents. These currents are computed using a center-tapped single phase transformer model. Results of this research show that a measurable LOL can occur due to PHEV charging. Areas of high ambient temperature show larger LOL over areas of low ambient temperature and highly loaded transformers show higher LOL over transformers with excess capacity. The LOL of transformers is very sensitive on whether the combined residential load and PHEV is near or exceeds the rating of the transformer.

Sixth, the impact of PHEV charging in terms of (a) primary fuel utilization shifts, (b) pollution shifts, and (c) total fuel cost for yearly vehicle operation is described. Vehicle and power system simulations are used. The vehicle fleet simulations compute: the amount of added electric load demand to charge the PHEV fleet, amount of gasoline used by both IC vehicles and PHEVs, and the amount of environmental air pollution (EAP) generated by both IC vehicles and PHEVs. The power system simulations simulate how much fuel usage and subsequent EAP are generated by a specific power system. Results from this research indicate that PHEVs offer cleaner transportation (depending on the generation mix used to charge the vehicles) with decreased gasoline utilization at a lower cost to consumers. Specifically, three different power system generating mixes are simulated with varying levels of PHEV penetration (defined as the percentage of the light duty vehicle fleet in the power system area replaced by PHEVs). Two of the three power system generating mixes simulated show a decrease in total system NO_x EAP and all three showed a decrease in CO₂ EAP.

Seventh, the benefit of using a heavy penetration of PHEVs to act as support to the grid during contingencies and also the costs incurred with security constrained control is described. PHEVs provide a completely new way to store massive amounts of energy from the power grid. It is found that (1) PHEVs have a great potential to save grid operating costs and reduce critical contingencies and (2) PHEVs have a significant effect on unenforceable security constrained optimal power flow (SCOPF) contingencies and maximum line overloads.

Eighth, a comparison of vehicles powered from hydrogen fuel to PHEVs is described. The significant hurdles involving production, storage, distribution, and use of hydrogen are outlined. Conclusions drawn are that hydrogen use with a fuel cell or even injected directly into an IC engine is not a near-term prospect for reducing the use of petroleum-based fuels.

Ninth, a comparison of battery-electric ZEVs to PHEVs is described. The advantages of ZEVs over PHEVs are: a simpler less expensive powertrain, less maintenance with only an electric drivetrain, zero tailpipe emissions, electric energy that could be produced by renewable sources. The disadvantages of ZEVs are large battery packs to get a reasonable range, and very long recharging times. The advantages of PHEVs over ZEVs are: that an appreciable amount of the driving energy comes from the electrical grid thus reducing the use of petroleum-based fuels and tailpipe emissions compared to conventional vehicles, range limitations are not limited as charge-sustaining operation is available, smaller battery packs can be used. The disadvantages of PHEVs are (a) more

complex and costly powertrain, and (b) use of a petroleum-based fuel with some tailpipe emissions when driven longer distances.

Volume II

Two studies are presented quantifying the impact of plug-in hybrid vehicles (PHEVs) on the power grid. The first study quantifies this impact in terms of (a) primary fuel utilization shifts, (b) pollution shifts, and (c) total cost for consumers. The second study quantifies this impact on distribution transformers.

In the first study vehicle fleet and power system simulations are used. The vehicle fleet simulations compute the amount of added electric load demand to charge the PHEV fleet, the amount of gasoline used by both internal combustion (IC) vehicles and PHEVs, and the amount of environmental air pollution (EAP) generated by both IC vehicles and PHEVs. The power system simulations simulate how much fuel usage and subsequent EAP are generated by a specific power system.

In the second study the impact on distribution transformers is quantified through a loss-of-life (LOL) calculation that is based on the transformers hot-spot temperature. This temperature is estimated using an electro-thermal transformer model and is a function of the transformer currents. These currents are computed using a center-tapped single phase transformer model.

The results from this research indicate that PHEVs offer cleaner transportation (depending on the generation mix used to charge the vehicles) with decreased gasoline utilization at a lower operating cost to consumers. The impact to the utility infrastructure is favorable from the security point of view and additional revenues to the utility and unfavorable to the expected life of distribution transformers. The last issue can be addressed in a variety of ways, including monitoring of distribution transformers and replacing them with larger units if the loading from PHEVs results in substantial loss of life.

In general the impact of PHEVs on the power grid is favorable. The unfavorable effect on the expected life of distribution transformers is not much different than the effect of increasing loads in a household or commercial building. Power companies deal with this problem routinely. It is suggested as a follow up to this research project to develop transformer life expectancy monitor. The technology exists today to develop a smart monitoring device that will track the loading and thermal history of distribution transformers and compute the loss of life in real time. This technology can provide alarms that quantify the impact of increased loading on the transformer life which can be used by utilities to prioritize the replacement of transformers. The increase of total load on the power grid, assuming expected gradual penetration of PHEVs in the market, is at a level comparable to what utilities have experience under normal economic conditions, i.e. few percentage points annually. Therefore gradual penetration of PHEVs can be easily handled by typical power system planning scenarios.