An Evaluation of PHEV Contributions to Power System Disturbances and Economics

Steven L. Judd and Thomas J. Overbye

Abstract--**As fossil fuels prices climb higher, the search for alternative modes of transportation intensifies. Several solutions have been proposed: increase fuel economy of current vehicles, expand use of ethanol, enlarge the current hybrid electrical vehicle fleet, create a hydrogen fuel cell vehicle, or create a more effective electric vehicle. One other possible solution is the transformation of current hybrid electric vehicles into larger capacity plug-in hybrid electric vehicles (PHEVs). It has become a promising advancement in technology with a small amount of innovation.**

Pluggable hybrids provide a completely new way to store mass amounts of energy from the power grid. With larger battery storage, the PHEV has the ability to run in all-electric mode for commuters, switch to conventional gasoline engine for longer trips, and provide support to the power grid needed in emergency situations. This thesis explores 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.

***Index Terms*—power grid, plug-in hybrid electric vehicle, PHEV, system security, optimal power flow, OPF, security constrained optimal power flow, SCOPF.**

I. Introduction

A. Motivation

DURING 2005, the United States imported 10.4 million barrels of crude oil per day in addition to the 5.18 Mb/day that are produced domestically. Over two-thirds of this fossil fuel is refined into gasoline to power passenger vehicles and trucks [1]. The effects of this "addiction to oil" place greater pressure on our economy and political establishment every day. With world-wide demand increasing and OPEC controlling 75% of the world's proven reserves [2], market prices have recently sky-rocketed to over $125 per barrel [3]. This along with increasing pressure to reduce greenhouse gas emissions from the burning of fossil fuels has intensified the pursuit of alternate technologies. It becomes critical for our nation to find a solution to reducing our overall consumption of oil and find an alternative for the future.

B. Possible Solutions to Reducing Oil Consumption

Several solutions have been proposed to solve this enormous problem: finding more oil (for example the drilling of ANWR in Alaska or in the deeper regions of the Gulf of Mexico), increasing the fuel economy of our vehicle fleet, implementing the use of E85 fuels containing ethanol, creating a viable hydrogen fuel cell vehicle, and widening the use of conventional hybrid electric vehicles (HEVs).

A newer option has emerged in the past few years, the plug-in HEV (PHEV). The only difference between a standard hybrid and a PHEV is an increase in the capacity of the battery pack, a connection to charge from an electrical outlet, and modifications to the power electronics [4]. PHEVs have a new advantage of running in all-electric-mode for longer distances, typically 30-60 miles, and could become a new source of energy storage for the bulk power grid.

Current HEVs charge their batteries from the cars' internal combustion engine or regenerative breaking and deplete their energy while the car is stationary or during acceleration. This method is referred to as *charge-sustaining* since the batteries will maintain a set state of charge, typically 70% - 80%. The major change in a PHEV is the use of a *charge-depleting* strategy where the car batteries will be steadily used while driving to maximize fuel efficiency and the state of charge will decrease over time, typically as low as 30%. The car will also be connected to the power-grid while not in use to provide energy to the batteries from the grid and/or provide support to the grid in emergency situations.

C. Overview

This thesis will focus on the support PHEVs can provide to grid security and possible economic benefits for grid operation. Plug-in hybrids also have a large potential to save money for those that own one. An analysis of the economic benefit to individual owners will be described. An in-depth formulation of how much power PHEVs can provide will also be shown. To show the economic benefit of grid connection, the IEEE 24, IEEE 118, and a utility 2,574 bus test system will demonstrate costs associated with PHEVs. These systems with several different levels of support will be simulated to see what potential cost benefits and increased grid security can be achieved.

II. Literature review

A. Justification for Integrating PHEVs to the Power Grid

The concept of vehicle-to-grid (V2G) connections started in 1997 with Professor Willett Kempton [5], exploring the potential economic and system potential of electric cars connected to the power grid. To show the potential power of

The authors would like to acknowledge the support of the Power System Engineering Research Center (PSERC) and NSF through its grant EEC 96-15792. Steven L. Judd (email: sjudd@uiuc.edu) and Thomas J. Overbye (email: overbye@ece.uiuc.edu) are with the Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801 USA

untapped energy, look at the capacities of the grid and electric vehicles.

According to the 2007 EIA Energy Outlook, the total generation capacity of U.S. electric utilities is almost 920 GW (0.92 TW) [1]. Let us assume a grid connection of all light duty vehicles (cars, SUVs, and small trucks) to a standard 120-V 15-A electrical outlet (1.8 kW of output power). According to the 2005 statistics, there were approximately 238.3 million light duty vehicles [6]. This represents a total possible output power of 429 GW, nearly half the current capacity of all U.S. generators combined with only a standard outlet connection. With improved outlet connections, this number could be even larger.

Another false rumor is that the majority of this potential power would not be available to the grid. According to a 2001 survey, the average car is only used 62.32 min per day; in other words, the average vehicle is idle for 96% of the time [7]. Studies have shown that even during peak travel hours, 90% of the vehicle fleet is not in use [8]. This shows that during peak load a large majority of the electric vehicle capacity will be ready for control room operators to use.

B. Evaluation of Potential Grid Uses for PHEVs

Plug-in hybrids have been envisioned to help the power grid in several different ways. Such methods include: base load generation, peak demand, spinning reserves, regulation, reactive power, and grid security improvement. Some of these ideas show promise, while others do not show much potential.

One method that does not show promise is base load generation [8]. Currently nuclear power stations constitute the majority of base load generation and produce very cheap electricity, often 3 to 5 ¢/kWh, much lower than the cost to operate a PHEV to supply base load power.

Peak demand generation, on the other hand, has much different potential. During peak demand period, around 3-6 pm, electricity prices can spike to well over 30 ¢/kWh. This is because of where the last few megawatts of power are generated. Often small, very expensive generation units come online to supply peak power. These units are often powered by natural gas or oil and can also be highly polluting.

If PHEVs were charged at night when electric rates are low, then sold its stored energy back onto the grid during the peak, a profit could be made. The drawback to this method is the percentage of time this event occurs. It may only be possible to use this method a couple hundred hours a year [8]. This would not earn much money for consumers and may not be worth their effort.

One large potential for plug-in hybrids is their use in regulation. Grid operators at an ISO are constantly adjusting the amount of power generation to closely match the amount of power consumption at any one time. This method of adjustment, called regulation or automatic generation control (AGC), can be very costly. For example, California ISO typically spends up to 80% of their ancillary service expenditures on regulation [9].

Another potential use of PHEVs is the supply of reactive power to the grid. Current technology in power electronic converters can change the power factor of the alternating current to the grid to supply real and reactive power support [10]. In the future, most ISOs are planning reactive power markets. Once this happens this could be a great additional source of revenue for PHEV owners.

A final proposed use for PHEV is use in improving grid security. During a system disturbance, generators are quickly asked to increase or decrease output to suppress the effects of the change in the system. A PHEV's inverter has a much faster response time than a turbo-generator governor's and could react rapidly to a disturbance. This would improve overall reliability of the system and potentially allow the grid to run at a lower overall cost with this rapid response [11]. This paper will explore the use of PHEVs for grid security and cost reduction in much greater detail.

C. Beginnings of Vehicle-to-Grid Connections

Several cities and states are already taking the initiative to push the idea of plug-in hybrid electric vehicles. One example is Austin Energy, a city owned utility, in central Texas. They have launched a recent campaign – called Plug-In Partners – to line up potential buyers once PHEVs are in production. So far they have had over 8,000 pledges from residents and organizations. Their own city council has already set aside $1 million in rebates for the first 1,000 customers and also plans to change city building codes to require plugs available in parking lots [12].

The Michigan Public Service Commission (MPSC) also initiated a pilot program to integrate PHEVs to the Michigan power grid. Their location near some of the largest auto makers in the world will put them in a unique position to be a leader in V2G testing and connections. They will study the effects on the grid at low, medium and high levels of PHEVs and how that fits in with current smart grid projects [13].

III. CASE FOR CONVERTING VEHICLE FLEET TO PHEVS

A. Personal Savings Over Current Vehicles

By increasing the battery capacity of the current HEV, the Plug-in HEV becomes a dual-fuel vehicle. The electric utility can supply off-peak energy during the night to replace gasoline for daily commuting. This new source of energy has the potential to be very attractive to the consumer.

For example, gasoline has an energy content of 124,000 BTU per gallon or 36.36 kWhr per gallon [14]. Taking a US average of $3.84 per gallon [15], the cost of energy from gasoline is about 10.56 cents per kWhr. Considering the average price of electricity of 8.90 cents per kWhr for 2006 [16], there does not seem to be a large advantage until one considers the energy conversion efficiencies.

Moving energy from the wall socket to a battery pack and an electric motor has an average efficiency of around 61% [17]. This is vastly higher than the efficiency of the current internal combustion engine of 12.6% (see Fig. 1). Hence, taking efficiencies into account, it costs 83.8 cents per usable kWhr for gasoline but only 14.6 cents per usable kWhr using electricity or the equivalent of buying gasoline at $0.67 per gallon. In addition, cars would mainly be charged during the nighttime off-peak hours when spot electricity prices are usually much lower. Utilities could set up programs for

PHEV owners to give discounted rates or real-time pricing to take advantage of this cheaper electricity.

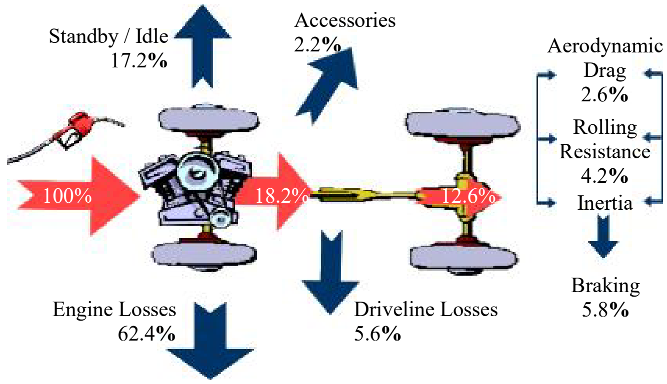

FIG. 1 INTERNAL COMBUSTION POWERTRAIN ENERGY LOSSES [18]

To see the potential to the US economy, look at the nation-wide fleet of vehicles. If each vehicle drives an average of 11,800 miles per year [19] and makes an average 22.9 mpg [20], a typical vehicle will use about 515 gallons of gas per year. This translates to an annual savings of over $1,600 per PHEV. As mentioned earlier, with 238.3 million light duty vehicles (passenger cars, SUVs and small trucks), if only 20% of the current fleet is replaced by plug-in hybrids, it would save $78 billion annually. These savings will only increase as oil and gasoline prices continue to rise.

B. Greenhouse Gas Reduction

Another large benefit of the plug-in hybrid is its beneficial impact on the environment. The current light duty vehicle fleet consumes approximately 6.5 million barrels of oil equivalent per day, or 52% of the entire nation's oil imports [21]. All of this gasoline is burned and produces harmful greenhouse gas emissions nationwide. Switching this fuel consumption to the production of electricity, more efficient and advanced technologies can remove those harmful gases from the emissions.

A November 2007 study performed a nationwide simulation of this theory to see how much it would impact emissions. The study concluded that greenhouse gases, mainly carbon dioxide (CO_2), are expected to reduce by 27%. This varied by as much as 40% for the ERCOT region, which has a large number of natural gas plants, to slightly negative for the Midwest with a large amount of coal generation. The largest impact is seen with volatile organic compounds (VOCs) and carbon monoxide (CO) emissions having a reduction of 93% and 98%, respectively. This number could be exaggerated since it is assumed that all PHEVs will only run on electric mode and does not take into effect longer trips that will use the internal combustion engine. Nitrogen oxide (NO_X) emissions are also projected to decrease 31% mainly due to reduced refining of gasoline [21].

Not all emissions will have a positive effect. Particulate emissions (PM10) and sulfur oxide (SO_X) emissions are expected to increase by 18% and 125%, respectively. This is largely due to the increase in coal-fired power generation. The positive side will be that the most harmful emissions will be removed from urban areas to a few hundred generation sites across the country. This can add pressure to increase funding in carbon sequestration technologies to further reduce emissions [21].

It should be noted that these values could be reduced even further with the increased use of wind energy, which produces zero greenhouse gases during generation. Wind also generally blows more during the nighttime hours, which is when most plug-in vehicles will be charging and storing more power from the grid.

IV. US VEHICLE AND GRID CONNECTION INFORMATION

A. Estimation of PHEV Penetration

Besides the obvious individual economic benefit PHEVs can provide, they also have a large potential for the electric power grid because they represent a large amount of energy storage. To analyze the benefits to the grid, an estimate of the amount of support from PHEVs needs to be determined.

As of July 2006, the US population is 299.398 million people [22]. The peak load during the same time period was 789,475 MW [23]. This equates to 2.637 kW per person or 379.24 people per MW. According to the 2006 Census, there were 111.6 million occupied houses in the US and 91.2% of these houses have at least one vehicle [24]. Using these numbers, there is an average of 2.68 people per house, 141.5 houses per MW of peak load, and 129.05 houses with vehicles per MW of peak load. If we estimate 20% of houses own a PHEV, this translates to 25.8 plug-in hybrids per MW of peak load.

To analyze how much power can be delivered by PHEVs, one must consider the amount of "energy flow" that can be achieved. The main constraint is the connection to the grid. Current technology of bidirectional converters and practical limits of residential service could support a maximum power transfer of about 10 kW. Commercial installations could theoretically take maximum power straight from the electric motor in the range of 100 kW. This amount of power transfer cannot be achieved in the standard home or business without a major change to the wiring and circuit breakers and a large cost to consumers. This would be a large deterrent to potential PHEV buyers.

The PHEV power inverters could also adjust the power factor coming from the vehicle to allow reactive power support to the grid. This study, however, will only look at real power support since consumers are not charged for reactive power and would not see a monetary benefit from this type of support. In the future, reactive power markets could be created, giving incentive to users to provide reactive support.

We will examine what can be achieved with minimal or no upgrade to a house's wiring. If the hybrid was plugged into a standard 120-V, 15-A wall outlet, it would be able to provide a power transfer of 1.8 kW. Using the number of PHEVs per MW of peak load, they can provide 46.45 kW per MW or 4.6% of relief. This paper will also take a look at other possible connections to see the wide range of possible support available from PHEVs.

V. TEST CASES

To show the benefits of plug-in hybrids, a typical power system needs to be analyzed. For the purposes of this research, three different test cases were examined: IEEE 24 bus, IEEE 118 bus, and a utility 2,574 bus case. To see the cost benefits of PHEV support, a steady-state power flow will be run for the case to determine the system state and costs associated with generation.

A. Solving an Optimal Power Flow for a Test Case

The first step was to evaluate the operating cost of the system using optimal power flow (OPF). OPF can trace its origins back to 1962 [25]. The goal is to schedule the generation of a system to minimize an objective function while not violating any constraints on the system. Common constraints on the system can include power balance, voltage profiles for buses, and thermal constraints on transmission lines. Usually the objective is to minimize cost, but it could also be to minimize losses or minimize control shifts.

To formulate the OPF problem [26], we define $\underline{x}$ as the vector of state variables and $\underline{u}$ as the vector of control variables. The objective function is defined as $f(\underline{x},\underline{u})$. The equality constraints such as the power flow equations and total power generation equaling power consumption plus losses, are defined as $g(\underline{x},\underline{u})$. The inequality constraints including voltage profiles and thermal constraints, are defined as $h(\underline{x},\underline{u})$.

$$\begin{aligned} &\min f(\underline{x},\underline{u}) \\ &s.t. \quad g(\underline{x},\underline{u}) = \underline{0} \\ &\qquad h(\underline{x},\underline{u}) \le \underline{0} \end{aligned} \tag{1}$$

The function $f(\underline{x},\underline{u})$ for this OPF will be to minimize the overall operating cost of the power generation, shown in (2).

$$f(\underline{x},\underline{u}) = \sum_{i\in G}^{n} \alpha_{gen,i} + \beta_{gen,i} P_{gen,i} + \gamma_{gen,i} P_{gen,i}^2 \tag{2}$$

where G is the set of all generators and PHEV support for the power system. The generator coefficients for the cost function are given in Table II, $(\alpha = a \quad \beta = b \quad \gamma = c)$.

The function $g(\underline{x},\underline{u})$ contains the power flow equations (3) - (4) and the power balance equation (5).

$$P_i(\underline{x}) = \left\{ \begin{array}{l} \left|\hat{V}_i\right| \sum\limits_{k\in C_i} \{\left|\hat{V}_k\right| [G_{ik}\cos(\theta_i - \theta_k) + \\ B_{ik}\sin(\theta_i - \theta_k)]\} + P_{load,i} - P_{gen,i} \end{array} \right\} = 0 \tag{3}$$

$$Q_i(\underline{x}) = \left\{ \begin{array}{l} \left|\hat{V}_i\right| \sum\limits_{k\in C_i} \{\left|\hat{V}_k\right| [G_{ik}\sin(\theta_i - \theta_k) - \\ B_{ik}\cos(\theta_i - \theta_k)]\} + Q_{load,i} - Q_{gen,i} \end{array} \right\} = 0 \tag{4}$$

$$\sum P_{gen} - \sum P_{loss} - \sum P_{load} = 0 \tag{5}$$

where $\hat{Y}_{ik} = G_{ik} + jB_{ik}$ is the complex admittance from bus i to bus k and C_i is the set of all buses connected to bus_i.

The function $h(\underline{x},\underline{u})$ contains all the inequality constraints for the problem. These include voltage constraints at each bus, generator constraints, and thermal constraints on transmission lines. The equations are given in (6) - (9).

$$V_i^{\min} \le V_i \le V_i^{\max} \quad \forall i \in H \tag{6}$$

$$P_{gen,i}^{\min} \le P_{gen,i} \le P_{gen,i}^{\max} \quad \forall i \in G \tag{7}$$

$$Q_{gen,i}^{\min} \le Q_{gen,i} \le Q_{gen,i}^{\max} \quad \forall i \in G \tag{8}$$

$$\left|S_{flow,ij}\right| \le \left|S_{flow,ij}^{\max}\right| \quad \forall ij \in L \tag{9}$$

where H is the set of all buses in the system, G is the set of all generators, L is the set of all lines and transformers, and $\left|S_{flow,ij}\right|$ is the magnitude of the complex power flowing from bus i to j.

Using all of these equations we construct the Langrangian of the minimization problem defined in (1):

$$\mathcal{L}(\underline{x},\underline{u},\underline{\lambda},\underline{\mu}) = f(\underline{x},\underline{u}) + \underline{\lambda}^T g(\underline{x},\underline{u}) + \underline{\mu}^T \underline{h}(\underline{x},\underline{u}) \tag{10}$$

The variables $\underline{\lambda}$ and $\underline{\mu}$ are defined as the Lagrange multipliers. To minimize this function we set the gradient to zero and solve for the control variables and multipliers.

$$\nabla \mathcal{L}(\underline{x},\underline{u},\underline{\lambda},\underline{\mu}) = 0 \tag{11}$$

B. Solving a Security Constrained OPF for a Test Case

Security constrained OPF (SCOPF) takes the original OPF problem and adds additional constraints. The OPF solves a system optimally for $N-0$ contingencies, or the system at steady state with all lines and generators in service. The SCOPF solves the system to minimize cost while also making the system secure for $N-1$ contingencies, or the system with any one transmission line or generator out of service. Since the SCOPF has more constraints it will always be equal to or more expensive than the OPF. The SCOPF problem formation is shown in (12).

$$\begin{aligned} &\min f(\underline{x}^{(0)},\underline{u}) \\ &s.t. \quad \left.\begin{array}{l} g(\underline{x}^{(j)},\underline{u}) = \underline{0} \\ h(\underline{x}^{(j)},\underline{u}) \le \underline{0} \end{array}\right\} j = 0,1,\ldots,C \end{aligned} \tag{12}$$

where $j = 0$ is the base case and $j = 1,2,\cdots,C$ is each $N-1$ contingency case.

C. IEEE 24 Bus Test Case

To test the theories of PHEV support, a test case is needed. For this we choose the IEEE 24-bus Reliability Test System (see Fig. 2) [27]. This system contains 34 generation units with a total capacity of 3,405 MW, 17 loads totaling 2,850 MW and 580 Mvar, and 38 transmission lines. At peak load, this system has several contingencies and high congestion which will show larger impacts versus an extremely secure system.

Since this case was created in 1979, the cost data for generators has become extremely outdated. To fix this, updated cost figures for different fuel types were found and can be seen in Table I and Table II [28].

TABLE I - FUEL COST FIGURES FOR GENERATORS

Fuel Type	Fuel Energy Density [kcal/kg]	Fuel Costs [$/kg]	Fuel Costs [$/kcal]	Fuel Costs [$/MBtu]
#6 Oil	11,200	0.6	5.35 E-05	13.50
#2 Oil	12,000	0.65	5.41 E-05	13.65
Coal	6,000	0.05	8.33 E-06	2.10
Nuclear	2.00 E+21	60,000	3.00 E-17	~0.00

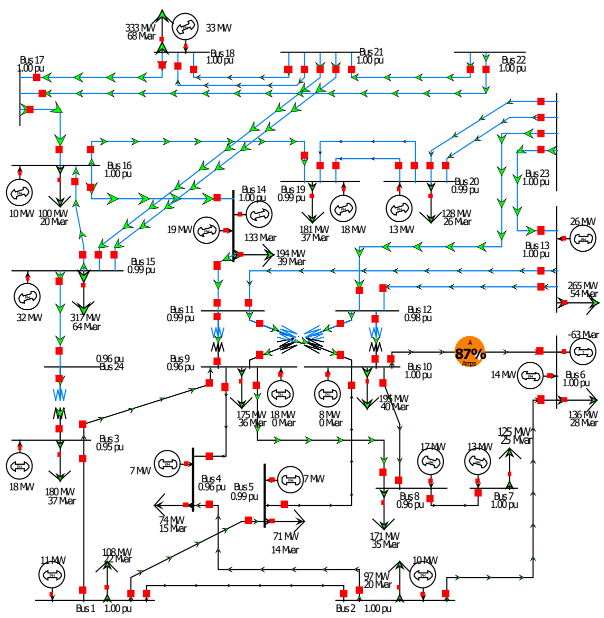

FIG. 2 IEEE 24 BUS TEST SYSTEM

TABLE II - COST CURVE VALUES FOR GENERATOR TYPES

Size MW	Gen Type	Fuel Type	a [MBtu/ kWh]	b [MBtu/ kWh]	c [MBtu/ kWh]
12	Fossil Steam	#6 Oil	18.24	-1.25 E-06	6.09 E-14
20	Combustion Turbine	#2 Oil	17.00	-1.25 E-06	0.00
50	Hydro	Water	0.00	0.00	0.00
76	Fossil Steam	Coal	18.24	-1.97 E-07	1.52 E-15
100	Fossil Steam	#6 Oil	15.94	-1.39 E-07	8.06 E-16
155	Fossil Steam	Coal	13.63	-5.58 E-08	1.97 E-16
197	Fossil Steam	#6 Oil	12.40	-3.02 E-08	8.25 E-17
350	Fossil Steam	Coal	11.96	-1.63 E-08	2.67 E-17
400	Nuclear Steam	LWR	14.84	-2.71 E-08	3.78 E-17

Currently all fixed costs are set to zero and hydro units are assumed to have no fuel costs. For this study, we will only consider the system under peak load conditions. To simulate the support of PHEVs, a "generator" was inserted at every load bus. This would represent the entire amount of support available from all PHEVs in a city with a corresponding MW load value. After running an OPF and contingency analysis on the system before the addition of PHEVs, there are numerous problems.

An initial OPF, with no plug-in support, produced an overall cost of $139,068 per hour. Checking all $N-1$ contingencies for lines and generators, the system has 9 insecure contingencies. An initial SCOPF had a cost of $167,089 per hour with 2 unenforceable contingencies and 1 binding contingency, an increase in cost of 20% and a 78% reduction in violating contingencies.

Some trouble spots during contingencies include low voltage violations on the left side of the grid and line overloads on the right side.

D. IEEE 118 Bus Test Case

The next system to be examined is the standard IEEE 118 bus case [29]. This system contains 54 standard generation units with a total capacity of 7,220 MW, 91 loads totaling 5,318 MW and 2,085 Mvar, and 186 transmission lines. Generation cubic cost coefficients, generator limits, and transmission line power limits were taken from a previous paper concerning unit commitment [30], [31]. Fuel cost figures were matched similarly to the generators in the IEEE 24 bus case based upon their maximum output. As with the 24 bus case, a PHEV "generator" was added to every load bus and set to produce or consume the specified amount of support.

After running an initial OPF with no plug-in support, there were 26 separate $N-1$ contingency violations with an overall cost of $330,823 per hour. The initial SCOPF produced 3 unenforceable contingencies, 4 binding contingencies, and a cost of $443,552 per hour. This was an increase in costs of 34% and a reduction in violating contingencies of 85%.

E. Utility 2,574 Bus Test Case

The final test system used for this simulation was a 2,574 bus case from a region of a North American utility. This system is much larger and was taken during a peak load day in 2007. It contains 220 generation units totaling 27,725 MW of capacity, 622 load buses with a total load of 20,823 MW and 3,166 Mvar, 95 switched shunts, and 3,315 transmission lines. Generator, transmission line, and interface limits were included along with 851 predefined contingencies. Cost figures for the generators were not included, so based upon the generator's upper limit, the units were classified similar to the 24 bus test case and given corresponding cost figures.

Starting with the base case and no plug-in support, an initial OPF was run and produced 588 $N-1$ contingency violations (mostly interface overloads) and a total cost of $1,096,327 per hour. The initial SCOPF produced 9 unenforceable contingencies and 9 binding contingencies at a total cost of $1,812,126 per hour, 65% more costly than the OPF but a 98% reduction of the original violating contingencies.

VI. TEST SCENARIOS USING PHEVS

A. Amount of PHEV Support for Simulations

To see a wide range of possibilities of the potential support PHEVs could provide, several factors were varied to view their impacts. Future penetration of plug-ins in society is highly uncertain. Several factors can determine future use including the availability of plug-ins from manufacturers, the amount of government incentives to consumers, and the future price of fossil fuels.

For the purposes of this study, penetration levels of 10% to 25% were examined. Also the type of vehicle connection can have a large impact on the available support. We looked at connecting the vehicle to both 120-V and 240-V circuits with circuit breakers of 15 A, 20 A, and 40 A. Amounts of PHEV support are shown in Table III.

TABLE III - PHEV SUPPORT IN PERCENT OF PEAK LOAD

10% PHEV	120V	240V
15A	2.3229%	4.6458%
20A	3.0972%	6.1944%
40A	6.1944%	12.3888%

15% PHEV	120V	240V
15A	3.4844%	6.9687%
20A	4.6458%	9.2916%
40A	9.2916%	18.5832%

20% PHEV	120V	240V
15A	4.6458%	9.2916%
20A	6.1944%	12.3888%
40A	12.3888%	24.7776%

25% PHEV	120V	240V
15A	5.8073%	11.6146%
20A	7.7430%	15.4860%
40A	15.486%	30.9720%

Since potential support can range from as low as 2% to just below 31%, SCOPF simulations of the three test systems will be run with support from 1% to 31% in 1% increments. All PHEV "generators" were given a piece-wise linear cost function. If the PHEVs were absorbing power they would pay a price of 5 ¢/kWh and would supply power to the grid for a price of 20 ¢/kWh.

VII. RESULTS

A. IEEE 24 Bus Test Case

As expected, larger vehicle penetrations and upgraded outlet connections have a larger effect on the support PHEVs can achieve. The support was not linear, however. For the first 10% of support, the cost had a steep decrease. With only a little more than 4% of PHEV support, the SCOPF became the same operating cost as the OPF. After a support level of 10-15%, any additional support had only a small incremental effect on the cost of the system. This can all be seen in Fig. 3.

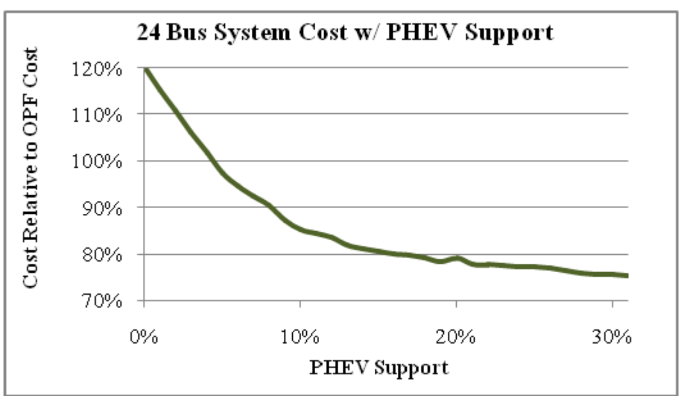

FIG. 3 24 BUS SYSTEM COST VS. PHEV SUPPORT NORMALIZED TO OPF COST

Contingencies did not see as immediate an effect as the system cost. The system still had two unenforceable contingencies until after 10% of support and the final unenforceable contingency was eliminated after 16% of PHEV support. Results can be seen in Fig. 4.

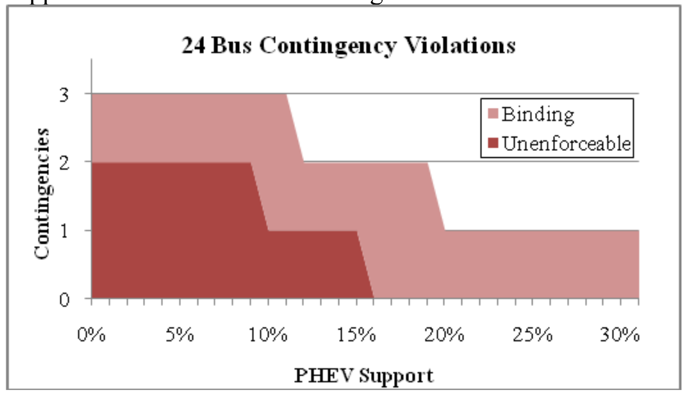

FIG. 4 24 BUS CONTINGENCY VIOLATIONS VS. PHEV SUPPORT

The maximum line overload had similar results. During the period of support from 0% to 16%, the overloads steadily decreased overall and after 16% when all unenforceable contingencies were eliminated the system was $N-1$ secure so every line was at or less than 100% of its limit.

It should be noted that the unenforceable contingencies and maximum line overloads might be larger than it should be due to the charging on the transmission line from bus 6 to 10. It is abnormally high causing a large amount of Mvar on the line and the overload.

B. IEEE 118 Bus Test Case

The 118 bus test case had similar results. For the first 10% of support the system cost had a sharp decrease and began to have a smaller effect larger than 20% (see Fig. 5). For this system it took a larger amount of support to reduce the cost to the base case OPF, a little more than 12%.

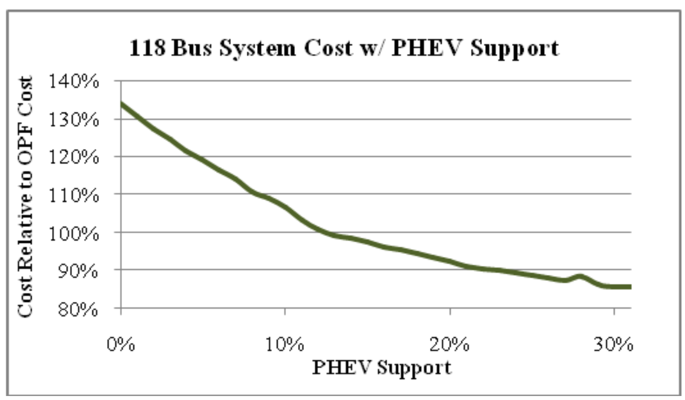

FIG. 5 118 BUS SYSTEM COST VS. PHEV SUPPORT

Unenforceable contingencies experienced an immediate benefit with only 1% of support reducing the overall number to two violations. From 12% to 14% of support, the remaining two unenforceable contingencies were eliminated, making the system $N-1$ secure (see Fig. 6). The number of binding contingencies fluctuated throughout the region of support but was not a large issue since the system cost continued to decrease as discussed earlier.

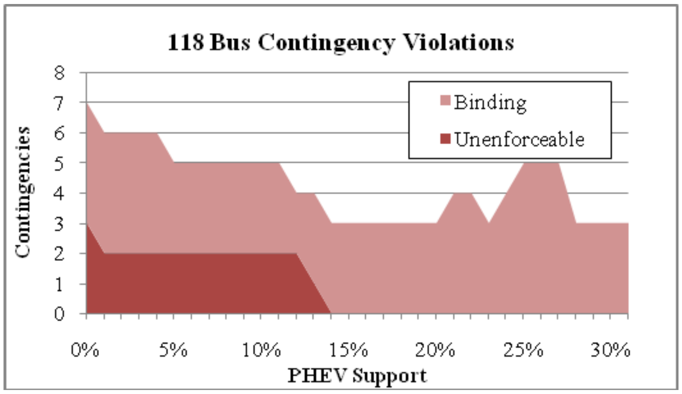

FIG. 6 118 BUS CONTINGENCY VIOLATIONS VS. PHEV SUPPORT

Maximum line overloads had a similar result as the previous case. They continued to decrease and reached 100% at the same time the system became completely secure. The overloads experienced a small bump around 25% of support coinciding with a small increase in binding contingencies. This is most likely due to tolerances in the algorithm and the system can still be considered $N-1$ secure.

C. Utility 2,574 Bus Test Case

The much larger utility system has some different results than the previous two IEEE test cases. The initial SCOPF with no plug-in support had a much higher cost, 165% of the base case OPF system cost. As PHEV power increased, it had a continually large effect on overall system cost (see Fig. 7).

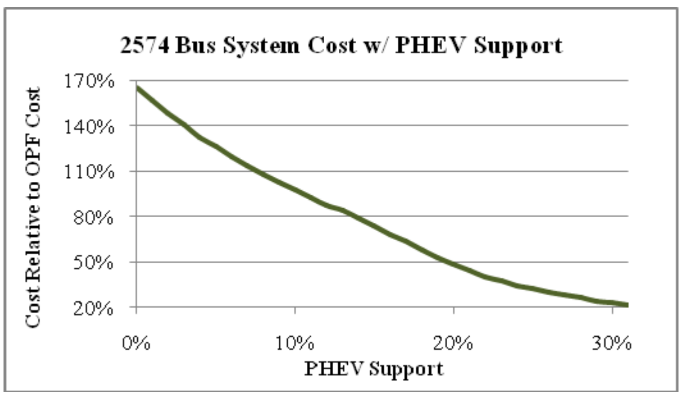

FIG. 7 2,574 BUS SYSTEM COST VS. PHEV SUPPORT

After 9% of support, the SCOPF became cheaper than the original OPF and continued to decline to only 22% with 30% of PHEV power. This is largely due to the inclusion of interface limits with the utility case. The initial maximum interface overload was over 400% of its stated limit with the OPF and greatly reduced to 100% with over 20% of support.

Contingency violations had a similar result as the other two cases. Unenforceable contingency violations decreased from 9 to 5 after only 4% of support. From 7% to 8%, 2 more contingencies were eliminated and the final 3 were eliminated after 22% of support making the system $N-1$ secure (see Fig. 8).

Maximum line flows continued to decrease steadily from over 116% to around 102% over the first 12% of PHEV support. From about 12% to 21% of support there was little change in the line overloads. This was most likely due to the SCOPF algorithm first eliminating the interface violations before satisfying every limit violation. During emergency situations a line violation of 102% may be acceptable if costs are being greatly reduced by eliminating interface overloads first.

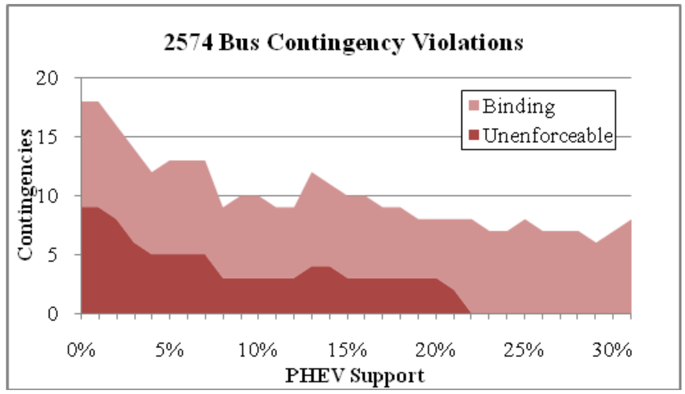

FIG. 8 2,574 BUS CONTINGENCY VIOLATIONS VS. PHEV SUPPORT

VIII. CONCLUSION

Plug-in hybrids have been shown to be a promising advancement toward meeting our future personal transportation needs. They can save the typical consumer over $1,600 annually, reduce our nation's dependence on foreign oil imports, and reduce overall pollution. They have also demonstrated great potential when simply parked in the home garage or at work plugged into an outlet providing grid support.

As we can see from the three test systems, plug-in hybrids have a great potential to save grid operating costs and reduce contingencies. It is interesting to note for the test systems that after 10% - 15% of support, the PHEVs have a minimal effect on the grid. This can be a good situation since it will take time for the pool of hybrids to grow and we can still see significant impacts very quickly as the penetration grows.

Plug-in hybrids had a significant effect on unenforceable SCOPF contingencies and maximum line overloads, but the contingencies required a larger amount of support. All test systems were made completely $N-1$ secure after PHEV support from 14% to 22%. It should be noted that plug-ins might have a larger effect on contingencies if they were also providing reactive support.

It will be crucial to the future of the transportation and energy industries as well as the environment to push the development and implementation of PHEVs. Currently at least 14 automakers are pursuing the development of the first line of pluggable hybrid vehicles [32].

General Motors is the most advanced of the American Big 3 in the process to develop a PHEV. They officially unveiled the Chevrolet Volt concept car at the North American International Auto Show on January 7, 2007, in Detroit, Michigan. This series electric vehicle is set for production as early as 2010-2012, once the batteries are fully developed and tested, currently underway as of February 2008 [33]. Some groups such as the Electric Auto Association have already taken it upon themselves to convert current HEVs like the Prius into a PHEV [34].

This technology has the potential to reduce and even eliminate our dependence on foreign oil, greatly reduce greenhouse gas emissions, and save large amounts of money for transportation. This issue needs to stay at the top of the list and is critical to our future energy independence.

IX. References

[1] J. Conti, "Annual energy outlook 2007, with Projections to 2030," Energy Information Administration, U.S. Department of Energy, Washington, DC, p. 135, 150, 153, February 2007.

[2] T. Hayward, "Statistical review of world energy June 2007," BP p.l.c., London, UK pp.7-9, June 2007.

[3] Energy Information Administration, U.S. Department of Energy, "Cushing, OK WTI spot price FOB (dollars per barrel)," May 2008. [Online]. Available: http://tonto.eia.doe.gov/dnav/pet/hist /rwtcD.htm.

[4] A. P. Meliopoulos, J. Meisel, and T. Overbye, "Power system level impacts of plug-in hybrid vehicles," 2006 PSERC Project Funding Solicitation, p.1, 2006.

[5] W. Kempton and S. E. Letendre, "Electric vehicles as a new power source for electric utilities," *Transportation Research*, vol. 2, no. 3, pp. 157-175, 1997.

[6] Bureau of Transportation Statistics, U.S. Department of Transportation, "Table 1-11: Number of U.S. aircraft, vehicles, vessels and other conveyances," December 2007. [Online]. Available: http://www.bts.gov/publications/national_transportation _statistics/html/table_01_11.html.

[7] P. S. Hu and T. R. Reuscher, Federal Highway Administration, U.S. Department of Transportation, "Summary of travel trends: 2001 national household travel survey," p. 30, December 2004. [Online]. Available: http://nhts.ornl.gov/2001/pub/STT.pdf.

[8] W. Kempton, J. Tomić, S. Letendre, A. Brooks, and T. Lipman, "Vehicle-to-grid power: Battery, hybrid, and fuel cell vehicles as resources for distributed electric power in California," Davis, CA, Institute for Transportation Studies Report #UCD-ITS-RR-01-03, pp. i-v, June 2001. [Online]. Available: http://www.udel.edu/V2G.

[9] A. Brooks and T. Gage, AC Propulsion, "Integration of electric drive vehicles with the electric power grid – A new value stream," in *18th Electric Vehicle Symposium*, Berlin, Germany, October 2001, pp. 2-3, 9-12 [Online]. Available: http://www.acpropulsion.com/reports /ACP_V2G_EVS18.pdf.

[10] S. De Breucker, P. Jacqmer, K. De Brabandere, J. Driesen, and R. Belmans, "Grid power quality improvements using grid-coupled hybrid electric vehicles," in *Power Electronics, Machines, and Drives*, 2006, pp. 505-509.

[11] D. Sutanto, "Alternative energy resource from electric transportation," in *Proceedings of the Power Electronics Systems and Applications Conference*, November 2004, pp. 150-151.

[12] J. J. Fialka, "In quest for cleaner energy, Texas city touts plug-in car," in *Wall Street Journal*, March 26, 2007, p. A1.

[13] Michigan Public Service Commission, Michigan Department of Labor & Economic Growth, "MPSC initiates pilot program to integrate plug-in hybrid electric vehicles into the electric grid, positioning state to become a technology and jobs leader," March 11, 2008. [Online]. Available: http://michigan.gov/mpsc/0,1607,7-159--187335-- ,00.html.

[14] Energy Information Administration, U.S. Department of Energy, "EIA – Energy basics – Converting energy units," March 2008. [Online]. Available: http://www.eia.doe.gov/basics/conversion_basics.html.

[15] Energy Information Administration, U.S. Department of Energy, "Gasoline and diesel fuel update," May 19, 2008. [Online]. Available: http://tonto.eia.doe.gov/oog/info/gdu/gasdiesel.asp.

[16] Energy Information Administration, U.S. Department of Energy, "Electric power annual, average retail price of electricity to ultimate customers by end-use sector," October 2007. [Online] Available: http://www.eia.doe.gov/cneaf/electricity /epa/epat7p4.html.

[17] Professor J. Meisel, Georgia Institute of Technology (private communication), 2008.

[18] FuelEconomy.gov, U.S. Department of Energy & Environmental Protection Agency, "Advanced technologies & energy efficiency," 2008. [Online]. Available: http://www.fueleconomy.gov/feg /atv.shtml.

[19] Bureau of Transportation Statistics, U.S. Department of Transportation, "Table 1-32: U.S. vehicle-miles," December 2007. [Online]. Available: http://www.bts.gov/publications /national_transportation_statistics/html/table_01_32.html.

[20] Bureau of Transportation Statistics, U.S. Department of Transportation, "Table 4.23: Average fuel efficiency of U.S. passenger cars and light trucks," December 2007. [Online]. Available: http://www.bts.gov/publications/national_transportation _statistics/html/table_04_23.html.

[21] M. Kintner-Meyer, K. Schneider, and R. Pratt, Pacific Northwest National Laboratory, "Impacts assessment of plug-in hybrid vehicles on electric utilities and regional U.S. power grids, Part 1: Technical analysis," November 2007. [Online]. Available: http://www.pnl.gov /energy/eed/etd/pdfs/phev_feasibility_analysis_combined.pdf.

[22] U.S. Census Bureau, "Annual population estimates 2000-2007," 2007. [Online]. Available: http://www.census.gov/popest/states/NST-ann-est.html.

[23] Energy Information Administration, U.S. Department of Energy, "Electric power annual," October 2007. [Online]. Available: http://www.eia.doe.gov/cneaf /electricity/epa/epa_sum.html.

[24] U.S. Census Bureau, "United States - Selected housing characteristics: 2006," 2006 Census. [Online]. Available: http://factfinder.census.gov/servlet/ADPTable?_bm=y&-geo_id =01000US&-_name=ACS_2006_EST_G00_DP4&s_name=ACS _2006_EST_G00_&-_lang=en&-_sse=on.

[25] J. Carpienter, "Contribution e l'étude do dispatching economique," *Bulletin Society Française Electriciens*, vol. 3, August 1962.

[26] A. J. Wood and B. F. Wollenberg, *Power Generation Operation and Control*, 2nd ed. New York: John Wiley & Sons, Inc., 1996.

[27] Subcommittee, P.M., "IEEE reliability test system," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-98, no. 6, pp. 2047-2054, November/December 1979.

[28] Professor A. P. Meliopoulos, Georgia Institute of Technology (private communication), 2007.

[29] University of Washington Electrical Engineering, "Power systems test case archive: 118 bus power flow test case," December 1962. [Online]. Available: http://www.ee.washington.edu/research/pstca /pf118/pg_tca118bus.htm.

[30] Y. Fu, M. Shahidehpour, and Z. Li, "Long-term security-constrained unit commitment: Hybrid Dantzig-Wolfe decomposition and subgradient approach," *IEEE Transactions on Power Systems*, vol. 20, no. 4, pp. 2093-2106, November 2005.

[31] Electrical and Computer Engineering Department, Illinois Institute of Technology, "Data for 118 bus test case," April 2007. [Online]. Available: http://motor.ece.iit.edu/Data/SCUC_118/.

[32] CalCars, The California Cars Initiative, "How carmakers are responding to the plug-in hybrid opportunity," February 2008. [Online]. Available: http://www.calcars.org/carmakers.html.

[33] GM Media Online, General Motors, "Chevrolet Volt – GM's concept electric vehicle – Could nearly eliminate trips to the gas station," January 2007. [Online]. Available: http://media.gm.com/servlet /GatewayServlet?target=http://image.emerald.gm.com/gmnews/view monthlyreleasedetail.do?domain=74&docid=31656.

[34] Electric Auto Association – Plug-In Hybrid Electric Vehicle, "Plug-in hybrids," December 2007. [Online]. Available: http://www.eaa-phev.org/wiki/Plug-In_Hybrids.

