Plug-In Hybrid Electric Vehicles as a Source of Distributed Frequency Regulation

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ABSTRACT

The movement to transform the North American power grid into a smart grid may be accomplished by expanding integrated sensing, communications, and control technologies to include every part of the grid to the point of end-use. Plug-in hybrid electric vehicles (PHEV) provide an opportunity for small-scale distributed storage while they are plugged-in. With large numbers of PHEV and the communications and sensing associated with the smart grid, PHEV could provide ancillary services for the grid. Frequency regulation is an ideal service for PHEV because the duration of supply is short (order of minutes) and it is the highest priced ancillary service on the market offering greater financial returns for vehicle owners.

Using Simulink a power system simulator modeling the IEEE 14 Bus System was combined with a model of PHEV charging and the controllers which facilitate vehicle-to-grid (V2G) regulation supply. The system includes a V2G controller for each vehicle which makes regulation supply decisions based on battery state, user preferences, and the recommended level of supply. A PHEV coordinator controller located higher in the system has access to reliable frequency measurements and can determine a suitable local automatic generation control (AGC) raise/lower signal for participating vehicles.

A first step implementation of the V2G supply system where battery charging is modulated to provide regulation was developed. The system was simulated following a step change in loading using three scenarios:

1. Central generating units provide frequency regulation,
2. PHEV contribute to primary regulation analogous to generator speed governor control, and
3. PHEV contribute to primary and secondary regulation using an additional integral term in the PHEV control signal.

In both cases the additional regulation provided by PHEV reduced the area control error (ACE) compared to the base case.

Unique contributions resulting from this work include:

- Studied PHEV energy systems and limitations on battery charging/discharging,
- Reviewed standards for interconnection of distributed resources and electric vehicle charging [1], [2],
- Explored strategies for distributed control of PHEV charging,
- Developed controllers to accommodate PHEV regulation, and
- Developed a simulator combining a power system model and PHEV/V2G components.

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LIST OF ACRONYMS

ACE	Area control error
AER	All-electric range – the distance a plug-in hybrid electric vehicle can drive using only electrical energy
AGC	Automatic generation control
AMI	Advanced metering infrastructure
BMS	Battery management system
CAISO	California Independent System Operator
CI/CV	Constant current/constant voltage charge profile typically used for Li-Ion battery charging; Commonly denoted CI-CV or CC-CV in literature
DCPF	DC power flowDER Distributed energy resources – including power generation and energy storage
DMS	Distribution management system
DOD	Depth-of-discharge of a battery, obtained by subtracting the SOC from 100
DR	Demand response
EPRI	The Electric Power Research Institute
EMS	Energy management system
EPS	Electric power system
ETS	Energy transfer system – includes both the vehicle and EVSE [1]
EV	Electric vehicle – a vehicle in that operates using only electrical energy stored in a battery system

EVSE	Electric vehicle supply equipment – "The conductors, including the ungrounded, grounded, and equipment grounding conductors, the electric vehicle connectors, attachment plugs, and all other fittings, devices, power outlets, or apparatuses installed specifically for the purpose of delivering energy from the premises wiring to the electric vehicle. [3]"
HEV	Hybrid gasoline electric vehicle whose battery is charged by the internal combustion engine or through regenerative braking
ICE	Internal combustion engine
ISO	Independent system operator
Li-Ion	Lithium-ion battery
LDV	Light duty vehicle – classification includes cars, light trucks, SUVs, minivans and trucks with gross vehicle weight less than 8,500 pounds
MIC	Monitoring, information exchange, and control
MPCA	Minnesota Pollution Control Agency
NiMH	Nickel metal hydride battery
NYISO	New York Independent System Operator
PCC	Point of common coupling - the point where the Area EPS and Local EPS (site where DER are connected) interconnect [2]
PHEV	Plug-in hybrid electric vehicle – a hybrid gasoline electric vehicle whose battery energy capacity is large enough to drive tens of miles using only electric energy and that charges from the power grid
PHEV XX	A plug-in hybrid electric vehicle with a particular all-electric range, which is denoted by XX, i.e. PHEV 20 denotes plug-in hybrid with 20 mile all-electric range
PJM	A regional transmission operator located in Norristown, Pennsylvania

ROC	Rate-of-charge of the battery
RTO	Regional transmission organization
SAE	Society of Automotive Engineers
SCADA	Supervisory control and data acquisition system – system for gathering measurement data from the power grid to be used by utilities, ISOs, etc.
SOC	Battery state-of-charge – expressed as a percentage of rated Amp-hour (Ah) capacity
SOH	Battery state-of-health – a subjective estimate of general battery health and usable lifetime compared to a new battery based on various parameters
V2G	Vehicle-to-grid – the capability for two-way energy flow and two-way communications between an EV or PHEV and the grid; Communications may be available between the vehicle and the system operator or utility business units, or any external stakeholder

1 INTRODUCTION

Plug-in hybrid electric vehicles (PHEV) are basically hybrid gasoline electric vehicles similar to those available today, but with a bigger battery and a cord to plug in for charging. The increased battery size provides greater energy storage so that a PHEV can be driven tens of miles using only electrical energy, with a typical all-electric range (AER) of twenty plus miles. Due to the increased energy storage capabilities of the battery, the batteries can no longer be recharged using the combustion engine and regenerative braking alone as in standard hybrid vehicles. Therefore the cars must plug in to recharge their battery system using grid electricity, thus the name plug-in hybrid electric vehicle.

PHEV have many advantages when compared to conventional vehicles[1] including the following:

- The average American drives less than 40 miles a day and therefore could use electrical energy for the majority of daily driving,
- Substantial fuel savings as a result of reduced gasoline consumption,
- Reduced primary energy consumption
- Substantial CO_2 emissions reductions, and
- Decreased dependence on foreign oil supplies.

In addition the continued development of advanced batteries, in particular Lithium-Ion technologies, has enabled feasible PHEV design. In order to provide the power and energy necessary to drive a vehicle using only electrical energy a large and heavy battery system must be integrated into the vehicle. Lithium-ion (Li-Ion) technologies are much lighter than traditional nickel metal hydride (NiMH) hybrid electric battery systems.

[1] Conventional vehicle refers to vehicles that use an internal combustion engine running on gasoline to provide all of the power and energy needed for driving.

Significant penetration of PHEV raises the question of whether the North American power grid can handle a large scale penetration of charging vehicles. In 2007 Pacific Northwest National Laboratory conducted a feasibility study to determine whether sufficient generating capacity exists to charge large numbers of PHEVs [4]. The study showed that the national power grid has the technical potential to support charging of 73% of light-duty vehicles[2] (LDV) in the U.S. Therefore, this is not an issue that will impede large scale use of PHEV in the near future. Chapter 2 provides a general discussion of the energy storage capacity and charging needs of PHEV battery systems.

Major automakers have attempted to commercialize electric vehicles (EV) in the past with limited success, for example the EV1 produced by General Motors in the early 1990's. However, increasing environmental concerns, rising gasoline prices and the desire to reduce oil consumption in the U.S. are key drivers in the current effort to commercialize PHEV and pure electric vehicles.

1.1 Motivation

Recently, distributed energy resources (DER) in the form of generation and energy storage have gotten a lot of attention in the power industry. DER come in many shapes and sizes and may be owned by utilities, system operators, or even utility customers. Once connected there are numerous ways in which DER can support normal and emergency grid operations, for example by providing spinning reserves or smoothing variable renewable generation resources. The integration and control of DER present many unique opportunities and challenges in grid operations. In particular, DER are typically connected at the distribution system level which presents the following issues:

1. Operators cannot "see" and therefore cannot control assets at this level, and
2. Distribution systems are not designed for power flow back to the transmission grid.

[2] The light-duty vehicle classification includes cars, light trucks, SUVs, minivans and trucks with gross vehicle weight less than 8,500 pounds.

Currently there are efforts under way to facilitate the interconnection of these resources along with modernization of the transmission and distribution system along with consumer services. One of the most significant changes with regards to infrastructure in the power grid is the addition of a two-way communications system that would reach from the control center down into every part of the power grid including into homes. This allows assets at all levels of the system, down to the end user to be monitored and controlled. In addition, digital electronics are increasingly being used in monitoring and control devices throughout the grid. These distributed processors enable large-scale integration of computational capabilities and intelligence throughout the system leading to a smart grid.

Transitioning to a smart grid provides increased opportunities for advanced communications, automation, and intelligent appliance control. These will enable increased efficiency throughout the system and better integration of distributed energy resources with the goals of a more secure, intelligent, and sustainable system. The spectrum of smart grid technologies includes:

1. Automated meter reading (AMR) and two-way advanced metering infrastructure (AMI),
2. Advanced sensing and communication infrastructure with cyber security and privacy provisions built in,
3. Standards for components, software, hardware and systems to interoperate seamlessly and securely,
4. Integration of distributed renewables into the grid along with storage (e.g. plug-in hybrid electric vehicles), and
5. Business models for end-use consumer integration.

As visibility and active control move towards the end user it will be infeasible for control centers to handle the computations and resulting information associated with monitoring the entire power system. The concurrent development of two-way communications and wide-scale integration of intelligent devices facilitates the use of a distributed control architecture to provide localized autonomous self-healing control. A power network with these infrastructure enhancements along with the resulting (and necessary) changes in grid monitoring and control capabilities is called a smart grid. A smart grid would provide the means necessary to control PHEV charging by simply delaying charging during periods of high demand or by using a more complicated control strategy accounting for real-time energy pricing or local demand.

Knowing that the grid can support charging of PHEV, the benefits of distributed storage, and the capabilities of the smart grid, the next question is: What could the vehicles offer once they are out there and plugged in? The answer is distributed mobile storage. The capability for two-way energy flow and two-way communications between an EV or PHEV and the grid is referred to as vehicle-to-grid (V2G). This dissertation aims to address key questions when considering the use of PHEV as DER to provide local frequency control. The following section gives an overview of work being done with V2G, and frames the approach used in this study.

1.2 Related Work

Significant research has been done to design energy supply systems for plug-in hybrid electric vehicles that match the performance and lifetime expectations of conventional vehicles. As an example the Electric Power Research Institute (EPRI) has performed two studies to design hybrid electric vehicles (HEV) to match the physical characteristics and performance of several classes of vehicles from a compact car to a full-size SUV [5], [6]. Hybrid electric vehicles with all-electric ranges of 0, 20, and 60 miles were designed and simulated to compare greenhouse gas emissions, and fuel efficiency and costs. The studies also look at the cost of producing and owning the hybrid vehicles Overall the studies showed that in fact HEV and in particular PHEV can be designed to provide the performance that people expect of standard combustion engine vehicles [5], [6].

Axsen, et al. from the University of California, Davis, discussed PHEV battery goals determined by the U.S. Advanced Battery Consortium (USABC), the Sloan Automotive

Laboratory at MIT, and EPRI in [7]. The report discusses the organizations' underlying assumptions and how the battery goals compare to the power and energy capabilities of Nickel Metal Hydride (NiMH) and Lithium-Ion (Li-Ion) battery chemistries. The goals for battery design which were evaluated include the following: peak power, energy capacity, calendar life, charge depleting cycle life, and charge sustaining cycle life. The operating modes of PHEV (charge sustaining and charge depleting) along with the battery design goals discussed in [7] are discussed further in Chapter 2.

Numerous studies have evaluated the environmental impacts of PHEV with a variety of results. The results of environmental studies depend on the location being considered and the underlying assumptions and methodologies used. As an example, the Minnesota Pollution Control Agency (MPCA) performed a study in 2007 to determine the impacts of varying penetrations of PHEV on greenhouse gas emissions in the state of Minnesota in 2020 [8]. PHEV with all-electric ranges of 20 and 60 miles were included in the study. The results of PHEV modeling were compared to traditional hybrid electric vehicles (HEV) and conventional combustion engine vehicles. Several generation mixes were considered with an assumed penetration of coal generation and wind generation (which includes nuclear generation). Coal was used to represent the entire thermal generation mix and other fossil-fueled generation (e.g. natural gas) was not broken out. The study concluded that PHEV produce less greenhouse gas emissions except in the case of SO_2 compared to conventional vehicles. With the simplified assumptions about Minnesota's generating mix they also found that PHEV produce slightly more CO_2, less than a tenth of a percent, than traditional HEV with a 60% coal 40% wind generation mix. If natural gas and petroleum generation where represented in the generation mix, it is likely that the simulations would result in PHEV producing less CO_2 than the PHEV. The significant increase in SO_2 emissions with PHEV is due to the fact that the majority of the power produced in Minnesota is coal based.

EPRI also performed an environmental study with the Natural Resource Defense Council in 2007 to determine the impacts that PHEV will have on greenhouse gas emissions [9]. The study looked at the impacts that PHEV will have over the period of 2010 to 2050 assuming varying levels of PHEV penetration and greenhouse gas content of the power generation mix. The study found that in all cases greenhouse gas emissions can be reduced as PHEV are phased-in over the study period when compared to conventional vehicles and traditional HEV. These results are particularly compelling considering that a low, medium, and high CO_2 generation mixes were considered, and in each case significant emission reductions were found. Both the EPRI and MPCA studies consider well-to-wheels emissions which includes emissions resulting from fossil fuel processing and delivery and electricity generation.

1.2.1 Interconnection and V2G

Several organizations are guiding the development of communications standards and standards necessary for PHEV connection to the grid for charging and V2G. In addition the University of Delaware (UD) and the University of Michigan currently have V2G research programs in place.

The program at UD has focused primarily on determining the economic payback that may be possible when using EV or PHEV to supply ancillary services [10]. Professor Willett Kempton, the lead PI for UD's V2G program owns a Scion xB which was converted by AC Propulsion to an all-electric vehicle called the eBox. The conversion includes AC Propulsion's proprietary electric drive train technology, tzero™, and the Lithium-Ion battery module and energy management system. Recently UD has begun to study the use of the eBox as a regulation resource which can be dispatched by PJM [11].

1.2.2 Ancillary Services

Several organizations are looking at the use of storage to provide frequency regulation services in place of central generation. Due to the smaller size and distributed nature of storage when compared to central generation assets, the way in which regulation needs are determined and met needs to be revisited.

The California ISO (CAISO) issued a white paper in May of 2008 discussing the integration of storage technologies into the grid [12]. The paper discusses the interconnection of storage assets at various levels of the power system in terms of present interconnection requirements, services they could provide, and asset ownership. In addition the opportunities and shortcomings of current energy and ancillary service markets are discussed. Of particular interest is a brief discussion of storage providing fast frequency regulation and which control signal responsive loads and storage should follow to provide regulation. Currently regulation dispatch is based on both frequency and tie-line power flow deviations; due to the unique characteristics of storage compared to generators, an AGC control signal may not be the most effective way to control storage assets.

In June of 2008 KEMA did a study on the use of energy storage as a fast regulation supply for The AES Corporation [13]. The study used dynamic simulations of CAISO, NYISO, and PJM including automatic generation control (AGC) and real time markets to determine the effects of using storage for regulation. The area control error (ACE), a filtered ACE and reference set point changes for machines on AGC were each considered as control signals for the storage systems. The impact on system performance and the economic payback when using storage for regulation were analyzed to determine whether storage is appropriate and viable as a regulation resource in the three systems. The study found that when providing the same amount of storage (MW) controlled using the filtered ACE signal resulted in improved system ACE performance compared to conventional generating units responding to AGC. With storage used for a portion of the regulation services, the conventional units were subjected to fewer raise and lower commands which results in less wear and tear on the conventional units. In addition asset utilization of conventional units can be increased if a larger amount of regulating reserve were provided by alternative means.

1.3 Objectives

Compared to the work being done by the team at UD this study takes an approach looking at the problem from a holistic smart grid point of view as opposed to looking at how V2G will operate in today's central-control based system. As the grid is modernized and monitoring and control are increasingly and necessarily decentralized, the role of V2G will need to change. PHEV will move from being a resource that is dispatched centrally to a resource that is utilized as a part of a local energy system. Therefore, in order to obtain results that may be useful with large penetrations of PHEV and when the necessary V2G infrastructure is widely implemented, the problem must be studied with the following in mind:

1. It will not be feasible for system operators to dispatch services over individual vehicles therefore the services must be dispatched locally, and
2. It is not feasible for local controllers to know the state of the entire system therefore the ancillary service needs must be determined based on local operating conditions.

Vehicle-to-grid may not come to fruition as envisioned here, for example due to a lack of consumer interest in V2G participation or if PHEV are not widely adopted in the first place. However, the role of PHEV as DER could also be filled by other forms of distributed storage such as banks of batteries in people's homes which are just as feasible especially with the advent of rooftop solar panels. However, PHEV is a more realistic starting point for an energy storage discussion in today's power system since the vehicles will be coming online in the near future. Using characteristics of PHEV currently being developed allows realistic constraints to be placed on the storage model. Because PHEV are a special case of distributed battery storage, these results can be readily extended to any type of storage that may be suitable for frequency control.

For the sake of this study and in light of the fact that specific standards for communications and interconnection will continue to develop and evolve, these topics are not considered here. Rather, key questions relating to how PHEV could feasibly and effectively supply distributed frequency control are addressed. The following questions are of particular interest for practical implementation and were used to determine the objectives of this study:

1. How could distribution system planning and design be impacted as PHEV penetration increases?
2. Without knowledge of the entire system, what local operating parameters should be used to determine what the PHEV should supply?
3. What impact will this have on the lifetime of the battery packs?

This dissertation aims to address these questions with the following objectives:

- Determine general approach that may be used to find the appropriate amount and duration of power which will contribute to bulk system frequency control, and
- Characterize aggregate PHEV regulation supply based on supply duration and limits on changes to individual charge rates.

The results will be used to determine how appropriate PHEV are for providing distributed frequency control. In addition the impacts on battery charging and consequently vehicle drivability can be used to inform vehicles owners as they decide if and how much they would like to participate in supplying frequency regulation through V2G.

1.4 Simulation

The Electric Power Research Institute (EPRI) released an open source version of their Distribution System Simulator, OpenDSS, in November of 2008. OpenDSS can be used as a stand-alone simulator or can interface with other programs through a COM DLL. The simulator allows users to create distribution system models and can be used to perform RMS steady-state analyses. There are features built in that were originally developed to support analysis of the integration of distributed resources at the distribution level. The simulator, source code, and references and updates are available from the OpenDSS wiki site at [14].

However to study the effects of PHEV as a source of regulation, the real power response of central generation due to changes in system loading and determination of the automatic generation control (AGC) raise/lower commands are necessary. Due to the fact that the distribution system is typically modeled using a three phase power flow and the lack of generator speed dynamics within OpenDSS, it was determined that a different modeling approach was needed.

Instead a power system simulator initially developed by the author as a Master's thesis project is used for simulations [15]. Additional functionality has been added to the simulator since initial completion in May of 2006, along with modifications to handle the unique timing issues involved with hybrid Simulink-MATLAB models. The IEEE 14 Bus System is used to carry out the simulations.

This power system simulator is augmented with additional controllers used to determine the amount of frequency regulation that may be supplied by local PHEV. In addition PHEV loading is modeled as an aggregate load at each of the 11 load buses in the 14 bus system. As a first step the PHEV supply frequency regulation simply through modulation of their charge rate while they are plugged in to recharge. This scenario minimizes the impacts on the battery cycle life and health compared to allowing both charge modulation and discharge of the battery system. In addition the impacts on the vehicle owner are minimized when only modulating charging.

1.5 Document Structure

Chapter 2 provides an overview of plug-in hybrid electric vehicles (PHEV) with a focus on the battery system and relevant Society of Automotive Engineers Standards for electric vehicle charging system. Vehicle-to-grid is discussed in Chapter 3 in terms of current standards for interconnection of distributed energy resources (DER) and the supply capabilities of PHEV as DER.

As a base the power system simulator originally developed in [15] will be combined with additional components to simulate the use of aggregate PHEV as a source of distributed frequency regulation. The general strategy and design of those additional components is outlined in Chapter 4. Chapter 5 provides a full description of the power system simulator including the aggregate PHEV load models and associated control components.

Simulation results are presented in Chapter 6 along with a discussion of the results and next steps for modeling work. Chapter 7 concludes with a discussion of the implications of this work and a look at the opportunities for future expansion of the modeling and simulator.

Appendix A contains data for the IEEE 14 Bus System which was used in the simulations discussed in Chapter 6. The MATLAB code for the IEEE 14 Bus System network model and DC power flow function is included in Appendix B. In addition to the basic control agents developed for V2G control, an extended agent development is presented in Appendix C.

2 PLUG-IN HYBRID ELECTRIC VEHICLES

A plug-in hybrid electric vehicle (PHEV) is a hybrid electric vehicle whose battery energy storage capacity is large enough to drive a number of miles using only electric energy and which charges from the power grid. The Electric Power Research Institute (EPRI) has performed studies to determine the energy and power ratings are necessary for different classes of PHEVs to perform similarly to their traditional hybrid electric vehicle[3] (HEV) and conventional vehicle[4] (CV) counterparts. In addition they looked at vehicle design across different all-electric-ranges (AER), specifically: 0 miles, 20 miles, and 60 miles [5], [6]. An example of a hybrid electric vehicle with a 0 mile AER is the current version of the Toyota Prius. The all-electric range of a particular vehicle is denoted by PHEV XX, where XX denotes the number of all-electric miles.

Most PHEV being designed today are able to drive at speeds up to about 60 mph using battery power alone. Beginning with a full battery, a PHEV will drive in charge-depleting mode using only electrical energy whenever possible until the battery reaches about 20%-50% state-of-charge (SOC), which is a typical threshold range for charge-sustaining mode. In charge-sustaining mode the PHEV will manage energy like today's hybrid electric vehicles to keep the state-of-charge close to this threshold. In this mode smaller amounts of electric energy provide a power boost when accelerating and this energy is then recovered through regenerative braking or power from the combustion engine while coasting or idle.

Another option for PHEV design is to use blended operation where both the battery and the combustion engine operate, while in the charge depleting mode. These vehicles technically do not have an all-electric range, although they will have a number of miles

[3] Traditional hybrid electric vehicle refers to hybrid gasoline-electric vehicles that have a 0 mile all electric range and do not charge from the grid. Hybrid electric vehicles also include vehicles with an electric battery system paired with a diesel engine or fuel cell.
[4] Conventional vehicle refers to vehicles that use only an internal combustion engine.

operating in blended charge-depleting mode before entering charge-sustaining mode once the minimum SOC has been reached. In this case the PHEV XX notation will denote the number of miles the vehicle is expected to operate in charge-depleting mode.

PHEV offer saving in several areas compared to their HEV and CV counterparts. Based on EPRI data, the primary energy and fuel cost savings possible with various classes of PHEV are shown in Table 1. Primary energy refers to energy contained in natural resources (both renewable and non-renewable) which are then typically transformed into a more useful form of energy such as electricity or heat energy. The environmental benefits of PHEV have been studied by several organizations and will not be discussed at length here; the reader is referred to [8] and [9] for further information.

Table 1
PHEV Savings Compared to Equivalent Conventional Vehicles

Vehicle Class	Primary Energy Savings		Fuel Cost Savings[5]	
	PHEV 20	PHEV 60	PHEV 20	PHEV 60
Compact Sedan	42%	56%	30%	34%
Mid-Size Sedan	46%	60%	35%	39%
Mid-Size SUV	48%	62%	37%	43%
Full-Size SUV	50%	64%	40%	45%

Sources: [5], [6] , Table 5.6.A [16], [17], and Tables A2 and G1 [18].

There are several contributors to the increased efficiency of PHEV compared to conventional internal combustion engine (ICE) vehicles. The biggest factor in the substantial energy and fuel cost savings in PHEV is the fact that electric motors are much more efficient than internal combustion engines. In a conventional vehicle, the ICE is largely operated outside of its maximum efficiency range to meet the power and energy demands under all driving conditions. While a PHEV is operating in charge sustaining mode both the engine and the battery system operate in tandem. The engine is used mainly to meet the base power and energy requirements while the battery contributes in

[5] Based on a national average of $1.78 per gallon of gasoline and 12 cents per kilowatt-hour for electricity.

the form of power boosts when needed, for instance when driving up hills. This means that the engine can be run closer to its optimum efficiency leaving the battery to pick up the slack. Besides increasing the efficiency of engine operations, fewer gears are needed which simplifies the vehicle drive system.

In addition, advanced control techniques used to determine the mix of electrical and engine power used to drive the PHEV. Finally the recovery of energy during braking or while surplus power is available from the engine (e.g. while driving down a hill) further increases the efficiency of PHEV compared to conventional ICE vehicles.

The most important function when vehicles are parked and plugged in is battery charging, and currently this is the primary interaction between PHEV and the power grid. There are two types of charging that are compatible with how the grid is currently operated:

1. "Dumb" charging – vehicle plugs in and the electric vehicle supply equipment (EVSE) supplies maximum available charge current until charging is complete or vehicle is unplugged, and
2. Smart charging – one way communications from utility or third party to PHEV to control when charging starts, interrupt charging to curtail energy consumption, or control the charge rate in a demand response scenario.

Dumb charging may be referred to as V0G, and smart charging as V1G where the one signifies one way communications and/or control. Smart charging allows vehicle charging to be controlled by an external source. This may be the utility delaying charge to periods of low demand, the owner setting rules for charging, or even a third party controlling a group of vehicles based on a utility's desired load curve. Utility control of charging would be a demand response program and one drawback of demand response with only one-way communications is that there is no way for the utility to tell if there has been a change. As a simple example, if the utility needs to decrease system loading they could send a signal to PHEV to stop charging, but without a return communications path they won't know how much power was actually saved. They wouldn't know how much a vehicle was consuming to begin with and they won't know if the PHEV actually responded to the signal.

As the smart grid develops, the capability for two-way communications and energy flow will make vehicle-to-grid (V2G) another option for control of PHEV charging. V2G allows PHEV and pure electric vehicles to supply energy back to the grid to provide a number of services. In addition with two-communications actual PHEV energy consumption can be tracked which overcomes the issue of not knowing if and how much the loads are responding to utility control signals.

PHEV being developed by major automakers for release in the next few years are designed to simply charge when plugged in without additional interaction with the grid. Additional hardware must be added to a PHEV to allow external control of charging and to allow bidirectional power flow, and there are a few companies that have developed the equipment to do this. As mentioned in Chapter 1 the infrastructure to support widespread V2G is a ways down the road. Opportunities for V2G enabled PHEV are discussed in more detail in Chapter 3.

The following sections discuss PHEV battery systems, the components and functional requirements of current energy transfer systems (ETS), and the impacts that PHEV may have on the power grid.

2.1 Battery System

The battery systems of PHEVs have two main components the battery management system (BMS) and the battery pack. The BMS monitors the battery state and health, and provides an interface between the battery and the rest of the vehicle including the on-board charger. The BMS may also handle energy management while the vehicle is operating based on the power and energy needs of the drive train. The following sections describe the battery system, the BMS, and several options for charging systems.

2.1.1 Lithium-Ion Battery Pack

A PHEV battery pack includes several interconnected battery modules, which in turn are comprised of individual battery cells connected in series and parallel. The battery chemistry which is most viable for PHEV applications is lithium-ion (Li-Ion) primarily because the energy and power density is several times greater than nickel metal hydride (NiMH) batteries which have been common in hybrid vehicle design until recently. It is only in the last few years that advances in Li-Ion technologies have made them viable for vehicle use when compared to more mature chemistries such as NiMH.

Li-Ion has a clear advantage when designing PHEV battery packs that preserve the size and weight of their conventional vehicle counterparts. To begin with, the cell voltage of Li-Ion is about three times the cell voltage of NiMH. In order to provide the same voltage, a series connection of three NiMH cells would be necessary, which means that fewer cells are needed to provide the same voltage simplifying battery system design. Also, the higher energy density per unit volume of Li-Ion chemistries allows for smaller and lighter battery systems compared to NiMH.

In addition Li-Ion batteries do not suffer from memory problems and have a low self-discharge rate of about 5% a month compared to other battery chemistries which may lose up to 1% a day through self-discharge. Finally the charging/discharging efficiency of Li-Ion batteries is largely independent of the charge rate or battery temperature. This is particularly important when used in PHEV that use only electricity in charge depleting mode where the power demands on the battery vary widely and change rapidly.

A PHEV battery pack is sized primarily to meet the energy and power needs when driving in the all-electric range. The energy storage requirements that EPRI found for four classes of PHEV with 20 and 60 mile all-electric range are shown in Figure 1.

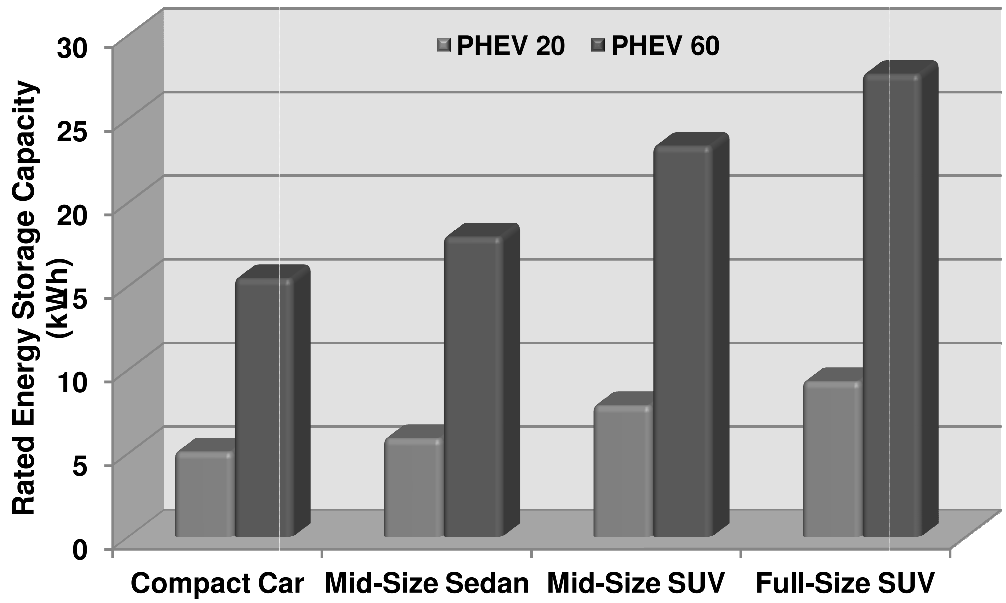

Figure 1
Comparison of Total Battery System Energy Capacity by Vehicle Class and All-Electric Range

Sources: [5] and [6].

Although the battery pack is rated at a certain energy capacity, there will be a minimum allowable state-of-charge (SOC) to prevent damage to the battery and prolong battery lifetime. The difference between the maximum and minimum SOC is referred to as the usable state-of-charge. Depending on the battery design and vehicle design this usable SOC will typically be in the range of 50% to 80%. Note that the storage capacities presented in Figure 1 represent total storage capacity.

A PHEV will operate in charge-depleting mode until the usable SOC has been consumed, and in terms of discharge/charge cycles would be considered a deep cycle[6]. Battery systems currently being developed for PHEV are designed to have a cycle life of 3,000 deep cycles or more. This means that if a vehicle maxes out its all-electric range nearly every day and charges fully overnight, the battery system should last for about 10 years or more. A battery's useful lifetime for PHEV applications is typically measured at the point where its usable SOC is less than 80% compared to a new battery, or when it is able

[6] A full cycle will include the recharging associated with discharging the usable SOC.

to supply less than 80% of the peak power required for vehicle operation. Battery lifetime is discussed further in the next section.

Li-Ion technologies continue to improve through the use of new materials for the cathode and anode and in particular the use of nanotechnology. As an example Toshiba has developed the SCiB™ battery that can be charged with currents up to 50 Amps which allows the battery to recharge to 90% of full capacity in 5 minutes. The battery also has a low annual capacity loss which contributes to its cycle life of over 6,000 cycles[7]. The SCiB™ is being used by Cannondale Sports Group in an electric bicycle called the Tailwind, and there are plans for electric vehicle applications in the future [19]. The reader is referred to [7] for a brief overview of Lithium-Ion battery chemistries that are being considered for use in PHEV along with several references for more detailed information.

2.1.2 Battery Lifetime

The lifetime of a battery system may be expressed in terms of cycles or years, and is measured according to some end of life criteria. In the context of this report the lifetime will be discussed in terms of its service life as a vehicle energy supply. As mentioned earlier a common measure of end-of-life as a PHEV energy supply is when the usable state-of-charge or the peak power capabilities fall below 80% of their rated values. Factors that impact the cycle and calendar life of a PHEV Li-Ion battery system include: storage temperature, charge/discharge temperature, overcharging, actual drive cycles, and the owner's driving style.

Battery systems for vehicle applications are designed to have the same cycle and calendar life expected of a conventional vehicle. This is typically 10-15 years, and includes the effects of deep cycling associated with the charge-depleting mode and the effects of shallow cycling associated with charge-sustaining mode. Several organizations have done studies to set goals for PHEV battery system cycle life in terms of deep and shallow

[7] These battery specifications are based on laboratory testing and may vary by application.

cycles [7]. The results depend on assumptions about vehicle design and operating conditions over the lifetime of the battery system. Table 2 compares the cycle lifetime and calendar life goals for PHEV batteries set by the US Advanced Battery Consortium (USABC), the Sloan Automotive Laboratory at the Massachusetts Institute of Technology (MIT), and EPRI.

Table 2
Comparison of PHEV Battery Lifetime Goals

Lifetime Metric	USABC		MIT	EPRI	
Charge Depleting Range	10 miles	40 miles	30 miles	20 miles	60 miles
Calendar Life	15 years	15 years	15 years	10 years	10 years
Deep Cycles	5,000	5,000	2,500	2,400	1,400
Shallow Cycles	300,000	300,000	175,000	< 200,000	< 200,000

Source: Table 2 [7].

Each of the vehicles compared in Table 2 are midsize cars except for the USABC PHEV with a 10 mile range, which represents a crossover SUV. Also, MIT designed the PHEV to operate using both electricity and gasoline (blended operation) while in charge-depleting mode instead of all-electric as was assumed by USABC and EPRI. The goals were determined without assuming a specific battery chemistry, rather the battery goals dictate which chemistries are viable to meet the needs of PHEV. The full report gives more details about the assumptions made by each of the organizations and gives some insight into the different goals they have set for PHEV battery system design [7].

Once a vehicle's energy pack is no longer viable for use in a PHEV, the pack may be repurposed and used in stationary storage applications increasing its total usable lifetime while supporting grid operations. This will reduce the amount of batteries needing to be recycled and also provides vehicle owners with an opportunity to recoup some of the costs associated with battery powered vehicles.

Several studies have been done to assess the feasibility of reusing EV/PHEV batteries in stationary applications at the end of their useful lifetime in vehicle applications, including a study by Sandia National Labs performed in 2003 [20]. The study looked at the technical feasibility in terms of power, energy, and duration requirements. In addition the economic feasibility of the applications was determined in terms of the cost to prepare the batteries for stationary applications, the buy-down for new EV batteries, and life cycle costs. The study found that it would be possible to use repurposed EV batteries for transmission support and light commercial load following, and found that residential load following presented a favorable application. Although the study was largely independent of the specific battery chemistry used, lithium-ion was not considered in detail because Li-Ion technologies were not as well developed when the study was conducted in 2003 as they are today.

2.1.3 Battery Management System

In general the battery management system (BMS) will track the battery's state, monitor the battery's health, and communicate with other vehicle or energy supply systems where appropriate. The BMS will interact with or may be integrated into the PHEV's energy management system. In addition the BMS may perform myriad functions and incorporate varying degrees of intelligence into its operation. For the purpose of this study it is not important how energy is handled while driving, instead the battery's state and associated energy characteristics are of primary importance. Table 3 describes various parameters that the BMS may track.

Table 3
Parameters of Interest in a PHEV Battery System

Parameter	Units	Description
Rated capacity	Ah	Total ampere-hours available in fully-charged battery for a specified set of test conditions
C/N rate	A	Constant current which will drain the battery in N hours, also used for charge rate. Example: 100 mAh battery discharged at C/2, would discharge fully in 2 hours with discharge current of 50 mA.
Voltage range	V	Allowable range of operating voltages
End of charge voltage	V	Voltage limit at which point constant voltage charge cycle changes to the constant voltage portion
Cutoff voltage	V	Minimum voltage allowed when discharging battery
Cutoff current	A	Charging is cutoff when current falls to this level
State-of-charge (SOC)	%	Ratio of Ah capacity remaining in the battery to its nominal rated capacity
Battery temperature, T	°C	Internal temperature of the battery.
Ambient temperature, T_a	°C	Temperature of battery's surroundings.
Internal resistance, R_{int}	mΩ	Equivalent internal battery resistance
Vehicle range	Miles	Based on SOC and additional data such as energy used and miles driven since last charge
History	-	Log of historical data, may include cycle count, and maximum/minimum of various parameters
Cycle count	Cycles	Running count of discharge-recharge cycles
State-of-health (SOH)	-	Estimate of general battery health and usable lifetime compared to new battery

While most of the parameters in Table 3 will be the same no matter what BMS is used, the history log and the state-of-health will vary depending on the implementation and user needs. There is no standard measure of the SOH, rather it is defined based on user preferences and is calculated based on factors such as the cycle count and internal resistance, etc.

Various strategies may be used to determine a battery's SOC, each of which has its benefits and shortfalls. The BMS may employ more than one method and may use a look up table to determine the stepwise performance of the battery based on current operating conditions. In addition advanced techniques such as Kalman Filters or Neural Networks may be incorporated into the determination of the SOC. A related parameter that is commonly used when discussing batteries is the depth-of-discharge (DOD) expressed as a percentage. The DOD is not determined directly, it is calculated by subtracting the state-of-charge from one hundred.

2.1.4 Charging Behavior

The power needed to charge PHEV will vary based on the specific battery pack and charging equipment and therefore it is desirable for the vehicle to control battery charging; currently charging systems will by default provide the maximum available current [3]. However the functionality detailed in SAE J2293-1 allows for the vehicle to control charging and also allows the utility to limit charging through a load management system [1].

The charge rate (A) will vary depending on the charge profile, for instance a battery pack may be charged using a simple constant current or constant voltage profile. However in general a combination of these will be used, and will vary by battery technology and manufacturer. In addition different charging strategies may be used throughout a single charge session as battery parameters reach thresholds or to improve the health of the battery. For instance SAE J1715 Hybrid Electric Vehicle and Electric Vehicle Terminology report includes definitions for finishing charge rate, float charge, and trickle charge [21].

Lithium-Ion batteries are typically charged using a combination of constant current and constant voltage profiles, denoted CI/CV. To begin with a constant current is applied while the voltage rises to its upper limit at which point the voltage must be held constant to avoid damaging the battery. During the constant voltage segment the charge current will begin to decrease as the battery approaches a full state of charge. Finally charging will be cutoff when the current has reached a minimum threshold, for instance 3% of the rated current. A sample charge profile illustrating constant current/constant voltage charging is shown in Figure 2.

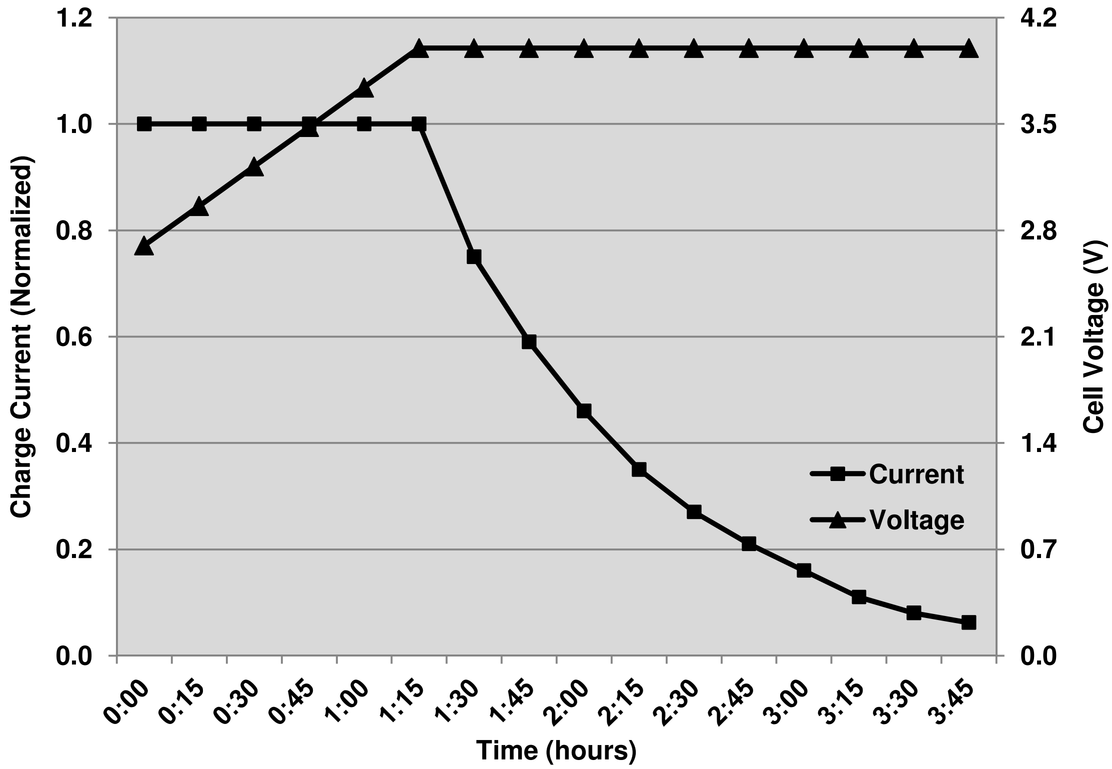

Figure 2
Sample Charge Profile for Lithium-Ion Batteries

For a single Lithium-Ion cell the maximum charging voltage will typically be limited to about 4 Volts or less, depending on the particular chemistry. An entire PHEV battery pack will have a nominal voltage of several hundred volts. The values for charge current in Figure 2 are normalized to show the general charge current trend, since the actual charge current will depend on the specific charge. In addition the charge time and cutoff current are somewhat arbitrary and will vary based on the actual charge rate and manufacturer specifications.

2.1.4.1 Charging Limits

A PHEV battery pack experiences very different power demands when used for vehicle propulsion than when recharging from the power grid. During driving cycles the power drawn from the battery pack varies greatly depending on the driving demands of the vehicle. This is particularly true of non-highway driving with frequent starts/stops and associated periods of heavy acceleration/deceleration where the power needs of a vehicle change frequently. For instance, a PHEV battery pack can go from supplying several kilowatts to absorbing several kilowatts in just a few seconds.

On the other hand, it is recommended to use the manufacturer's suggested charging profile, typically a constant current/constant voltage (CI/CV) profile, to maximize battery lifetime and health. Compared to driving demands when the power draw from the battery can change every few seconds the charging segments of the CI/CV profile may have a duration of several hours. To minimize impacts on battery health and lifetime, the on-board charge controller may also require a rest period between discharging and charging to allow for thermal equilibration and chemical relaxation.

Although charging characteristics depend on the specific Li-Ion chemistry, in general the charging efficiency of Lithium-Ion batteries particularly those used in PHEV drives is not as sensitive to changes in charge current or battery temperature as other chemistries.[8] With continuing advances in Li-Ion technologies it is feasible that the charge rate could be controlled in a manner similar to charge management during vehicle operation with little impact on battery health aside from additional cycling.

2.2 Energy Transfer System

SAE Recommended Practice J2293-1, Energy Transfer System Requirements for Electric Vehicles – Part 1: Functional Requirements and System Architectures, describes the current functional requirements of an electric vehicle Energy Transfer System (ETS) [1].

[8] Personal communication with Haresh Kamath, Senior Project Manager, Transportation and Stationary Energy Storage, EPRI.

The ETS is comprised of the Electric Vehicle (EV) and the Electric Vehicle Supply Equipment (EVSE). SAE committees are working on addendums to J2293 to include additional alternative fuel vehicles in addition to electric vehicles, namely plug-in hybrids and plug-in fuel cell vehicles. They are also considering topics such as V2G and reviewing communications mediums. Figure 3 illustrates the physical path and connections between the utility service point through the branch circuit and out to the ETS.

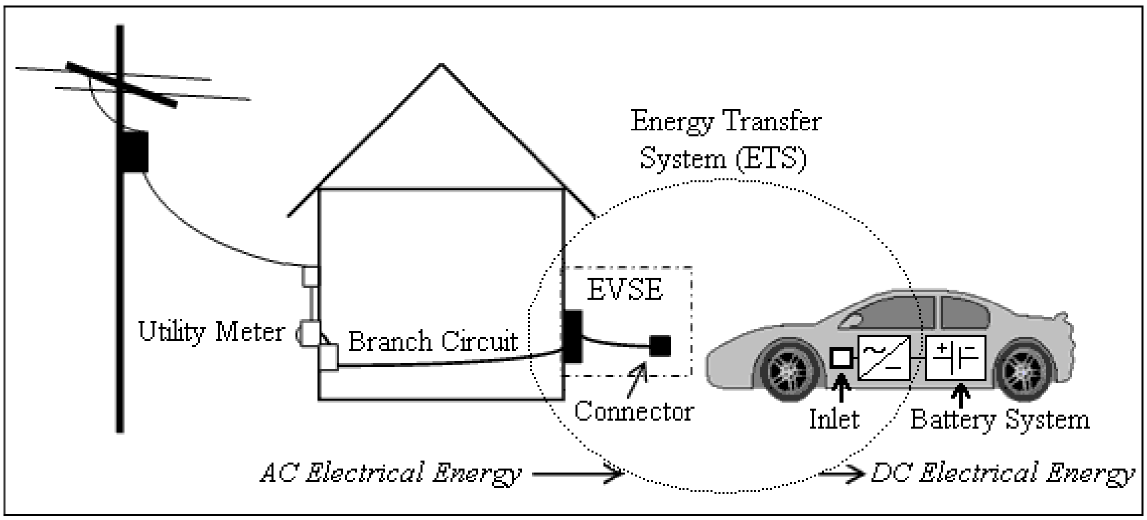

Figure 3
Electric Vehicle Energy Transfer Diagramvcv

Source: Adapted from figure 1 in [1].

The three major functions performed by the ETS are to: determine when the vehicle and EVSE are ready for energy transfer, switch and convert AC electrical power to DC, and control the transfer of energy to the vehicle [1]. These major functions are further decomposed into the following four categories or functional groups in [1]:

1. Utility Connection Services,
2. AC to AC Conversion,
3. AC to DC conversion, and
4. Energy Transfer Controls.

For AC charging systems the EVSE performs the functions necessary for utility connection services, while the conversion from AC to DC energy is performed on board the vehicle along with the energy transfer controls. For higher level charging systems, the EVSE will also convert the AC input to DC to be supplied directly to the battery system.

Conductive charging system classifications and communications within the ETS are discussed in the following sections. The SAE standards also address inductive AC charging systems; however inductive charging systems are not considered in this study.

2.2.1 Conductive Battery Charging Systems

Table 4 describes the characteristics of conductive electric vehicle charging classifications as recommended in SAE Recommended Practice J1722 for Electric Vehicle Charge Couplers [3].

Table 4
Comparison of SAE J1772 Standard Electric Vehicle Charging Systems

Classification	AC Level 1	AC Level 2	Level 3, DC
Nominal Supply Voltage	120 V AC	208 or 240 V AC	208 - 600 V AC
Phases	1-phase	1-phase or 3-phase	3-phase
Branch Circuit Breaker Rating	15 A	40 A	As required
Maximum Continuous Current	12 A	32 A	As required
Maximum Power Rating	1.4 kW	7.7 kW	25-160 kW
Charger Location (AC/DC Converter)	On-board	On-board	Off-board
Energy Supply/Interface	Charge coupler to NEMA 5-15R grounded receptacle	Dedicated Electric Vehicle Supply Equipment (EVSE)	Dedicated EVSE
Energy Supply Location	Home or any appropriate electrical outlet	Private or public	Private or public

Sources: [3] and [21].

J1772 covers both the charging system and the charge coupler. The charge coupler includes the vehicle inlet and the connector and includes all of the connections necessary for power flow, charge control, and data exchange (see Figure 3). Specifically there are nine physical connections: two for AC power flow, two for DC power flow, one for equipment ground, the control pilot line, two serial data lines, and a data ground. In addition, the coupler includes functionality for proximity detection when the connector is near the vehicle inlet.

The control pilot circuit is used to verify proper vehicle connection, grounding, and ventilation. After the EVSE verifies that everything is connected properly and that the EV is ready to begin accepting charge the control pilot will commence charging. As the vehicle charges the control pilot monitors the connections and will interrupt charging if there is an issue with EVSE or EV connection or if utility power becomes unavailable.

The EVSE will indicate the maximum current capacity available to charge the vehicle based on the branch circuit rating and EVSE rating. The vehicle's on-board charger is used in Level 1 and Level 2 charging to convert the AC input from the electric vehicle supply equipment (EVSE) into DC power to charge the battery. The serial data lines are optional for Level 1 and Level 2 charging which is controlled by the on-board charger. If the maximum allowable current changes based on mandates by an external load management system, the EVSE will modify the control pilot signal and the on-board charger must alter its maximum current draw.

For DC charging, an off-board charger located in the EVSE is used to rectify the AC supply and the DC output is supplied directly to the vehicle's battery. DC charging requires the use of serial communications to allow the vehicle to control charging. The off-board charger must respond to requests from the vehicle to increase or decrease the charge current which will be signaled by a change in pilot signal pulse width.

The location and purpose of the battery charger will largely dictate what type of charger is used. For instance when charging at home, AC Level 1 charging is ideal because a standard three-prong outlet is used and no additional equipment is needed. Levels 2 and 3 are ideal for public charging stations and include dedicated off-board electric vehicle supply equipment (EVSE) which acts as an interface between the electrical supply and the vehicle. If additional charging capability is desired Level 2 or Level 3 systems may also be installed in homes where service is adequate to meet the higher power needs of the EVSE.

2.2.2 Communications

The network and data communications requirements for communication among on-board vehicle components are outlined in SAE Standard J1850 Class B Data Communications Network Interface [22]. A J1850 network is also used for communications between the electric vehicle (EV) and electric vehicle supply equipment (EVSE). SAE Standard J2293-2, Energy Transfer System for Electric Vehicles – Part 2: Communication Requirements and Network Architectures, details the communications requirements between the EV and EVSE to meet the needs of J2293-1 using a J1850 compliant network [23].

Additional SAE standards address messaging requirements for a Class B communications network as defined in J1850. Since details of the communications networks and protocols used for interconnection of PHEV and V2G are not addressed in this study, the reader is referred to [22] and [23] for further information regarding communications requirements for and EV energy transfer system.

Use cases describing the general sequence of communications and information exchange expected with interconnection of PHEV to the electrical grid are discussed at the end of Chapter 3 and in Chapter 4.

2.3 Impacts on the Power Grid

As mentioned in the introduction, there is sufficient generating capacity to charge the majority of light-duty vehicles (LDV) today on a national level. At the regional level this varies and may find different impacts for each neighborhood. The impact on the distribution system is the most significant when determining whether or not the power grid can handle the demand once PHEV are out there and charging. Distribution system design is based on many variables, one variable being system loading. Designers need to consider what the load characteristics will be to begin with and also determine how the load will change and grow in the future. This information is used to determine the capacity of the lines feeding the load and the rating of system equipment such as distribution transformers. In addition the loads must be somewhat balanced amongst the phases at a certain voltage level.

To manage the effects of large-scale penetration of PHEV, the use of smart charging (V1G) will be essential. At the very least smart charging will allow charging to be delayed in the evening to avoid increasing the system's peak and to allow better utilization of generation assets overnight. V2Green, a V2G technology provider, has developed software algorithms for utilities that control the charging of groups of vehicles to produce a smooth load curve and disperse charging throughout the night. This software can also be used to manage the vehicles' energy storage to allow greater penetration of variable renewable resources among other things.

3 VEHICLE-TO-GRID

Chapter 2 discussed the concepts of V0G as simple vehicle charging and V1G or smart charging where one way communications with the utility allows external control of charging. In light of today's electricity infrastructure and operational paradigm it is expected that the first generation of charge control will simply be widespread smart charging controlled by the utility or a third party such as V2Green. The next step is allowing two-way energy flow to and from the PHEV energy transfer system (ETS) along with two-way communications with the utility, and this is commonly referred to as vehicle-to-grid (V2G). The external infrastructure needed for V2G will naturally develop as the smart grid evolves and distributed energy resources become more common. At that point, the concept of V2G will fit a more naturally with how the grid is designed and operates.

On the demand side, additional hardware and/or software may also be incorporated into the PHEV and the EVSE also to enable V1G or V2G capabilities. An electric vehicle ETS interfaces with the power grid through the Electric Vehicle Supply Equipment (EVSE) which may be a charging station or simply the charge coupler and a standard grounded outlet. The smart grid will allow PHEV to connect in a plug-and-play fashion where the vehicle will identify itself and provide any information that may be needed for an energy transaction.

The following sections discuss the energy supply capabilities of PHEV and the roles that they could play in frequency regulation. Current standards for interconnection of distributed resources are discussed next and finally issues associated with V2G and possible incentives for owner participation are discussed.

3.1 PHEV as an Energy Source

PHEV are essentially mobile distributed storage and can act as both a controllable load and source of energy within V2G. There are several ways in which the energy stored in PHEV might be used including:

1. Peak shaving,
2. Load smoothing,
3. Smoothing output of intermittent generation,
4. Backup power supply, and
5. Ancillary services (e.g. voltage control, frequency regulation, etc.).

There are several benefits when using distributed energy resources (DER) versus conventional large generating units to meet the system's power and reliability needs. For instance, PHEV as distributed resources are located near load and distributed generation (DG), where it can conveniently be integrated into load and DG management systems. This is particularly useful when distributed grid management is desired so that energy management decisions can be made locally without needing to confer with the system operator or other remote resources. The storage resources and DG are right there with the load and these components together can be controlled to meet local objectives avoiding the need to rely on remote large-scale storage or generating units for local management.

In fact some power and energy services are better served locally. For instance, voltage control through VAR support is best supplied locally. Real power can be supplied remotely but transmission and distribution losses may be as high as 7-10% and these losses increase in proportion to the square of load increases. Depending on the energy or power needs and the time of day, using PHEV can decrease congestion on transmission lines and could provide transmission loading relief (TLR). These factors combined result in opportunities for utilities to defer capital investment in generation and transmission upgrades and increase the asset utilization.

3.1.1 Building[9] Supply Capacity Potential

A building EMS may use a PHEV as a controllable load or energy source where the objective may be to smooth the load profile, respond to peak signals, or minimize cost. The energy stored in a PHEV Li-Ion battery system will vary based on the driving and design needs of the vehicle. To meet the driving needs of conventional combustion engine vehicles over a range of classes from compact car to full-size SUV, rated capacities are in the range of about 5 up to 20 plus kilowatt-hours [5], [6].[10]

As a point of reference, in 2007 Minnesota had 2,267,167 residential electricity customers and had residential retail electricity sales of 22,646 GWh [24]. This gives an average daily consumption of about 27 kWh per day per household, which is on the same order as the rated storage capacity of a PHEV battery system. This suggests that PHEV could be used as a home backup supply to power critical loads over a period of hours to days following a loss of electrical service.

As a load in a residential setting most likely a standard 120 V grounded outlet or a Level 2 charging system will be used, meaning a PHEV may range from several hundred up to several thousand Watts while charging. This large a load could be compared to a plasma TV and a large central air-conditioning unit on the higher end, therefore a PHEV in most cases would represent the largest single load in a typical household. They are a highly controllable load, and as such they offer a wider power supply range compared to other controllable loads since they act as both a load and power source.

These characteristics suggest that PHEV could be ideal for providing energy or power on a household scale. If a home were outfitted with V2G capabilities – where the home's power network is the grid – there are several ways the PHEV could be used in household energy management schemes. Often times, appliances have a load profile that includes brief periods of high energy draw and a PHEV battery system could offset these peaks. As an example while a load is operating at peak power battery charging could be delayed

[9] Building refers to a household or commercial building.
[10] Please refer to Figure 1 in Chapter 2 for more information and sources.

for a short duration to smooth the home's load profile. On the other hand a fully charged vehicle could offset the peaks in appliance load cycles by providing energy to the home.

Appropriate hardware and line capacity must be available in order to use a PHEV as a backup supply for a home either in dynamic load balancing or in the event of system blackout. Specifically 240 VAC, 100 A service would be necessary to power higher powered appliances like central air-conditioning while riding through a blackout. Additional energy can be obtained from the vehicle once the battery is depleted by running the combustion engine. Depending on the drive architecture of the hybrid vehicle the power from the engine may recharge the battery to provide additional electrical energy, or the engine power may be directly converted to electrical energy using the on-board electrical motor.

3.1.2 Aggregate Supply Capacity Potential

To determine which services storage is best suited for, both the power and energy capacity must be considered. Dividing the energy capacity by the power gives the duration of storage, or the amount of time that the storage can supply energy at a particular power level. To gain an intuitive feel for the duration of PHEV as an energy supply, let's consider the technical potential for energy and power supply in Minnesota with a 5% penetration of PHEV each containing a 10 kWh battery. In 2007 approximately 4.7 million cars and trucks were registered in the state of MN [25]. Assuming that all the PHEV are fully charged once a day and 80% of the energy capacity is available, as an aggregate the vehicles represent a total storage capacity of:

$$235,000 \text{ vehicles} \times 10 \text{ kWh} \times 0.8 = 1.88 \text{ GWh}$$

The power supply capacity depends on what type of charging systems are used and the charging capabilities of the PHEV battery systems. Table 5 shows the aggregate power rating and resulting storage duration available for the three levels of AC conductive charging systems as defined in SAE J1715 [21].

Table 5
Technical Potential for Energy Supply and Duration with 5% Penetration of PHEV in Minnesota

Charger Class	Power Level[11]	Total Power[12]	Total Energy	Storage Duration[13]
AC Level 1	1.4 kW	0.33 GW	1.88 GWh	**5 h 43 min**
AC Level 2	7.7 kW	1.81 GW		**1 h 2 min**
Level 3	160 kW	37.6 GW		**3 min**

The total power and energy numbers represent the technical potential for PHEV as an aggregate power and energy supply. To get a more realistic feel for PHEV supply potential additional factors need to be considered including:

- Residential parking without access to power outlets,
- Customer participation rates,
- PHEV and V2G usage patterns,
- Instantaneous state-of-charge, and
- Instantaneous discharge rate (A).

Comparing PHEV to conventional generation in MN, the total nameplate capacity of generation from all sources in MN in 2007 was about 14 GW [26]. Depending on the power level used in charging, the aggregate PHEV supply capacity is on the same order as Minnesota's generating capacity even considering a relatively small PHEV penetration of 5%.

The results in Table 5 suggest that PHEV are ideal for providing services with typical duration on the order of minutes to hours. Although the aggregate power capacity is on the same scale as current generating capacity in scale, the short duration of the energy supply illustrates the fact that PHEV are not suited to be a baseload power supply.

[11] This is the maximum power rating for the charging classification.
[12] Calculated by multiplying the power level times 235,000 vehicles.
[13] Total energy divided by the total power.

3.1.3 Summary

The following conclusions can be made about the use of plug-in hybrid electric vehicles as a distributed energy resource (DER) based on the power and energy characteristics discussed in Sections 3.1.1 and 3.1.2:

1. Not suitable for baseload power supply,
2. Ideal for short duration services such as frequency regulation, load following, or spinning reserve, and
3. Ideal for household scale services such as load smoothing or peak reduction.

Overall, an aggregation of PHEV is able to respond more quickly to load reference set point changes than large generators and in some cases has the potential to play the role of central generation. There are several possibilities for PHEV to contribute to load management at the household or system level depending on vehicle usage and the preferences of the vehicle owner.

3.2 Balancing Generation and Load

Regulation services along with several other levels of central generation dispatching are used to keep generation matched to the bulk system load. The use of storage for regulating reserve is of current interest and fits well with the operating characteristics of a PHEV Li-Ion battery system. Based on the previous discussions PHEV could be used to balance generation and load in two ways:

1. Smooth building load to reduce variations from the bottom, and
2. Provide regulating reserve as an aggregate energy source from the top.

The following sections discuss how frequency regulation is supplied traditionally using large conventional generating units under automatic generation control (AGC) signal and how PHEV could fit into regulation supply.

3.2.1 Traditional Frequency Regulation

Currently frequency control is performed at the bulk system level and regulation is used to match generation to the constantly changing load (non-emergency load fluctuations). There are two main categories of frequency regulation:

1. Primary: generator governor response to damp out frequency excursions, and
2. Secondary: automatic generation control to bring system frequency back to the nominal 60 Hz.

Initially after a load/generation imbalance the system frequency will change, increasing if load is less than generation and decreasing if load exceeds generation. This speed deviation will cause the generators' governors to respond, which will slow the frequency excursion and eventually the frequency will settle at a new steady-state value and the load/generation balance is restored. Automatic generation control (AGC) is used to change the operating setpoint of generators on AGC control to correct the frequency error and return system frequency to 60 Hz. Primary governor response can arrest frequency deviations in a few seconds, and secondary control can restore system frequency in several minutes.

The AGC raise/lower commands are derived from the area control error (ACE) which is calculated based on the deviation in system frequency and scheduled tie-line flow. A negative frequency error signals that system load exceeds the amount of power being generated and AGC units will be asked to increase their output to provide regulation up. Conversely when total generation exceeds the system load leading to a positive frequency error, AGC units will be asked to decrease their output to provide regulation down.

As the system frequency returns to 60 Hz after AGC action, the primary response that initially supplied the new load will be released due to the governor response of generators. After all AGC actions, generators providing frequency control will have done their job and met the changing load needs of the system and generators not on AGC control will return to their initial operating state.

Typically generating units on AGC control will be required to respond to raise/lower signals in a minute or less, with typical service duration on the order of minutes. Compared to contingency reserves—such as spinning reserves—which might only be dispatched once or twice a year, regulating reserves may be adjusted hundreds of times a day [10].

Participating generation units submit their operating parameters which include ramp rate and supply duration to the Area EPS operator along with a price to bid into the regulation market. A regulating reserve contract is for energy and capacity, therefore penalties are assessed if the resource is unavailable when regulation is needed. Units chosen to supply regulating reserve receive a capacity payment just for being available and an energy payment for actual energy supplied for regulation.

Large scale storage has been used in limited installations to provide AGC support for the power system. For instance, Xcel Energy's Wind-to-Battery was launched in 2003 to study the integration of a 1 MW sodium sulfur (NaS) battery with a wind generation installation in Luverne, Minnesota. The project will investigate how much storage is needed to smooth the output of wind turbines and explores using the battery to provide ancillary services such as frequency regulation to optimize the financial payback of the battery system. The press release introducing the Wind 2 Battery project and subsequent updates are available online at [27].

3.2.2 Incorporating PHEV into Frequency Regulation

At the top of the system, system operators are able to track total load and generation in their area, and system frequency is used as a control input to match generation to the system load on a continual basis. In order to match generation to the system load the system essentially needs to wait until the generators have "seen" the change in system loading which results in a frequency deviation, the governor response will temporarily meet the load deviation resulting in a steady-state frequency error. It is at this point that control action is initiated to correct the resulting frequency error.

Load forecasting for the Area EPS is done over long time horizons to facilitate system planning, and may be done on a daily or hourly basis in order to facilitate day-ahead and real-time energy markets. The load curve for an entire area is a fairly continuous curve which typically has two peaks during the day, one in the morning when people are getting ready for work and another in the afternoon as people return home from work. An area's load curve will vary somewhat depending on the particular location, season, and a number of other patterns.

At the other end of the system at the point of service, a customer's electric meter tracks building power demand and the accumulation of energy consumption over time. Home smart grid technologies may be used to gather more detailed information about energy consumption, to the point where individual device controllers monitor consumption of a single plug load to aid in scheduling and load shifting.

Building level load prediction is feasible in the context of homes with energy management system that has built in intelligence and the ability to learn. This is particularly true with the use of individual intelligent load controllers. For instance, when temperature inside a refrigerator begins increase a controller could predict when the compressor will start up based on the current rate of temperature increase and historical behavior. At the distribution level, intelligent controllers could also perform load prediction.

With a smart grid, load prediction could be happening at several levels of the system. Due to changes in variability as more loads are aggregated and the composition of the loads (i.e. commercial versus residential), the predictions at the different levels will provide a unique view of system operating status. If regulation was to be supplied and dispatched in a distributed manner, load prediction becomes necessary since frequency calculations are not reliable on the user end of the system.

As discussed in Chapter 1, KEMA performed a study to explore the use of energy storage for fast regulation using several signals derived from the ACE [13]. The study found a reduction in the amount of raise/lower signals that large generators had to respond to with the used of fast regulation resources. The storage available in PHEV is ideal for supplying "fast regulation" and could be controlled in a fashion similar to central generation using automatic generation control (AGC) or some other form of the area control error (ACE). However, since the vehicles are tied into the system through customer service points it makes sense to take advantage of locally available information in addition to system-wide indicators such as frequency to determine how much the PHEV should supply.

With a sizable penetration of PHEV on the grid, it makes sense to use an intermediate controller to coordinate several PHEV energy transfer systems (ETS) and act as a middleman between the system operator and individual PHEV V2G controllers. Besides facilitating information exchange between system operators and the distributed PHEV, the location of the coordinator also gives it a unique vantage point where it can keep an eye on system behavior in both the Area EPS and the local electric power system (Local EPS). The distinction between Area EPS and Local EPS is presented in the next section.

Unique Characteristics:

- Supplied at point of consumption
- No power-frequency dependence
- Cars move and capacity moves with it
- Virtually no ramp rate compared to thermal generating units
- Both a controllable load and energy source

Table 6 describes the control actions that would be used with PHEV providing regulation and the effects on the need for regulation supplied by central generating units on AGC control.

Table 6
PHEV as a Source of Regulation

Service	Regulation Up	Regulation Down
Condition in Area EPS	Load > Generation	Load < Generation
Charge Rate	Decrease; mitigate regulation provided by central generation	Increase; mitigate regulation provided by central generation
Discharge Rate	Increase; transfer regulation provided by central generation	Decrease; transfer regulation provided by central generation

There are several benefits that may result from using PHEV for regulation, including:

1. CO_2 offsets,
2. Decreased transmission and distribution losses,
3. Revenue for ancillary service supply,
4. Fuel cost savings, and
5. Increased utilization of central generating assets.

The benefits of using PHEV for regulation will vary based on the type and location of the central generation being replaced, and the location of the PHEV. For instance, it makes sense to provide regulation using a PHEV when charging during peak times. In this case, the market price for wholesale energy will be higher than off-peak such that the payoff for providing energy may be higher than regulation for large generating units. There are also economic benefits for the vehicle owner if there is dynamic pricing for retail electricity.[14] The PHEV would decrease its charge rate and in turn decrease the energy consumed during higher price periods and provide revenue for providing regulating reserves. Depending on the generating source used to supply the charging power and the incremental generation that would be dispatched for traditional AGC, there may be a decrease in net CO_2 emissions also.

[14] Dynamic pricing may be time-of-use, real-time, or critical peak pricing.

3.3 Interconnection

Currently IEEE Std 1547™ Standard for Distributed Resources Interconnected with Electric Power Systems is being developed by Standards Coordinating Committee 21 on Fuel Cells, Photovoltaics, Dispersed Generation, and Energy [2]. The 1547 series includes eight standards, four of which are in the draft stage at this point. This section discusses two of the non-draft standards in the 1547 series which are the most relevant to this study.

These standards distinguish between the bulk power system, referred to as the area electric power system (Area EPS), and the local electric power systems (Local EPS) that it serves. A Local EPS consists of a single building or a group of buildings where one or more distributed resource units (DR units) are located. [15] The point where the Area EPS and Local EPS are connected is referred to as the point of common coupling (PCC). [2]

IEEE Std 1547™-2003

Standard for Distributed Resources Interconnected with Electric Power Systems

This standard provides technical and testing requirements for the interconnection of distributed resources with an aggregate capacity of 10 MVA or less [2]. Its primary focus is on DR units installed on radial primary and secondary distribution systems; interconnection to primary and secondary network distributions systems is briefly addressed and will be addressed further in future revisions.

For interconnection of PHEV, the PCC is the point where a home or business is coupled to the electric grid, where the PHEV is considered the DR unit. If there are several PHEV energy transfer systems (ETS) in a single building, such as a parking garage then several DR units may be controlled through that single PCC. Figure 4 illustrates the relationships

[15] The phrase distributed energy resources (DER) is used to refer to distributed resources throughout the document to avoid confusion with demand response which is commonly abbreviated DR. To remain consistent with the terminology used in IEEE 1547, the phrase ‘DR unit’ is used in this section to refer to distributed resources.

between the Area EPS and DR units within local EPS as outlined by the IEEE Std 1547 standards. Note that in Local EPS 3 multiple DR units are connected through the PCC.

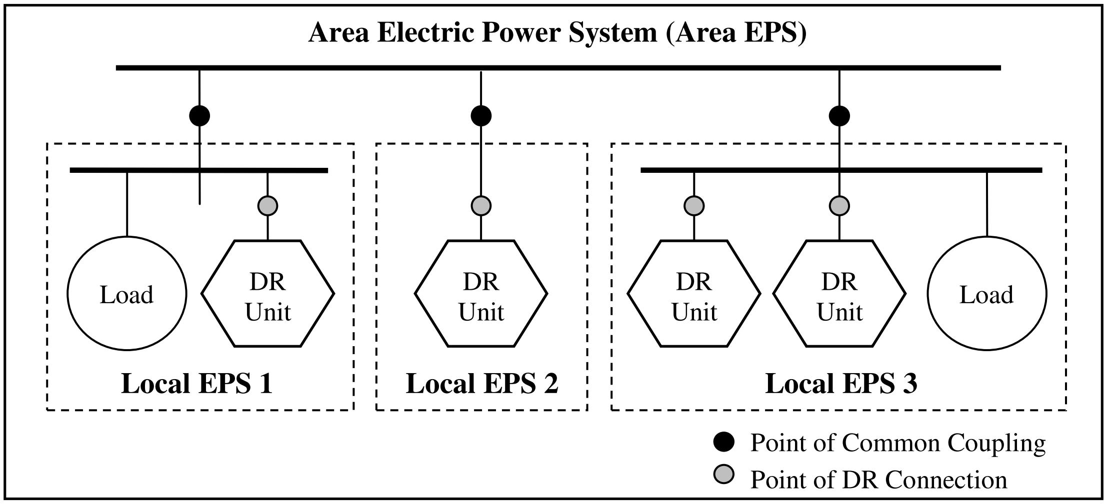

Figure 4
Distributed Resource Interconnection Diagram

Source: Adapted from figures in [2] and [28].

Of particular interest in this study are the requirements for the operation of DR units during abnormal operating conditions in the Area EPS. Distributed resources must cease to energize the Area EPS within the clearing times[16] shown in Table 7 after an abnormal system voltage is first detected at the PCC or the point of DR connection. The times represent the maximum clearing time for installations of less than or equal to 30 kW, and default times for installations greater than 30 kW.

Table 7
Distributed Resource Clearing Time in Response to Abnormal Area EPS Voltage

Voltage Range (% of base voltage)	Clearing Time (seconds)
V < 50	0.16
50 ≤ V < 88	2.00
110 < V < 120	1.00
V ≥ 120	0.16

Source: Table 1 [2]

[16] Clearing time is the time between the onset of the abnormal condition and the DR ceasing to energize.

The clearing times[16] required for DR units in response to abnormal system frequency are shown in Table 8. Again the times represent the maximum clearing time for installations of less than or equal to 30 kW, and default times for installations greater than 30 kW.

Table 8
Distributed Resource Clearing Time in Response to Abnormal Area EPS Frequency

DR Size	Frequency Range (Hz)	Clearing Time (seconds)
≤ 30 kW	> 60.5	0.16
	< 59.3	0.16
> 30 kW	> 60.5	0.16
	< {59.8 – 57.0} (adjustable set point)	Adjustable 0.16 to 300
	< 57.0	0.16

Source: Table 2 [2]

Currently 1547 does not allow DR to actively manage the voltage at the PCC and requires DR to disconnect when the adjacent portion of the Area EPS has become islanded. Allowing DR to energize the Local EPS during intentional islanding poses safety issues for grid maintenance workers, but is being considered for future versions of 1547. This would be necessary to balance load in the Local EPS or a portion of the Area EPS with the local DR output if the concept of microgrids reaches fruition in the future. In addition, the ability of an inverter to provide voltage regulation is very attractive considering that reactive power must be supplied at the point of need.

IEEE Std 1547.3™-2007: Guide for Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems

This standard provides guidance for the monitoring and information exchange necessary between DR and stakeholders in the Area EPS in order to properly maintain and operate DR units [28]. Several stakeholders which will have direct interaction with the DR units are identified and defined in [28] and they include: Area EPS Operator, DR aggregator, DR operator, and DR maintainer. A PHEV is unique as a DR unit since the vehicle owner plays the role of DR owner, maintainer, and operator. Figure 5 illustrates the information exchange paths between DR units, the DR controller, and interested parties in the Area EPS. The bold dashed lines represent the specific information paths addressed in 1547.3.

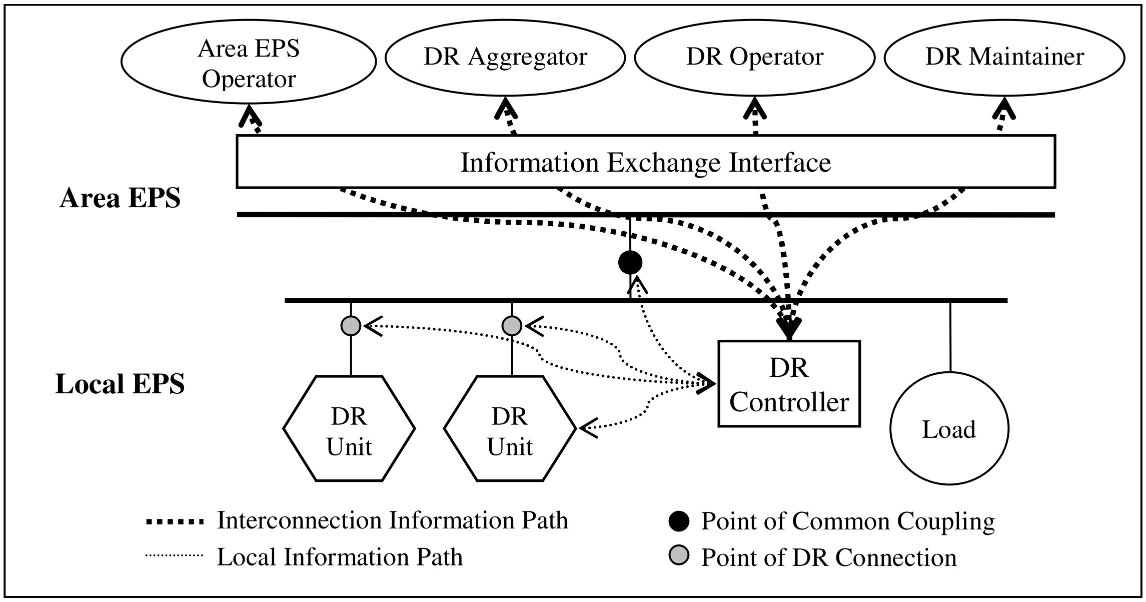

Figure 5
Information Exchange Paths between DR Units, Controller, and Stakeholder

Source: Adapted from Figure 1 in [26].

If the building includes a building energy management system (EMS), the DR controller may also exchange information with the EMS to jointly manage energy supply and demand in the Local EPS. In the case where the Local EPS contains multiple PHEV energy transfer systems (ETS) as in a parking ramp, a single DR controller can manage all of the ETS or each ETS may include its own DR controller. For charging installations available today that largely do not include provisions for V2G functionality, a single DR controller would be an easy retrofit. By the time large penetrations of PHEV are connected to the grid this functionality may be built into individual charge stations without the need for additional components.

IEEE 1547.3 gives an overview of the different categories of distributed resource systems that might be interconnected, along with options for energy conversion technologies. A PHEV is a storage device that uses an inverter to convert the DC energy output from the battery to AC electrical energy that can be fed into the power grid. Compared to an induction or synchronous generator used to convert the energy output from other DR sources, using an inverter makes re-synchronization with the grid much simpler.

Distributed resource installations are classified according to their aggregate MVA rating, and PHEV are likely to fall into Class 1, installations less than 250 kVA. If there are several charging stations at a single premise totaling 250 kVA or more then the DR installation is Class 2. The main distinction operationally is that Class 1 installations have no requirements for monitoring, although the Area EPS operator may wishes to track DR connection status. Connection status, real power output, reactive power output, and the voltage at the point of DR connection must be monitored for Class 2 installations. Regardless of the monitoring requirements, the connection status and real power output (or input) will likely be tracked on a per vehicle basis even without V2G. [28]

Ideally the monitoring, information exchange, and control (MIC) should facilitate interoperability between DR units and the Area EPS using an open systems approach. In addition, the information modeling used to standardize information exchange between parties should be easily extended to additional forms of DR and added functionality. The standard also discusses options for communications protocols and addresses security for MIC of distributed resources. Security of DR monitoring and control will depend on the specific type of information exchange as well as the communications path between the DR controller and stakeholders. In light of recent security threats to the nation's power grid, the specific communications implementation and protocols should be chosen to meet the needs of the particular stakeholders and systems involved.

3.3.1 Industry Use Cases

A common tool used when designing systems, specifically software systems, is the use case. Use cases are developed based on a scenario that occurs in a system and the users' interactions with the system that are necessary to carry out the scenario. For instance, a use case may be defined for a customer placing an order in a restaurant, and would describe the sequence of interactions and information exchange between the customer and waiter. Once a detailed scenario is developed, relevant business practices and system functionality are defined based on the users' interactions with a system.

IEEE Std 1547.3 provides sample use cases for monitoring, information exchange, and control of distributed resources (DR) interconnected with the power grid [28]. Annex F in [28] has seven sample use cases for distributed resource interconnection, including a use case for DR providing ancillary services to the grid. The seven sample use cases are:

1. DR unit dispatch,
2. DR unit dispatch for energy export,
3. DR unit scheduling,
4. DR aggregation,
5. DR maintenance,
6. DR ancillary services, and
7. DR providing reactive supply.

Southern California Edison (SCE) has been developing use cases for their smart metering system, Edison SmartConnect™, and AMI deployment [29]. These use cases were developed using the guidelines of EPRI's Intelligrid℠ Use Case framework. Late in 2008, SCE released a few plug-in electric vehicle (PEV) use cases for connection of PEV to accept energy from the grid, and customer enrollment in a demand response program. In addition a fourth use case is being developed for PEV providing advanced applications such as frequency regulation or spinning reserve.

A full repository for smart grid use cases is being managed by EPRI and includes the previously discussed SCE use cases along with several other PEV use cases under the heading of distributed energy resources [30]. These use cases will be used as a basis to define the requirements for the simulation components developed in this study and are discussed further in Chapter 4.

3.4 Issues and Incentives

The primary role that a plug-in hybrid electric vehicle plays is a mode of transportation for its owner. The vehicles—at least in the next several years—will be more costly than conventional vehicles powered with only a gasoline engine, and most of the cost comes from the battery system. Allowing vehicle charging to be controlled with a vehicle-to-grid scenario could impact the drivability of the vehicle and decrease battery lifetime, therefore there must be incentives for customers to participate in V2G. Possible incentives include:

- Economic payback for services provided, and
- Decreased fossil fuel consumption and CO_2 footprint.

First and foremost V2G could provide financial payback which would help offset the initial costs of purchasing a PHEV. If the amount of energy supplied by a PHEV were properly managed, the impacts on vehicle lifetime and drivability could be minimized. To minimize the contributions by a single vehicle, V2G makes the most sense in the context of large penetrations of PHEV where the service can be supplied in small amounts by many vehicles. If the battery system were also repurposed for a stationary application at the end of its useful life as a vehicle battery as discussed in [20], the costs associated with PHEV could be further reduced.

Several organizations are developing methods to more accurately calculate the CO_2 impacts and savings associated with various end-use technologies. For instance, EPRI performed a study to determine the CO_2 savings potential when replacing fossil-fueled equipment with highly efficient electrical technologies in the residential, commercial, and industrial sectors [31]. Calculating possible CO_2 savings is no trivial task since usage patterns vary greatly from one person to another, and in the case of electrical energy the carbon content depends primarily on the generation mix used to supply the electricity. In addition, to compare the carbon footprint of a gasoline vehicle to a PHEV requires assumptions to be made concerning how the gasoline vehicle would have been operated.

Providing regulation services through V2G is an example of the unique opportunities for customers to contribute to grid reliability which will be possible with a smart grid. If the contribution of PHEV to ancillary services is sufficient, utilities may be able to defer the need for capital investment which in turn helps to mitigate increases in retail electricity rates.

There are a multitude of issues that would need to be addressed before V2G becomes feasible; one major issue is how to design a market for regulation supplied by distributed assets. A market that accounts for the differences between large and small assets and their unique characteristics will be necessary to provide maximum financial incentives for vehicle owners to participate. No matter how technically feasible V2G may be or the incentives offered, ultimately user behavior will dictate if and to what extent vehicle-to-grid is adopted.

4 SYSTEM DESIGN

To determine the impact of plug-in hybrid electric vehicle charging and distributed frequency control the behavior of several levels of the power system need to be considered along with the addition of distributed controllers. Each level of a power system has physical components along with the monitoring and controls necessary to meet the operating needs in that part of the system. Table 9 compares the different levels of a power system in terms of equipment, stakeholders, and monitoring and control systems that are currently used.

Table 9
Comparison of Equipment, Control Systems and Stakeholders at Different Levels of the Power Grid

Level	Physical System	Monitoring and Controls	Stakeholders
Bulk Transmission System	High voltage lines, central generation, transformers, protection elements[17]	SCADA/EMS, switching, load shedding, protection and compensation equipment	Transmission owner, operators, and maintainers, generation owners, market participants, regulators
Distribution System	Primary and secondary feeders, transformers, protection elements[17], distributed resources	SCADA/DMS, switching, protection and compensation equipment, load shedding	Distribution system owners, operators and maintainers, end use customers, regulators
Home or Business	Mains, breakers and fuses, appliances, all other end uses	Utility revenue meter, overcurrent protection, switching	Building owner and/or maintainer, occupants, utility, regulators

PHEV will be tied in to the power grid at the point of customer service therefore distribution system behavior must be considered in order to study the effects of vehicle-to-grid (V2G) on traditional distribution system design and operation. To study an aggregation of PHEV as a source of distributed frequency control the behavior of system

[17] Here protection elements include monitoring and protection equipment.

generation, AGC dispatch and even ancillary service markets need to be considered also. Traditionally power system modeling considers either:

1. Transmission level modeling with distribution level loading aggregated at the bus level and assuming balanced loading across phases, or
2. Distribution level modeling with the bulk system represented by an equivalent voltage source at the head of the feeder using a three phase power flow.

For a more comprehensive model it would be desirable to model the behavior of the transmission level down to the feeder level or the point of customer service. However this involves using a full three phase power flow for the entire system. Therefore a more simplified approach will be used for the purposes of this study.

Although the vehicles are tied in at the distribution level, their behavior as an aggregate load and source of frequency regulation is better viewed from the bulk system level. This is mainly because the frequency response of central generation and computation of a traditional AGC control signal need to be incorporated into a system model to study how effective PHEV could be as a source of frequency regulation. As a first step in modeling PHEV as distributed energy resources a transmission level model of the power system will be used and an aggregate PHEV load will be tied to each load bus in the system. The power system model will be based on a modified version of the power system simulator developed in [15]. A detailed description of the power system simulator along with the implementation of the vehicle-to-grid components follows in Chapter 5.

Additional components and controllers are necessary to study the effects of PHEV on the power system and load/generation balancing. Section 4.1 describes the additional components that will be used with the power system simulator and Section 4.2 discusses the overall V2G system control strategy in terms of controller hierarchy and control objectives. Previous work applying distributed intelligent control to underfrequency load shedding is discussed in Section 4.3.

4.1 Additional Components

A physical model of the behavior of the PHEV battery system during charging and discharging is the most obvious piece that needs to be incorporated into the system model. In addition, a vehicle-to-grid (V2G) controller is necessary to control charging and oversee the operation of the PHEV as a distributed resource (DR). To aid in balancing load and generation the frequency error (deviation from 60 Hz) will be the main variable used to control the local supply of frequency regulation. An additional level of controller is necessary if PHEV are to be used to supply frequency regulation because frequency measurements are not reliable at the building level. To oversee the operation of multiple PHEV in a particular locale a PHEV coordinator controller will be employed to monitor system conditions and make recommendations for energy supply to the local PHEV.

Table 10 extends Table 9 to show where these additional pieces fit into the power system. The monitoring and control functions included in Table 10 are specific to performing frequency control and load smoothing. Based on the objectives of the PHEV Coordinator and PHEV Controller these monitoring and control functions may be different or augmented.

The PHEV coordinator may be implemented as part of a more general control unit that performs advanced monitoring and control appropriate to that level of the power system. For instance, the functions performed by the PHEV Coordinator may be a module in a distribution level distributed controller which provides sensing and communications capabilities to be used by several different control modules. For a system that needs to be scalable, this viewpoint is ideal since additional control modules can be added to the existing smart grid backbone to perform specialized functions without needing to replace entire monitoring and control units in the system. If open standards are used for the sensing, monitoring, and control systems the infrastructure will be more readily expandable.

Table 10
Components to Augment the Power System Model

System Level	New Component	Operations, Monitoring and Controls	Stakeholders
Distribution	PHEV Coordinator	• Monitor system frequency • Determine supply recommendation for local PHEV • Communicate local participation (aggregate PHEV supply) to system operator	Transmission system operators, equipment owner, distribution system (DS) operators and maintainers
Home or Business	PHEV Battery Model	• Rated energy capacity • Vehicle plug-in time • Remaining state-of-charge (SOC) • Desired charge/discharge profile	Vehicle owner, utility
	V2G Controller	• Control battery charge current • Track battery state (e.g. power draw, energy consumption, charge time) • Forecast load curve based on power draw and SOC (possible learning loop here) • Determine available storage power and duration • Accept vehicle owner input regarding use of PHEV as DR • Summarize services provided, etc. for owner	Vehicle owner, utility
	Electric Vehicle Supply Equipment (EVSE)[18]	• Communication portal between PHEV and the rest of the electric power system • Allow user to opt out/override utility control	Vehicle owner, EVSE owner (and operator)

[18] The EVSE is not explicitly modeled here but may be included in future work that includes modeling of communications systems.

Figure 6 illustrates proposed paths for information and energy exchange between these additional components and the bulk power system.

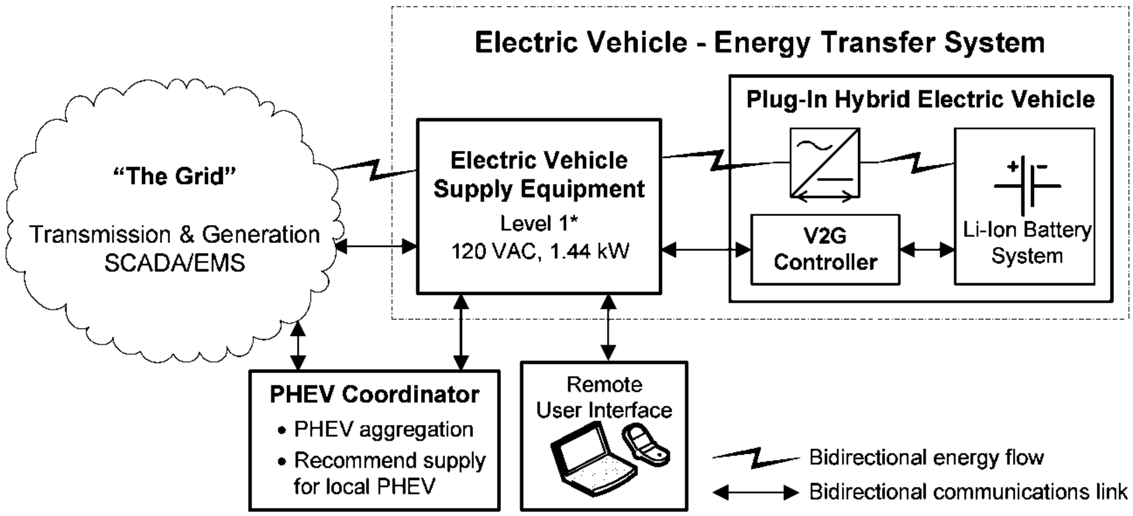

Figure 6
Energy and Data Flow between the PHEV and External Systems

The following sections discuss these components in terms of their functionality including their objectives and collaborative interactions. Section 4.2 goes on to discuss the general system control strategy and architecture. Implementation details follow in Chapter 5. Concepts and terminology from the current versions of several IEEE and Society of Automotive Engineers (SAE) standards are used in the following sections; the reader is referred to Chapters 2 and 3 for a more complete description of these terms and concepts.

4.1.1 Plug-In Hybrid Electric Vehicle

Per SAE Recommended Practice 2293-1, the PHEV energy transfer system (ETS) transfers energy from the utility to the PHEV battery system and includes both the electric vehicle supply equipment (EVSE) and the vehicle itself [1]. Charging at home using a standard 120 VAC outlet was considered as a starting point for modeling, in which case the EVSE is simply the charge coupler. The ETS model will consist of the Li-Ion battery system and the V2G controller which makes decisions about vehicle participation in regulation and controls charging/discharging while plugged-in.

4.1.1.1 Battery System Storage Model

As a first step in modeling, all PHEV battery systems will use the same model and will approximately represent mid-size sedans. Based on EPRI data for PHEV characteristics the PHEV modeled in this study are assumed to have a 40 mile all-electric range, with a consumption of 0.2 kWh/mi in the all-electric range (AER). The battery system model will have a total storage capacity of 10 kWh with a usable state-of-charge (SOC) of 80%. The battery system state will be defined as follows:

1. Present state-of-charge as a percentage of the total capacity, denoted SOC,
2. Expected end time of charging session, denoted t_{full}, and
3. Present charge rate in kilowatts, denoted p_{veh}.

This study will only consider charging at home and will assume that all vehicles charge using a standard grounded 120 VAC outlet rated at 12 Amps. This is a good starting point for modeling of PHEV loading since many homes have some sort of electrical access outside. It is not unusual for a garage to have 240 VAC service also for large tools or the like, however this option along with charging at public facilities will be left for future studies. This charge level corresponds to level 1 AC charging as defined in [21] and has a maximum rated power of 1.44 kW.

The results of the 2001 National Household Travel Survey can be used to approximate vehicle usage patterns to model PHEV energy needs when plugged-in to charge [32]. Probability functions for the number of vehicles arriving home during each hour of the day and the number of miles traveled based on analysis of the data in [32] were provided by EPRI. EPRI used the number of vehicles ending their travel day at home and the number of miles traveled, along with an estimate that an average vehicle is driven 12,000 mi/year to find an expected number of vehicles. An estimated 14% of vehicles are driven 0 miles during a given day based on the expected number of vehicles for the sample group. Table 11 summarizes key findings from the survey data.

Table 11
Summary of Vehicle Characteristics based on the 2001 NHTS [32]

Parameter	Ending Travel Day at Home
Number of vehicles ending travel day at home	28,890 vehicles
Total miles traveled	1,104,541 mi
Miles traveled per vehicle used during travel day	38 mi/vehicle
Total expected number of vehicles	33,597 vehicles
Vehicles driven ≤ 20 miles per day	50%
≤ 40 miles per day	73%
≤ 60 miles per day	85%

Source: Based on EPRI analysis of the data in [32].

Vehicle charging will be monitored and controlled by the PHEV's V2G controller which is discussed in the next section.

4.1.1.2 V2G Controller

The V2G Controller will control battery behavior and will make the decision as to how much power and energy the battery system can provide for frequency regulation. Determining how much energy a vehicle will supply or absorb for frequency regulation will depend on the following: the battery system state as defined in the previous section and the supply recommendation made by the PHEV coordinator.

As a simplifying assumption in this study a vehicle will remain plugged-in for the full expected charge duration once it returns home. Also, in the interest of minimizing the impact on vehicle drivability, it is assumed in this study that any PHEV participating in V2G has some gasoline in its tank. In the case that supplying regulation extends the expected charge duration and charging is interrupted the vehicle could still be driven.

Constant power charging will be used as a first order model, and vehicles will begin charging as soon as they are plugged in. Using the number of miles traveled d, the current time t, and the parameters discussed in the previous section the expected time of charge completion can be calculated as:

$$t_{full} = t + d * \frac{0.2 \text{ kWh/mi}}{p_{veh}}$$

The general approach of the V2G controller is to begin charging at a mid-level rate, say 1 kW, such that there is margin to increase or decrease charging to supply frequency regulation. Figure 7 illustrates the guidelines used by the V2G controller for determining the regulation supply options based on the battery system's state.

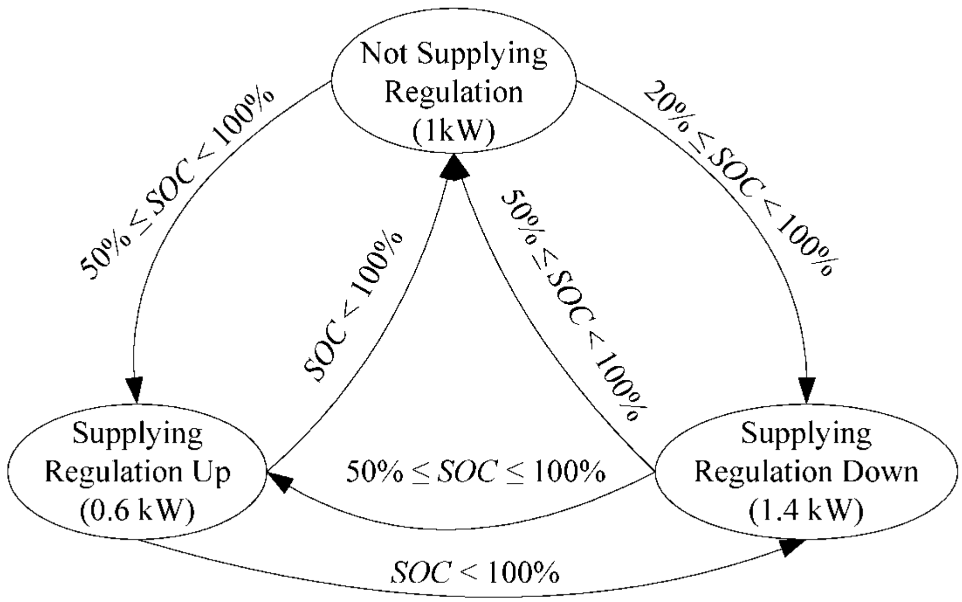

Figure 7
Regulation Supply State Transitions with Current Battery State-of-Charge (SOC)

The duration of regulation supply from a PHEV could be several hours depending on the current battery state and how long the vehicle remains parked. However, when considering the fact that the vehicle may be unplugged or V2G control overridden at any point a shorter supply duration may make more sense. Therefore several supply durations ranging between 5 minutes and an hour may be considered to determine the effects on aggregate supply curve. The specifics of V2G controller supply decisions will be discussed with its implementation in Chapter 5.

The functionality of the V2G controller may also be integrated into a home energy management system (EMS) which monitors household energy consumption in real time and acts as a communications gateway between devices within the home and beyond the point of utility metering. The home EMS may control several loads in the home in an effort to smooth or shift the load profile. Here a PHEV could aid in managing the energy profile of a home without consideration for external system needs. The same general PHEV controller functionality will be useful in either situation: controlling the charge rate to provide smoothing, or discharging to supply part of the load over short periods. The vehicle V2G controller will interact with the local PHEV coordinator which provides a supply recommendation for frequency regulation, and tracks the aggregate local PHEV regulation supply based on the control actions taken by the V2G controllers.

4.1.2 PHEV Coordinator

Frequency measurements are not reliable at the point of customer service where PHEV will be connected to the grid therefore the V2G controllers are not able to perform frequency control independently based on purely local information. Reliable frequency measurements can be made beginning at the high side of distribution substation transformers. A controller called a PHEV Coordinator located at a higher voltage level where reliable frequency measurements are available will be used in this study to oversee and coordinate local PHEV participating in frequency regulation through vehicle-to-grid. Here local PHEV refers to all vehicles that are below the coordinator in the distribution system which are participating in V2G. The PHEV Coordinator will act as a link between the area electric power system (EPS) and the local plug-in hybrid electric vehicles. The PHEV Coordinator would also be the natural choice to act as an aggregator to perform market functions for the local PHEV.

Because each level of the power system has different operational needs, “local energy needs” will be defined differently throughout the system. For instance, determining the amount of local energy needed to contribute to improving system frequency performance will depend on the load fluctuations and nearby generation at that point in the system. In addition, the market price for energy and ancillary services will behave differently at different nodes in the transmission system.

The PHEV Coordinator will necessarily interact with local sensing and measurement devices in order to perform its functions. However, the PHEV Coordinator will also need to interact with the system operator in the area EPS, as well as neighboring PHEV Coordinators, and of course the local V2G controllers. Table 12 describes the interactions and information exchange between the PHEV coordinator and external systems.

Table 12
PHEV Coordinator Interactions with External Systems

External System	Interaction
System Operator/ Central AGC Control	Send updates on local regulation supply
	Receive notifications to cease local regulation supply
Local V2G Controllers	Send updates of supply recommendation
	Notify to de-energize with abnormal system frequency per IEEE Std 1547™ or when utility requests to cease supply
Neighboring PHEV Coordinators	Exchange frequency and rate of change of frequency data

Current distribution systems are passive networks and in turn do not have a robust sensing and measurement system. The SCADA system typically reaches as far as substations where primary feeders deliver power to end users via the distribution system. As the smart grid develops and distribution automation becomes more prevalent the distribution system will have sensing and measurement on the same scale as the transmission system. Therefore it is a fair assumption that PHEV Coordinators will have access to the measurements needed to determine local operating conditions.

4.1.2.1 PHEV Recommendation Methodology

A PHEV coordinator will make a supply recommendation for local PHEV that have chosen to supply frequency regulation. The supply recommendation will include the sign of the supply, negative for regulation up and positive for regulation down, and a magnitude (MW) of local supply.[19] The main control inputs are the system frequency

[19] Generator convention is used for regulation up and down. For instance a negative frequency deviation requires regulation up which translates into a reduction in PHEV charge current.

deviation from 60 Hz and the rate of change of frequency (ROCOF) as measured at the coordinator's location. The sign of the frequency deviation will determine the sign of the supply recommendation and the ROCOF will be used as a predictor of the frequency deviation. The aggregate PHEV load and the amount of demand/supply available for regulation up or down will be used to determine the magnitude of the recommendation. Table 13 describes the variables used in making a supply recommendation to the PHEV.

Table 13
Variables That May be Used in Determining the PHEV Supply Recommendation

Parameter	Symbol	Units	Source
Bus frequency deviation	Δf	Hz	Measured
Rate of change of frequency deviation	$\Delta f'$	Hz/s	Calculated as $\frac{d(\Delta f)}{dt}$
Local area frequency response characteristic	β	MW/Hz	Constant, tuned during simulation development
Local automatic generation control (AGC) gain	k_{AGC}	-	Constant, tuned during simulation development
Current aggregate PHEV load[20]	p_{PHEV}	MW	Tabulated based on PHEV supply state updates from V2G controllers
Total change in regulation up	Δp_{up}	MW	
Total change in regulation down	Δp_{down}	MW	
Regulation reserve, up	$\Delta p_{up,res}$	MW	Total regulating reserve based on updates from V2G controllers
Regulation reserve, down	$\Delta p_{down,res}$	MW	

The methodology for determining a supply recommendation is similar to that used in the distributed intelligent load shedding work discussed in Section 4.3. As the coordinator updates the supply recommendation the individual V2G controllers will send a status update if they adjust their power level to contribute to frequency regulation.

[20] This includes only vehicles participating in frequency regulation through V2G.

The general methodology is described by the following steps:

Step 1: Estimate the local area control error (ACE) using Δf , $\Delta f\,'$, and the local area frequency response characteristic β.

Step 2: Neglecting tie-line power flow determine the local automatic generation control (AGC) signal as the integral of the ACE signal with a gain of k_{AGC}.

Step 3: Update the local AGC recommendation with local V2G controllers.

Step 4: Local V2G controllers update their regulation supply status with the PHEV coordinator to notify of change in supply and supply availability.

Step 5: Update the system operator with updates to local PHEV regulation supply. System operator will modify central AGC dispatch signal accordingly.

As a first step in modeling, the PHEV coordinators will not exchange information and dispatch without updates from neighbors. If time permits it may be beneficial and necessary to exchange local frequency, load, and regulation supply information. The V2G controllers will be responsible for notifying the coordinator when V2G control has been overridden or the vehicle is no longer available. The details of PHEV coordinator implementation including computation of the supply recommendation and tuning the local frequency bias constants are discussed in Chapter 5.

4.2 System Control Strategy

Aside from the objectives of the area electric power system and PHEV controllers, we would like the integrated distributed control system to achieve the following with respect to traditional automatic generation control (AGC):

1. Minimize generation control efforts,
2. Balance generation and load in closer-to-real time, and
3. Minimize the impacts on individual PHEV.

Two layers of control are used in power systems today the first consists of the automatic protection system which includes relays and circuit breakers protecting individual pieces of equipment. This control acts locally and quickly with a time scale on the order of milliseconds and is reactive in nature. This means that if a measured quantity is outside of safe operating limits the equipment is taken out without considering the context surrounding the disturbance or the actions taken by neighboring controllers.

The second layer of control is the Supervisory Control and Data Acquisition/Energy Management System (SCADA/EMS) which gathers measurement data throughout the system to determine the system’s operating state. After state estimation is complete security analyses are performed and control decisions made. It can take several minutes to gather the system data and perform the state estimation after which time it may be too late to mitigate the effects of a cascading failure.

Therefore, it is desirable to employ a control system that combines the speed of the local primary protection system with the more intelligent approach used at the system operator level. A multiagent system can be used to perform the duties of the PHEV coordinator and the V2G controllers in combination with the power system simulator. In implementation a power system agent will simply be a processor with some memory located within power system monitoring and control equipment.

These agents will perform control functions based on local operating data which results in huge computational savings when compared to performing state estimation for an entire power system. Based on the local operating state, agents will determine what actions need to be taken and may consider historical trends and information from neighboring agents to determine the context surrounding system behavior at their location. The agents will provide autonomous, proactive control within their local system. The following section describes the relationships between the various control components used in this study.

4.2.1 Control Architecture

The multiagent system used to perform distributed frequency regulation will have a hierarchical structure. As discussed in Section 4.1 the V2G controllers and PHEV coordinator will work together to determine regulation needs and control local dispatch. The simplest controller, the V2G controller will reside within each PHEV to monitor and control battery charging and discharging while a vehicle is plugged in. The objective of the V2G controller is to control charging based on the owner's preferences and while minimizing the impact on the life of the battery system. Although the V2G controller relies on the PHEV coordinator to inform its control decisions, it will necessarily make the decisions without regard for what neighboring V2G controllers are doing. Therefore the V2G controller layer represents decentralized control.

On the other hand, interacting with neighboring coordinators may improve the quality of local control a PHEV coordinator provides. Therefore the PHEV coordinator level represents distributed control. Figure 8 illustrates the architecture of controllers throughout the system and shows the coordination among different components.

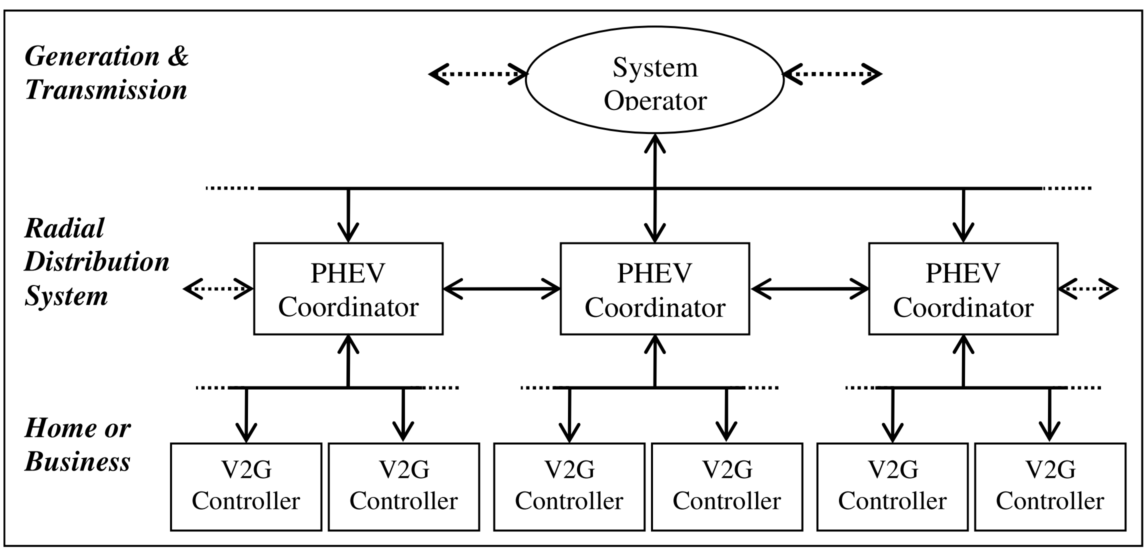

Figure 8
Distributed Controller Hierarchy

Appendix C presents agents that may be used for a more comprehensive V2G implementation. The agents are based on the multiagent system outlined in the article Toward Self-Healing Infrastructure Systems", by Dr. Massoud Amin [33].

4.3 Previous Work with Distributed Intelligent Load Control

One application of distributed control in electric power systems is underfrequency load shedding (UFLS) which is used to avoid blackouts following events that lead to underspeed tripping of generators. The loss of a large generator or large increases in system load causes synchronous machines to slow down. To avoid damage to machines damaging generators and keep them following events that lead to restore load-generation balance in a power system. The use of intelligent agents located at each generator and load bus in the system allows for an adaptive response to generation shortages. The agents detect the onset of disturbances and dynamically determine the amount, location, and timing of load shedding.

The following work was initially carried out as a class project during the fall of 2006 in Artificial Intelligence, a course offered by the Department of Computer Science and Engineering [34]. A dynamic simulation of the standard IEEE 14 Bus System developed by the author was used as a basis to test distributed intelligent underfrequency load shedding [15]. The work was a joint effort with Geteria Onsongo, a PhD Candidate in Computer Science. The power system simulator has been upgraded and several bugs identified and fixed. The results presented here differ slightly from the original report prepared for the class per simulator updates and additional debugging.

The power system simulator is implemented in MATLAB and Simulink and models the speed response of synchronous machines due to changes in system load to study frequency control in power systems. The IEEE 14 Bus System includes five generators modeled as synchronous machines and 11 loads with an initial steady-state load of 329 MW. Generator 2 on also includes automatic generation control (AGC) logic to eliminate steady-state frequency error following a load-generation imbalance. Figure 9 shows the topology of the IEEE 14 bus system.

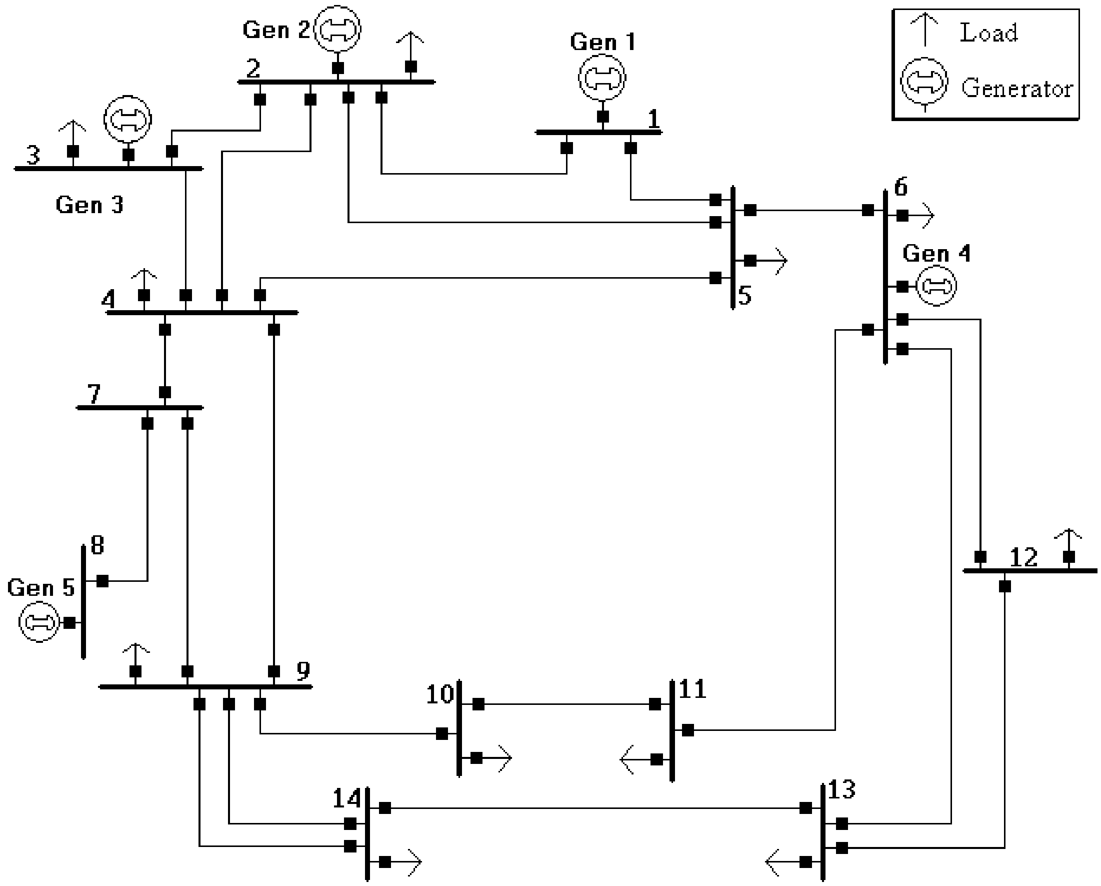

Figure 9
Oneline Diagram of the IEEE 14 Bus System

Two UFLS schemes were used to study the speed response of generators and consequently system frequency with a shortage of generation capacity. The first UFLS scheme that was used is similar to UFLS implementations currently in use today and the second used intelligent agents to dynamically determine the amount of load to shed based on local operating parameters.

To study system behavior islanding is induced by removing four transmission lines from service electrically isolating bus 6. In the rest of the system generators 1-3 and 5 effectively see a 59% increase in load and begin to slow down as a result. To avoid damage to the synchronous machines underspeed breakers are included in the synchronous machine models, set to trip at 59.6 Hz. Figure 10 shows that generators 1-3 and 5 trip offline due to underspeed leading to total system blackout in under a second following islanding.

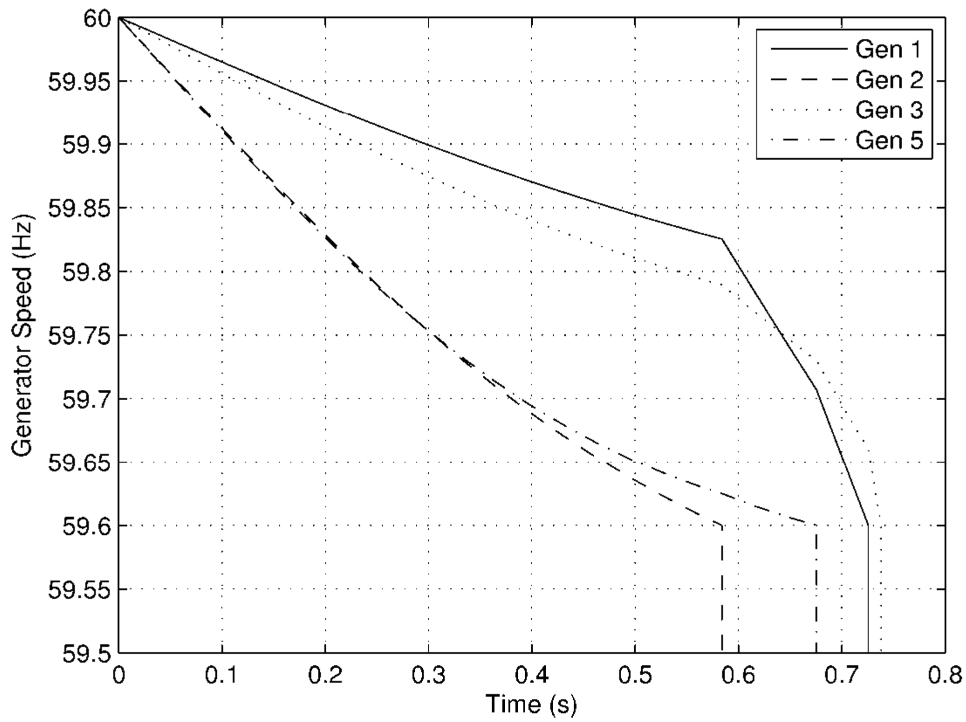

Figure 10
Generators with Tripping Due to Underspeed Following Islanding

The UFLS program requirements set forth by the Mid-Atlantic Area Council (MAAC) was used as a model [35].[21] The MAAC criterion requires distribution companies within its region to shed 30% of their load in three 10% steps at 59.3 Hz, 58.9 Hz, and 58.5 Hz. In the IEEE 14 Bus System, UFLS was implemented using two shedding levels at 59.8 Hz and 59.7 Hz. The frequency step sizes for the shedding levels are higher than what might be used in real power systems in order to achieve the desired simulation scenario. The initial load in the 14 bus system is 329 MW, and a value of 400 MW is used for the peak load in the system. So, at the each of the two underfrequency thresholds, 10% of the peak load (40 MW) is shed. The locations of the load shedding were chosen arbitrarily and can be seen in Table 14.

[21] The program outlined in [35] is a legacy criteria which augments the reliability standards of Reliability*First* and is not an enforceable reliability standard.

Table 14
Load Shed Increments for Traditional UFLS Scheme

Bus Number	Level 1	Level 2
3	-	10 MW
4	10 MW	10 MW
5	10 MW	20 MW
9	-	10 MW
11	-	10 MW
12	10 MW	10 MW
14	10 MW	10 MW
TOTAL	**40 MW**	**80 MW**

Using a traditional UFLS scheme all generators remain online and blackout is avoided. Figure 11 shows the machines' responses with traditional UFLS where level 1 shedding occurs at 0.24 s and level 2 shedding occurs at 0.55 s.

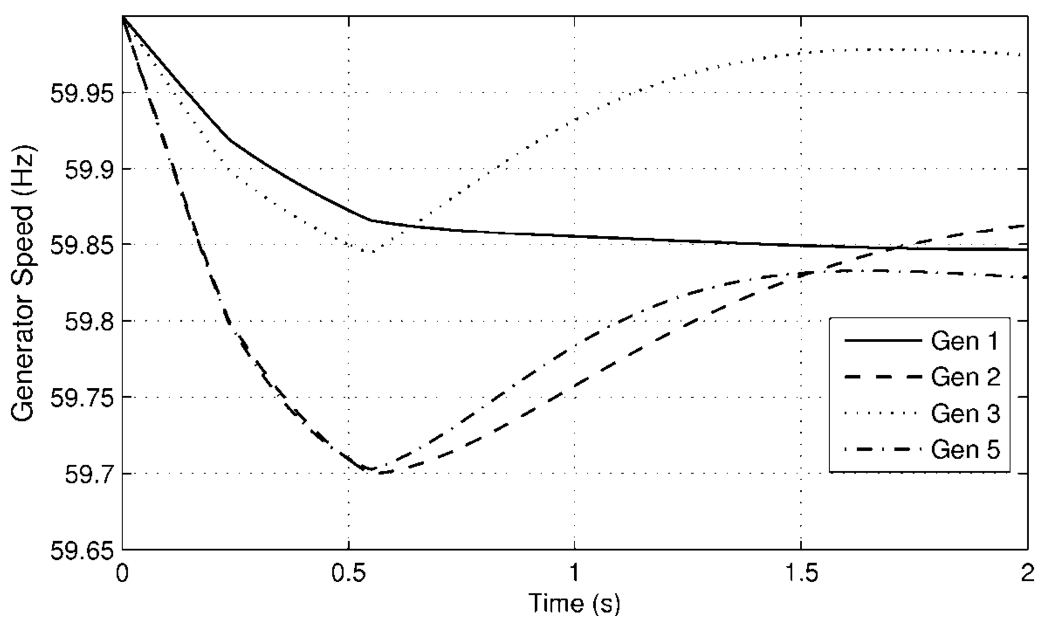

Figure 11
Frequency Response using a Traditional UFLS Scheme

Note that the speed of several of the generators sees a large swing in the opposite direction indicating that UFLS may have overcompensated for the severity of the generation shortage. Tightly coupled system will swing together following the same general response, in reality the response will depend on the geographic location of a load change or in this case the redistribution of generator demand following change in network topology.

The goal of the project was to use autonomous agents located at buses with generation and/or load to determine the amount of load to shed dynamically based on the local system state. Two types of agents were proposed, generator agents for each synchronous machine and load agents for each bus that serves load. Generator agents are able to determine if they are approaching trip point by estimating the maximum frequency swing and the amount of additional load the machine can serve before the underspeed breaker trip point. A load shed request is then sent to the closest load buses (including load on own bus).

In this scenario the amount of load dropped is proportional to the generator's frequency deviation (as measured by noting the rate of change of its phase angle) at the local generator bus and therefore the amount of load dropped will be just enough to avoid underspeed tripping.

A load agent's state includes current load in megawatts MW load value, and the status of all lines attached to the bus. The generator agent state includes generator angular acceleration, deviation from synchronous speed (60 Hz), underspeed breaker status, and MW flow and status of attached lines. The objective of for the generator agent includes the machine being online, and for the load agent, the objective is to restore the load-generation balance in the system with the minimum amount of load shed. A simplifying assumption was made that all buses have the necessary sensors to define their agent's state and that these measurements contain no noise or error. The following steps were used by generator agents to generate load shed trip signals for nearby loads.

Step 1: Use the difference between the generator's output Δp_m, and the electrical demand on the machine Δp_e, to estimate the maximum swing in generator mechanical power output, where α is the generator's acceleration and M its inertia constant:

$$\Delta p_{est} = \Delta p_m - \Delta p_e = M\alpha(t)$$

Step 2: Use Δp_{est} Estimate the maximum frequency deviation Δf_{est} using the machine's speed droop constant R (Hz/MW):

$$\Delta f_{est} = -R \cdot \Delta p_{est}$$

Step 3: Add Δf_{est} to the current frequency deviation at the load bus, Δf to find the total estimated deviation from 60 Hz:

$$\Delta f_{total,est} = \Delta f + \Delta f_{est}$$

Step 4: Request load shedding from a nearby load agent according to the total estimated deviation $\Delta f_{total,est}$:

If $\Delta f_{total,est} \leq -0.4\text{Hz}$, then set level 1 alarm,
Else if $-0.4\text{Hz} < \Delta f_{total,est} \leq -0.35\text{Hz}$, then set level 2 alarm.

Step 5: Estimate the amount of load the generator could supply without tripping, using a "safe" frequency deviation limit of -0.3 Hz (underspeed breakers set at 59.6 Hz) and R:

$$\Delta p_{safe} = -0.3\frac{1}{R}$$

Step 6: Determine the amount of recommended load shed using Δp_{est} found in Step 1 and Δp_{safe} from Step 5:

$$p_{shed} = \Delta p_{est} + \Delta p_{safe}$$

Note that the sign of Δp_{est} will be positive and the sign of Δp_{safe} negative when generators are decelerating following an apparent increase in load. To allow time for governor response and AGC action before underfrequency load shedding is used, a time delay of 3 cycles (0.05s) was used before load agents responded to level 1 trip signals and less severe level 2 trip signals were delayed until after 6 cycles (0.1 s). The amount of load to shed was updated continuously by generator agents and if the trip signal was still present after the 3-6 cycle shed delay a load agent would shed according to the latest value of p_{shed}. When islanding occurs in the system AGC function ceases so governor action is the only type of frequency control acting within the simulation. A similar set of steps will be used by the PHEV coordinators to determine a frequency regulation supply recommendation for the local V2G controllers.

Agent operators were also developed for the project to facilitate communications between the agents in the system, however due to time and simulation constraints the messaging was not implemented in the simulation. The main simulation constraint during the project was the simulation timing in Simulink and the effects of zero-crossing detection on the network model implemented as a MATLAB function block within the Simulink model. When Simulink is pinpointing a zero-crossing event the simulation time will step backwards and the system state within the Simulink blocks is also rolled back to match the simulation time. Within the power flow calculation changes are made to the system's state and without proper handling, the network model remains in its updated state while the Simulink model state steps backwards. Since the project was carried out modifications have been made to the power system simulator to handle zero-crossing detection. These issues and modifications are discussed in more detail in Chapter 5.

As a workaround the estimation calculation was coded in the power flow function and the resulting load shed trip signals and drop estimates were analyzed to find when agent load shedding would occur. The resulting trip signals and load shedding were then hardcoded in the power flow. Two cycles of load shedding were necessary to respond to the apparent load increase after islanding occurs in the IEEE 14 Bus System as follows.

1. Level 1 trip signals from generators 2 and 5 at $t = 0$ seconds granted after 3 cycles,
2. Second level 1 trip signal by generator 5 at $t = 0.05$ again granted after 3 cycles.

Following the second round of load shedding, no further trip signals were generated and the system began to settle at a new steady-state operating point. Table 15 shows the resulting trip signals and shedding information for the system.

Table 15
Load Shed Increments for Agent UFLS

Trip signal	Level	Generator	Load Bus	Time of Shed	Shed Amount
1	1	2	2	0.05 s	18.9 MW
2	1	5	9	0.05 s	4.76 MW
3	1	5	9	0.1 s	2.97 MW

The speed swing of generators 1-3 and 5 following islanding using the distributed intelligent load shedding scheme can be seen in Figure 12.

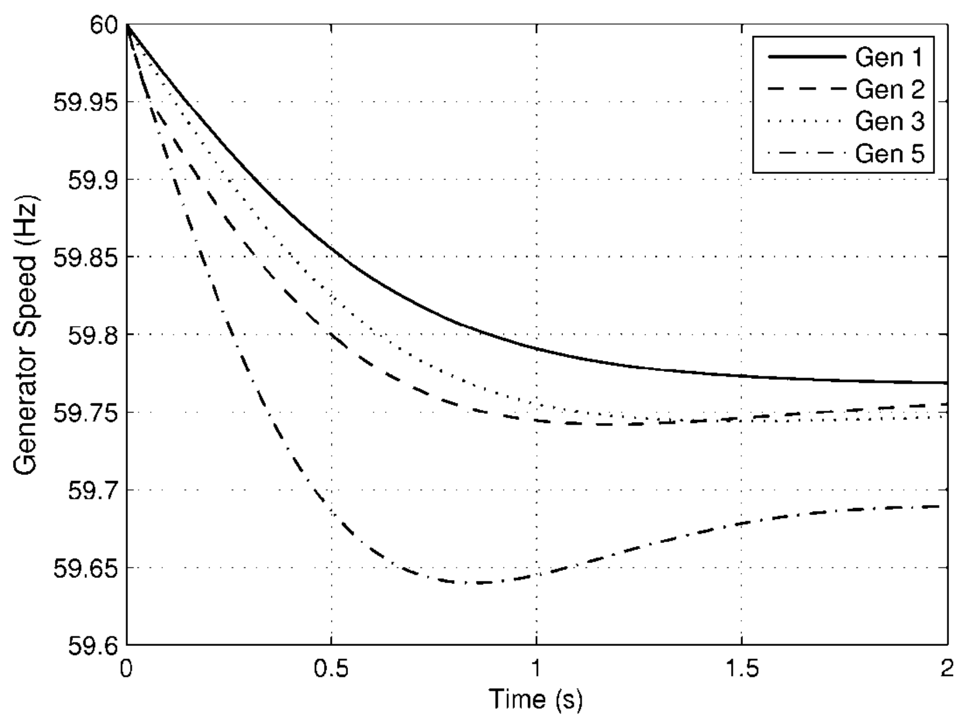

Figure 12
Frequency Response with Distributed Intelligent UFLS Scheme

This load shedding strategy ends up targeting generators 2 and 5 which see the biggest frequency swing due to their location. Agent based load shedding provided a more even speed response across all generators in the system compared to the traditional UFLS scheme. Overall 63% less load was dropped when the quantity of load to be shed was determined based on local operating parameters and predicted frequency swings. Figure 13 shows the system response to both UFLS schemes side by side.

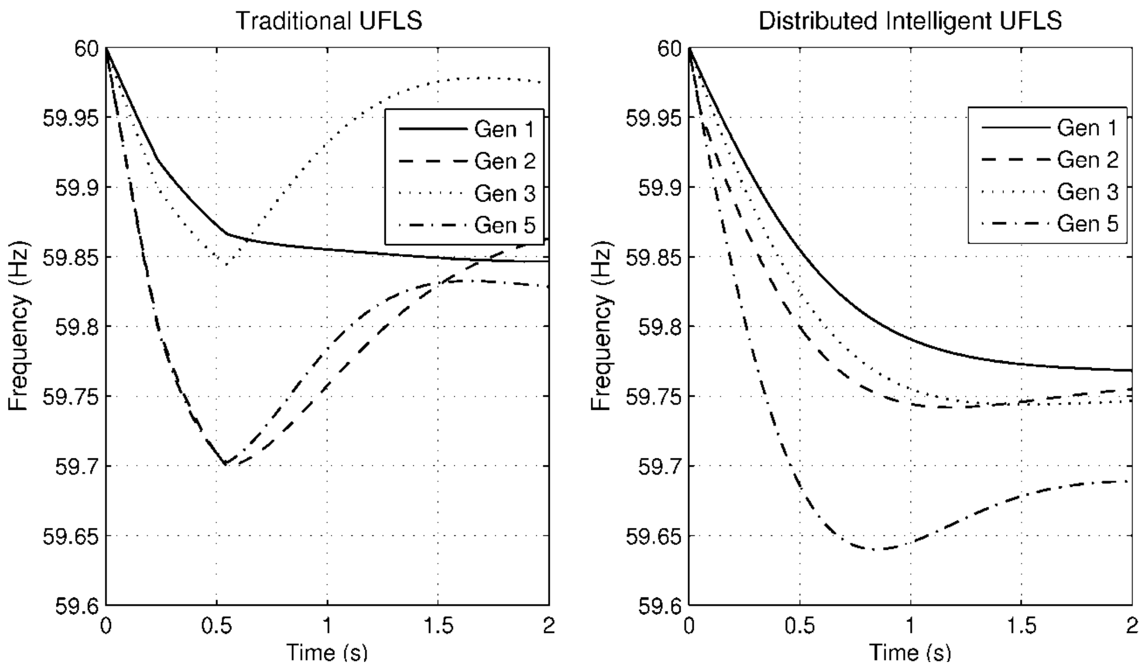

Figure 13
Comparison of Traditional and Distributed Intelligent UFLS Schemes

Agent based load shedding had a less drastic effect on generator speed than the traditional UFLS, however both schemes were able to arrest the frequency deviation following islanding in the IEEE 14 Bus System. Although generator 5 sees a bigger swing with agent based UFLS, underspeed tripping was successfully avoided. Upon inspection of the event log from the simulation trip signals were continuously generated by generator 5. The amount of load shed requested when the trip signals are initially generated would have damped the swing experienced by generator 5. UFLS is specifically meant to restore load-generation balance after a generation shortage and is not meant to be used in daily load-generation balancing. The delay before agent shedding allows primary and secondary frequency control to contribute as much as possible which then minimizes the amount of load shed with UFLS. In this way primary and secondary frequency control are allowed to perform their functions and UFLS contributes only as needed.

5 SIMULATOR

In the context of the bulk power system the basic objective is to make sure that there is enough power being generated to supply the power drawn by the system load; providing customers with a secure and reliable electrical energy supply. There are several types of measures to determine how well the system is operating including: power balance, voltage performance, and financial returns. Each consumer and stakeholder will have a unique set of expectations and desired outcomes with respect to power system performance.

To simulate the use of plug-in hybrid electric vehicles (PHEV) as a source of distributed frequency regulation a model including power system behavior, PHEV loads, and additional controllers is necessary. Originally EPRI's OpenDSS distribution system simulator had been considered to model power system behavior [14]. However, the bulk power system is represented by an equivalent voltage source and, to capture the relevant behavior of the system a dynamic generator model along with calculation of the area control error (ACE) is needed. Instead of using OpenDSS, a transmission level power system model developed at the University of Minnesota will be used [15].

The generation model will basically represent the speed response of generators to changes in loading. Using the system frequency the ACE can be calculated and from that a traditional automatic generation control (AGC) dispatch signal can be derived. This AGC signal is of primary importance here since we'd like to see how it is affected when storage is used to supply regulation.

The IEEE 14 Bus System will be used as a testbed for this study. The system is quite small but as a first implementation is much less cumbersome than using a larger system. The 14 bus system includes 5 generators and 11 buses with load attached. To capture the behavior of PHEV while plugged-in to the grid, an aggregate load profile will be included at each of the load buses in the system. Figure 14 shows the oneline for the 14 bus system with the aggregate vehicle load connected through a PHEV coordinator.

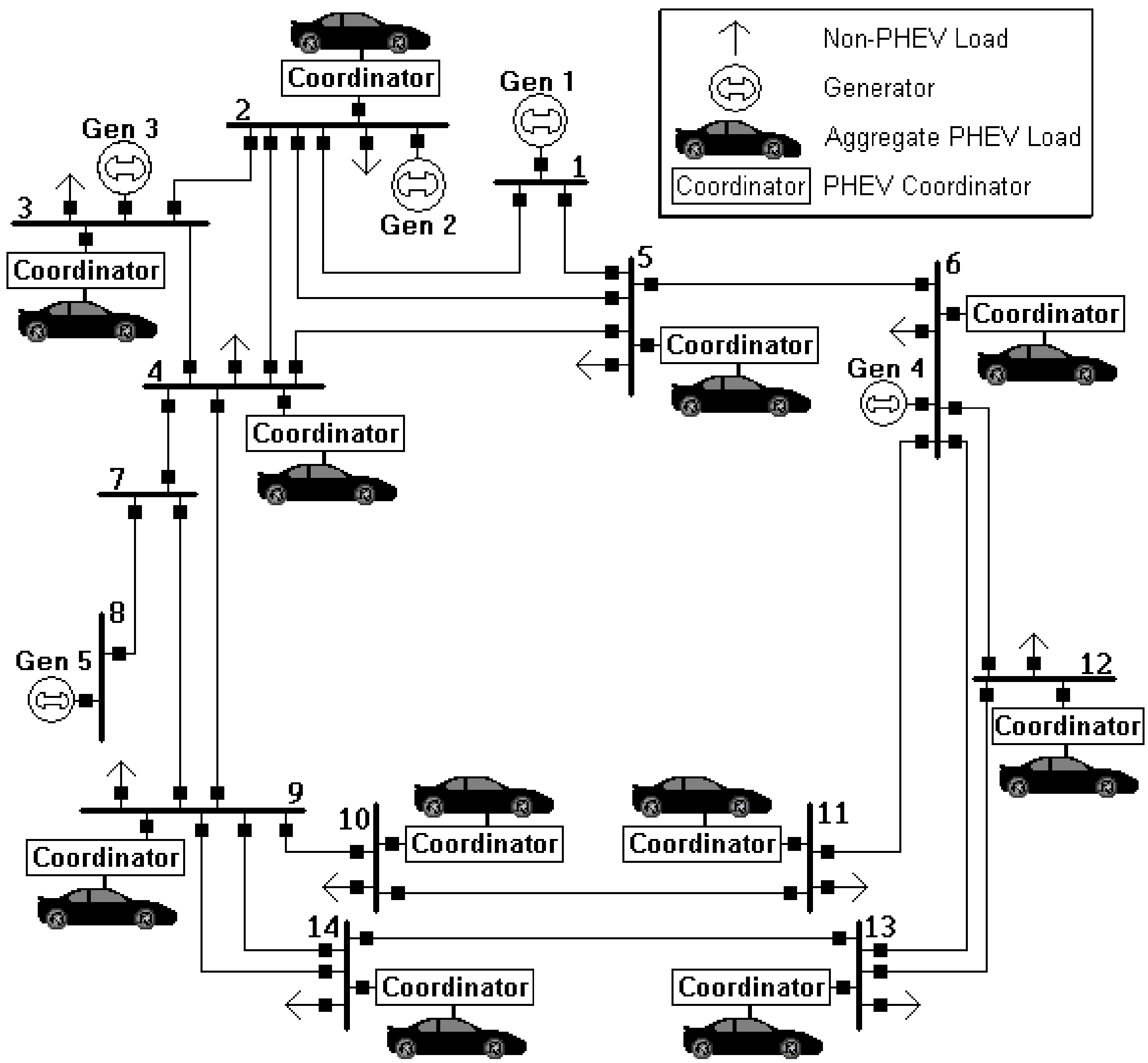

Figure 14
IEEE 14 Bus System with PHEV Coordinators and Aggregate PHEV Loads

The PHEV coordinator will not act as an interconnection for energy transfer to and from PHEV participating in V2G. However all communications necessary between the PHEV and the system operator to facilitate distributed frequency regulation will be handled by the coordinator. In addition although the PHEV coordinator is illustrated as connecting to the bus through a breaker, a physical disconnect would not be used in implementation. Instead the breaker represents the notion that at the behest of the system operator or due to abnormal conditions in the bulk system the V2G service provided by the local PHEV may be interrupted. For a PHEV interconnecting with the grid as a distributed resource a manual disconnect may indeed be required at the charging site for the safety of utility maintenance workers. Table 16 presents parameters for the total system including the power system simulator and the additional components used for PHEV testing.

Table 16
System Wide Model Parameters

Parameter	Value	Notation
Number of buses	14	-
Number of transmission lines	21	N_{lines}
Number of generators	5	N_{gen}
Number of load buses	11	-
Initial non-PHEV load	259 MW	p_{init}
Initial PHEV load[22]	39 MW	p_{PHEV}
Nominal system frequency	60 Hertz	f_{syn}, ω_{syn}
Initial total load	298 MW	$p_{total,init}$
Peak total load	382 MW	-
Frequency bias constant, bulk system	375 per unit	B_f
Automatic generation control gain	0.08	k_{AGC}
System base power	100 MW	$\mathrm{P}_{\mathrm{base}}$
Base frequency	60 Hertz	$\mathrm{f}_{\mathrm{base}}$

Communications systems are not considered in this study, neither the physical implementation nor the protocols that may be used. Standards for communications systems on the user end are currently being developed and will continue to be refined as

[22] The PHEV load includes a total of 83,270 vehicles assumed to be participating in vehicle-to-grid where the vehicles are charged when they arrive home using a base charge rate of 1kW.

the smart grid is implemented. Future studies may consider the communications system to get a more realistic picture of how well the distributed control works.

The rest of the chapter describes the implementation of the simulator, beginning with a discussion of the power system simulator in Section 5.1. Section 5.2 discusses PHEV load modeling and the additional control components.

5.1 Power System Simulator

The power system simulator is a Simulink model with generators modeled as synchronous machines; the generator models interface with a MATLAB subsystem which models the rest of the system. The generator models, system control models, and system behavior were originally developed at the University of Minnesota as a Master's thesis project implementing the IEEE 14 Bus System [15]. The network model consists of transmission lines and island checking is performed before calculating the DC power flow for the system. The simulator is designed to study the speed response of thermal generating units to changes in system loading, and to facilitate testing of novel control strategies for balancing load and generation. One example of this is distributed agent-based underfrequency load shedding (UFLS) which was discussed in Section 4.3.

With the support of Oak Ridge National Lab (ORNL) from July 2005 through August 2007[23], the simulator presented in [15] was modified with additional control functionality and updated to deal with simulation timing in Simulink as follows:

1. Line overload tripping after a constant relay plus breaker operating time,
2. Underfrequency load shedding to mitigate generator underspeed tripping,
3. Automatic generation control performed by all generators, and
4. Zero-crossing handling in the MATLAB network model when the Simulink model performs zero-crossing detection.

[23] Between July 2005 and August 2007 work was funded by the ORNL SensorNet project under support from Dr. Arjun Shankar, and by Professor Massoud Amin's research initiative grant provided by the Technological Leadership Institute (TLI) and the Institute of Technology at the University of Minnesota.

The behavior of the synchronous machines within Simulink is simulated using a variable-step size solver and when a zero-crossing is detected in a relay or absolute value block the simulation time steps backwards to pinpoint the time of the discontinuity. The network model must track the time at which system load or line statuses change so that when simulation time steps backwards the system state within the MATLAB network model responds accordingly. In addition, the simulator was expanded to the IEEE 118 Bus System including a sequence of contingencies events which leads to system blackout. Event logging was also added to the network model to record contingency events and system control actions such as UFLS.

Beginning September 2007 further modifications were made to the simulator to facilitate implementation of this study, with the support of the Electric Power Research Institute[24] (EPRI). The following adjustments were made to the Simulink and Matlab models:

1. Secondary frequency control loop (AGC) is external to the synchronous machine subsystems,
2. New Simulink masked[25] subsystem is used for AGC dispatch including computation of the average system frequency and the area control error (ACE),
3. Total AGC is parsed out based on each generator's AGC participation factor,
4. Bus loads are implemented within the Simulink as a 24 hour demand curve,
5. Frequency deviation is calculated in the Simulink model for buses with only loads using bus angles from the DC power flow, and
6. The rate of change of frequency is calculated for all buses with generation and/or load.

Figure 15 illustrates the interconnections between the various components of the power system simulator Simulink model.

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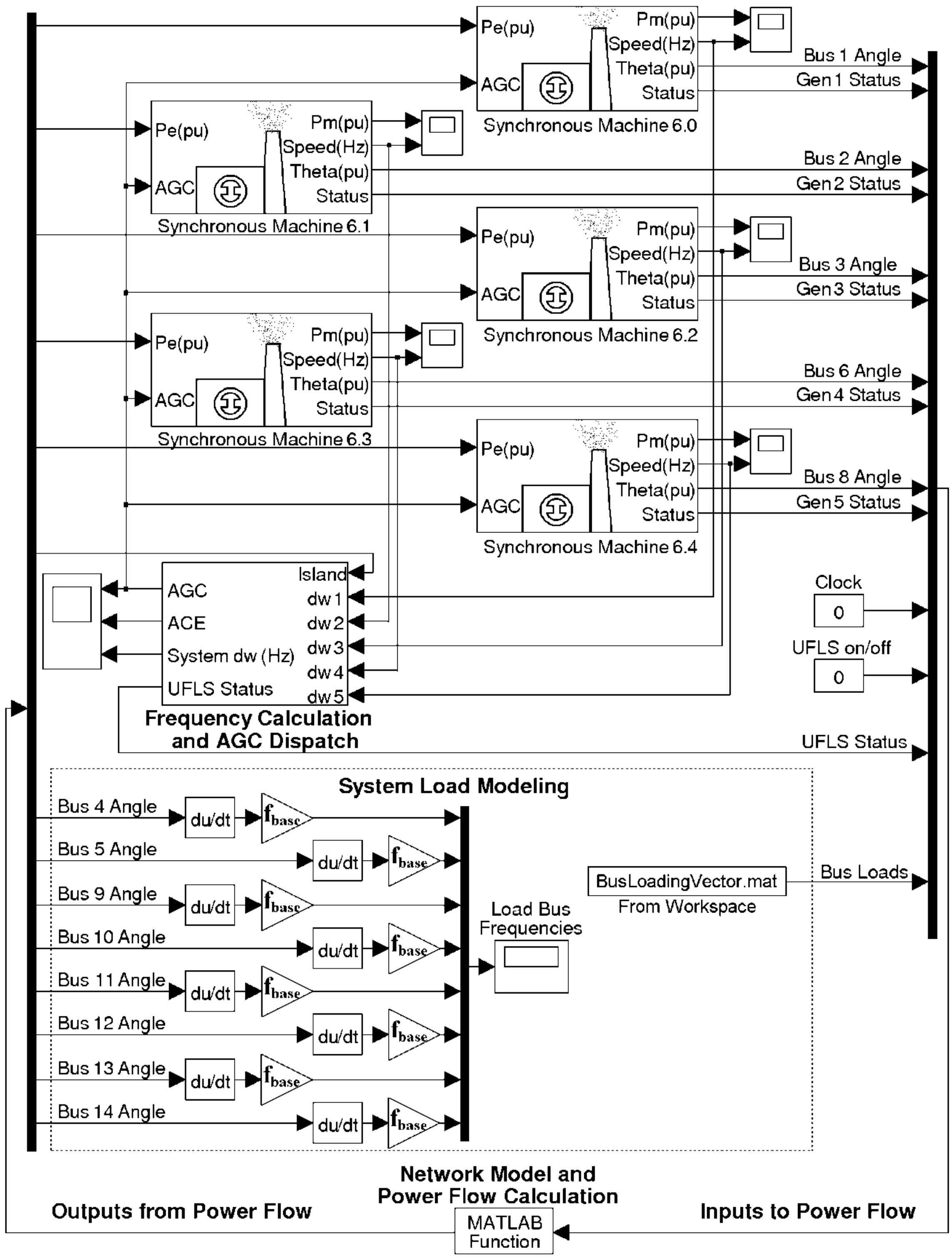
[24] Beginning in September 2007 through completion, work was supported through the EPRI PhD Innovation Fellowship.

[25] A mask is used to hide the contents of the subsystem so that users cannot modify the subsystem and provides a user interface where subsystem parameters may be entered. The masked subsystem blocks reside within a Simulink library model file and may then be placed in models as you would any other block from the main Simulink library.

Figure 15
Simulink Model of the IEEE 14 Bus System



Model Features:

1. Generator speed changes with changes in demand,
2. System ACE calculated using average generator bus frequency deviation,
3. Underfrequency load shedding may be enabled using the UFLS on/off constant block,
4. Induced contingency events are hard coded in the network model to take effect at a set time,
5. Scopes at each generator allow users to watch the mechanical power and machine speed swinging in response to load changes, and
6. Additional scopes are available to view additional system dynamics as needed.

The following sections describe the development and implementation of the synchronous generator model and controls, system load curves, automatic generation control, and the network model including the DC power flow calculation.

5.1.1 Synchronous Generator Model

Within the power system simulator generators are modeled as synchronous machines including a governor, non-reheat turbine and rotating mass. The model is based on the application of Newton’s law to the electrical and mechanical torques acting on the machine’s rotating mass.

In [15] a single machine within the IEEE 14 Bus System would contain an integrator loop to correct steady-state frequency error and in effect perform automatic generation control for the entire system. In later versions, each of the machine models had an internal AGC loop and the AGC gain for each machine could be input through the subsystem mask. To perform this study, AGC was taken out of the machine models and is performed for the system as a whole using the average frequency deviation across the generator buses. The implementation of AGC dispatch within the Simulink model is discussed in Section 5.1.3. The inputs and outputs for the synchronous machine block are shown in Table 17.

Table 17
Inputs and Outputs of the Synchronous Machine Model

User Input Machine Parameters	**Units**	**Source/Sink**	**Notation**
Governor speed droop, reciprocal	Per unit, MW/Hz	Subsystem mask	$1/R$
Machine inertia coefficient	Per unit, seconds	Subsystem mask	M
Initial steady-state power	Per unit, MW	Subsystem mask	-
Initial steady-state rotor angle	Radians	Subsystem mask	-
AGC participation factor	-	Subsystem mask	pf
External Inputs			
Electrical demand on machine	Per unit, MW	MATLAB power flow	p_e, p_{gen} [26]
AGC dispatch signal	Per unit, MW	AGC subsystem	u_{AGC}
Outputs			
Mechanical power output	Per unit, MW	Generator scope	p_e
Speed deviation from 60 Hz	Hertz	AGC subsystem	$\Delta\omega$
Generator rotor angle	Radians	MATLAB power flow	δ
Generator status	-	MATLAB power flow	-

The AGC dispatch signal, u_{AGC} is a control input to the machine which performs integral feedback control based on the speed deviations for all the generators. Changes in electrical demand Δp_e, are also input to the machine representing a measurable disturbance. The AGC participation factor pf is used to parse the AGC dispatch signal amongst the generators. The sum of participation factors over all of the generators must add to one. Within the machine model the time constants for governor and prime mover transfer function blocks are represented by T_g and T_{ch} respectively. Values of $T_g = 0.1$ and $T_{ch} = 0.2$ were chosen based on typical values. A load damping factor of $D = 0.001$ was used to represent the frequency dependence of the system load. The following state-

[26] Within the MATLAB DC power flow function the demand on a generator at a bus is referred to as p_{gen} which is the sum of the net power injected and the load at the bus.

space equations represent generator dynamics including the response to load changes and AGC dispatch, along with the output equation y:

$$\begin{pmatrix} \Delta\dot{\omega} \\ \Delta\dot{p}_m \\ \Delta\ddot{p}_m \end{pmatrix} = \begin{pmatrix} -\frac{D}{M} & \frac{1}{M} & 0 \\ 0 & 0 & 1 \\ \frac{-1}{T_g T_{ch} R} & \frac{-1}{T_g T_{ch}} & \frac{-(T_g + T_{ch})}{T_g T_{ch}} \end{pmatrix} \cdot \begin{pmatrix} \Delta\omega \\ \Delta p_m \\ \Delta\dot{p}_m \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ \frac{-pf}{T_g T_{ch}} \end{pmatrix} \cdot u_{AGC} + \begin{pmatrix} -\frac{1}{M} \\ 0 \\ 0 \end{pmatrix} \cdot \Delta p_e$$

$$y = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \cdot \begin{pmatrix} \Delta\omega \\ \Delta p_m \\ \Delta\dot{p}_m \end{pmatrix}$$

The machine model also includes over/underspeed breaker action which will cause the machine's status to go to zero when the speed deviation from 60 Hz is greater than or equal to 0.4 Hz. Within the network model a generator bus will become a generic load bus with zero load and unknown angle after the status goes to zero.

The outputs from the machine dynamics model are modified for use within the general Simulink model and the power flow calculation. The deviation in mechanical power from the initial steady-state operating point is summed with the initial power value to give the total mechanical power output of the machine. The change in angle $\Delta\delta$ is calculated by taking the integral of the speed deviation and then summed with the initial machine angle. The rotor angle is then used to calculate the power flow within the network.

The constituent pieces of the synchronous machine model are interconnected and packaged within a Simulink library model file as a masked subsystem. User inputs are entered through the subsystem mask when the block is placed within a Simulink model. Figure 16 shows the machine subsystem including the inputs and outputs. Note that the rotating mass is illustrated as a single block bus is implemented using several components to allow M to be a user input.

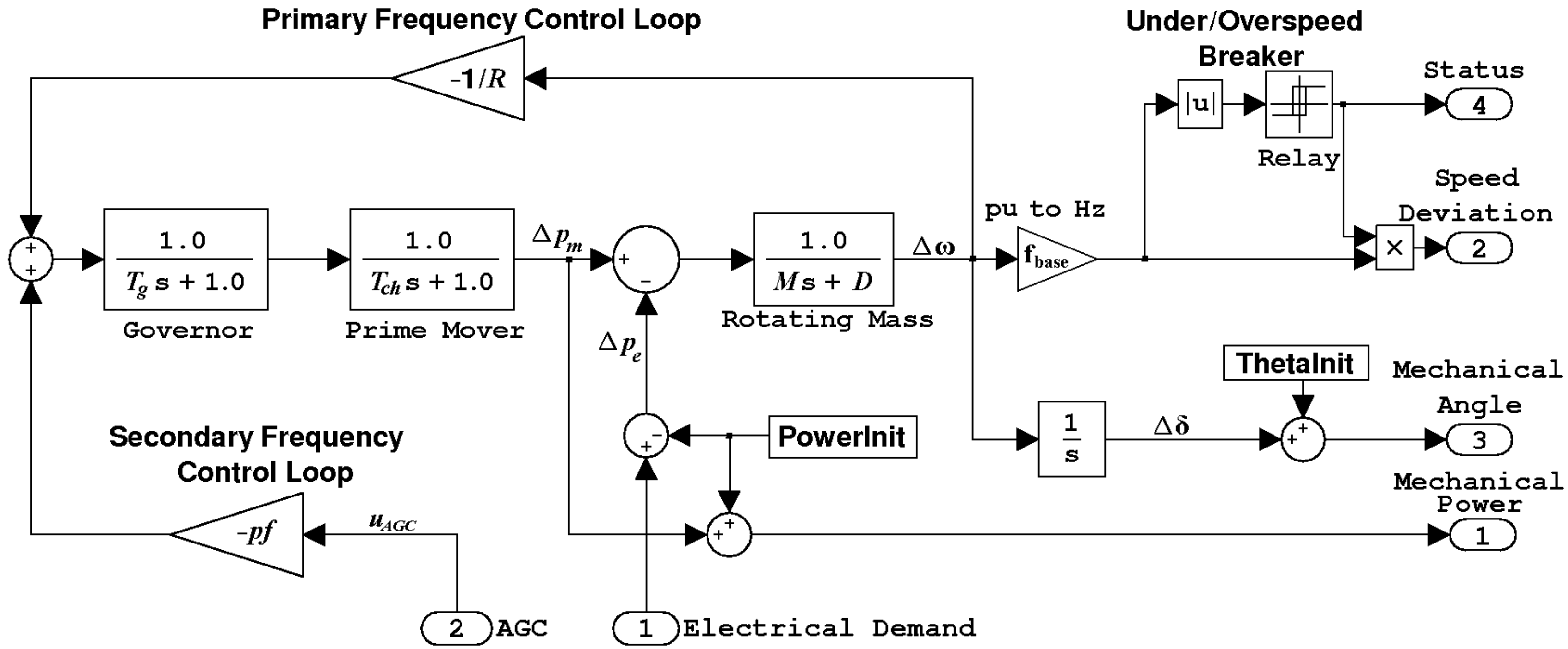


Figure 16
Simulink Model of Synchronous Generator

The deviation of the mechanical power output and electrical demand of a machine from the initial steady-state values are denoted by Δp_m and Δp_e respectively. Similarly the deviation in rotor angle from the initial value is denoted $\Delta\delta$ and the speed deviation from the nominal 60 Hz is denoted $\Delta\omega$. Table 18 shows the parameters used for the five machines in the IEEE 14 Bus System.

Table 18
Generator Parameters for the IEEE 14 Bus System

Generator	Bus	p_{init} (MW)	$1/R$ (per unit)	M (per unit)	AGC Participation Factor
1	Bus 1	54	75	25	0.2
2	Bus 2	40	75	25	0.2
3	Bus 3	60	75	25	0.2
4	Bus 6	70	75	25	0.2
5	Bus 8	74	75	25	0.2

The voltage magnitude is not modeled here, to save on computation time and with a focus on power imbalance and frequency a DC power flow is used which depends only on the voltage angle. An exciter model is typically included to perform voltage control, however here it is assumed that terminal voltage remains constant at 1 per unit. This assumption is based on the fact that exciter corrects voltage disturbances in tens of milliseconds, compared with governor action on the order of seconds to minutes. Compared to timescale of frequency control the voltage is corrected essentially instantaneously therefore an exciter model was not included. Based on these assumptions the machine's rotor angle is equivalent to the voltage angle and is therefore used to calculate the power flow for the system.

5.1.2 System Load Model

In earlier versions of the power system simulator the loads began each simulation with a predefined megawatt value (MW) defined in the network model. Load dynamics were represented as step changes in one of three scenarios: to initiate a load change event, to drop load as islands are deactivated, and to perform underfrequency load shedding. For this study the loads were moved into the Simulink model and are input to the MATLAB DC power flow function along with generator bus angles and other system variables.

A continuous load curve was desired to study the dispatch of frequency regulation over a period of several hours and a 24-hour load curve was used for both the bus loads and the aggregate PHEV loads. Although a clock signal is available within the MATLAB function, any discontinuous load behavior makes it difficult to recover the system state with zero crossing events. Therefore representing the loads within Simulink helps to streamline the simulation.

Non-PHEV bus loads were based on real-time 5-minute load data from the eleven nodes in the New York Independent System Operator (NYISO) territory [36]. Using weather data July 9th, 2009 was chosen as a basis for the bus loads; the day had highs and lows in the 70's (°F) with 0 in. precipitation. This implies that the NYISO system did not experience unusually high loading in the afternoon which might be experienced with higher temperatures. The plot of total NYISO load for July 9th is shown in Figure 17.

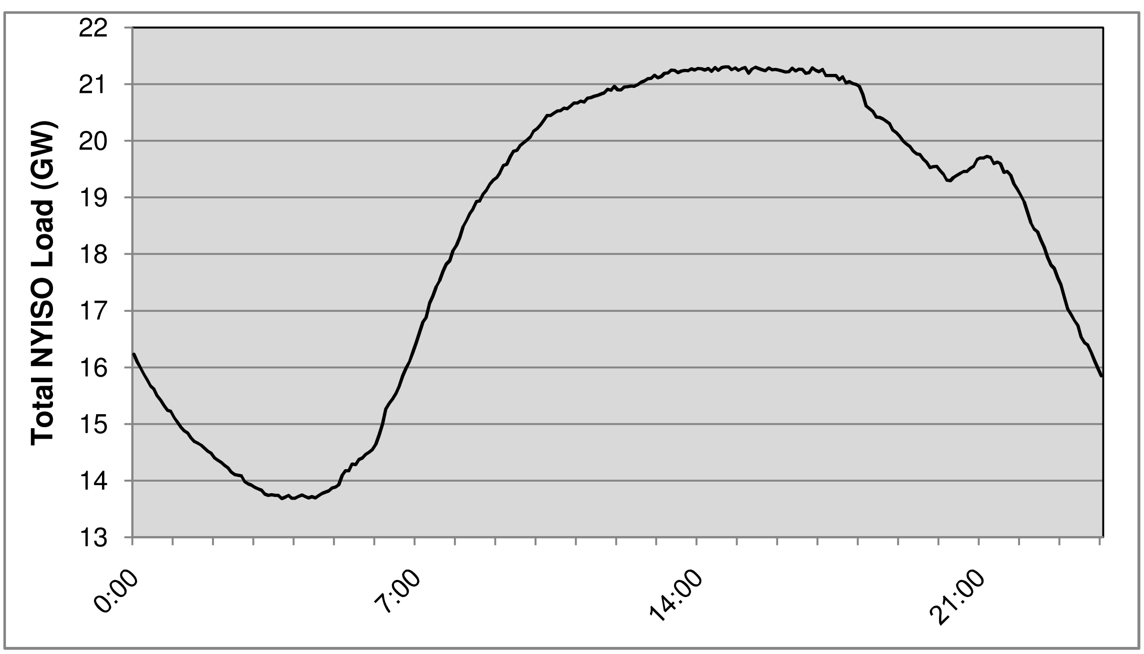


Figure 17
NYISO 5-Minute Real-Time Load Data for Total System on July 9th, 2009

Day-long load curves were developed using Microsoft Excel for each of the eleven load buses in the IEEE 14 Bus System using the following steps:

1. Nodal load values were normalized to the initial load (07/09/2009 0:00 AM),
2. Normalized 5-minute load data was scaled using the initial bus loads, and
3. Interpolated 5-minute load data to obtain 1-minute load data for each the eleven loads in the IEEE 14 Bus Sytsem.

The 1-minute load data and corresponding time stamps were saved as MAT-files to be used in a From Workspace[27] block in the Simulink model. The initial, peak, and average load for the non-PHEV loads along with the total system load can be seen in Table 19.

Table 19
Bus Non-PHEV Load Characteristics

Load	Bus	Initial Load	Peak Load	Average Load
1	Bus 2	22 MW	30 MW	25 MW
2	Bus 3	94 MW	137 MW	114 MW
3	Bus 4	48 MW	72 MW	62 MW
4	Bus 5	8 MW	10 MW	8 MW
5	Bus 6	11 MW	14 MW	11 MW
6	Bus 9	30 MW	42 MW	35 MW
7	Bus 10	9 MW	12 MW	10 MW
8	Bus 11	4 MW	5 MW	4 MW
9	Bus 12	6 MW	8 MW	7 MW
10	Bus 13	14 MW	17 MW	15 MW
11	Bus 14	15 MW	19 MW	16 MW
Total		**259 MW**	**362 MW**	**308 MW**

The final version of the simulator used a MAT-file with the total non-PHEV plus PHEV load for each bus. The From Workspace block outputs a vector of 11 bus loads which are

[27] A From Workspace block reads data from an array in the MATLAB workspace where the first element in each row is a time stamp and the remaining entries are the signal values corresponding to that time. The block outputs the data vector which corresponds to the current simulation time, for time values with no explicit entry the entry for the most recent time is output.

used in the MATLAB power flow. The development of the load models used for the PHEV participating in vehicle-to-grid is discussed in Section 5.2.1. A continuous 24-hour load curve for each bus was also developed, which fit a fourth order polynomial trendline to the 5-minute load bus data. The coefficients for these polynomials are available in Appendix A.

5.1.3 Automatic Generation Control

A primary concern in a power system is maintaining system frequency and scheduled tie-line power flow with adjacent systems. Traditionally these objectives are met by central generation units and as we move toward a self-healing grid these objectives may be met using varying operational paradigms and by a wider range of energy resources.

System frequency is an indicator of how well system generation matches the system load. As load increases synchronous machines will slow down and as load decreases the machines will speed up. Section 3.2.1 presented an overview of traditional frequency regulation and the two levels of regulation:

1. Primary: generator governor response to changes in rotor speed to arrest initial frequency excursions, and
2. Secondary: automatic generation control (AGC) to eliminate the steady-state frequency error and bring system frequency back to the nominal 60 Hz.

Governor action arrests frequency deviations in a few seconds, and AGC restores system frequency in several minutes. Generators participating in AGC will receive periodic signals to raise or lower their reference set point by a MW amount based on frequency deviation and tie-line power flow deviation. As system load increases generators providing AGC will be asked to increase their output to provide regulation up and conversely as load decreases the generators will be asked to decrease their output to provide regulation down. As generators respond to changes in their reference set point, system frequency will begin to return to 60 Hz and in turn governor action will cease. As a result any synchronous machines not participating in AGC will return to their initial operating state. Typically generating units on AGC control will be required to respond to raise/lower signals in a minute or less, with a service duration on the order of minutes.

The IEEE 14 Bus System was modeled as a single control area and therefore tie-line power flow was not considered when determining the ACE. As an initial implementation of AGC a single machine block included an integrator loop to eliminate steady-state frequency error in the IEEE 14 Bus System [15]. The AGC methodology was updated so that multiple machines could participate in AGC by including an integrator loop in every generator and allowing the user to input an AGC gain for each of the machines.

System-wide AGC was desired to be able to analyze the impacts of PHEV contribution to frequency control. As a result, a dedicated subsystem containing the automatic generation control system was used to determine the total AGC raise/lower signal. Table 20 shows the inputs and outputs for the system frequency and AGC system.

Table 20
Inputs and Outputs of the System Frequency and AGC Dispatch Calculation Model

User Input Machine Parameters	**Units**	**Source/Sink**	**Notation**
Frequency bias constant, bulk system	Per unit, MW/Hz	Subsystem mask	B_f
Automatic generation control gain	-	Subsystem mask	k_{AGC}
External Inputs			
Speed deviation of machines (from 60 Hz)	Hertz	Machine subsystems	$\Delta\omega$
Islanding indicator	-	MATLAB power flow	-
Outputs			
AGC raise/lower signal	Per unit, MW	Machine blocks	u_{AGC}
Area control error (ACE)	Per unit, MW	AGC scope	p_e
Average generator bus speed deviation	Hertz	AGC scope	$\Delta\omega_{sys}$
Maximum negative speed deviation	Hertz	MATLAB power flow	-

The generator frequency deviations from the machine blocks were used as inputs along with the island indicator from the MATLAB network model to determine the total AGC raise/lower signal. The island indicator is used to turn AGC "off" when there is islanding in the system. The maximum negative frequency deviation among the generator buses is also determined and output to the MATLAB network model to be used in underfrequency load shedding.

The average generator bus frequency deviation $\Delta\omega_{sys}$ is also computed and then used along with the system frequency bias constant B_f to determine the area control error (ACE) as follows:

$$\mathrm{ACE} = \mathrm{B}_f \times \Delta\omega_{sys}$$

Using the ACE, the total AGC raise/lower signal is calculated as follows:

$$u_{AGC} = -k_{AGC} \int \mathrm{ACE}\, dt$$

The total AGC raise/lower signal u_{AGC} is output from the system frequency and AGC dispatch calculation block to the machine blocks. The signal is parsed among the machines using the participation factors of the machines, where the sum of participation factors over all of the generators must be one. If a machine is not participating in AGC its participation factor can be set to zero.

As a first step in modeling the AGC control signal is continuous. In reality raise/lower commands are sent to generators on AGC every few seconds. A sample and hold block may be added to the subsystem to model this behavior and dispatch AGC at discrete time intervals.

For ease of use the Simulink blocks implementing the frequency calculation and AGC dispatch were grouped as a subsystem in a Simulink library along with the synchronous machine subsystem. A mask[25] is used to allow users to configure the subsystem blocks when they are placed in a Simulink model file. Figure 18 shows the blocks and interconnections within the subsystem.

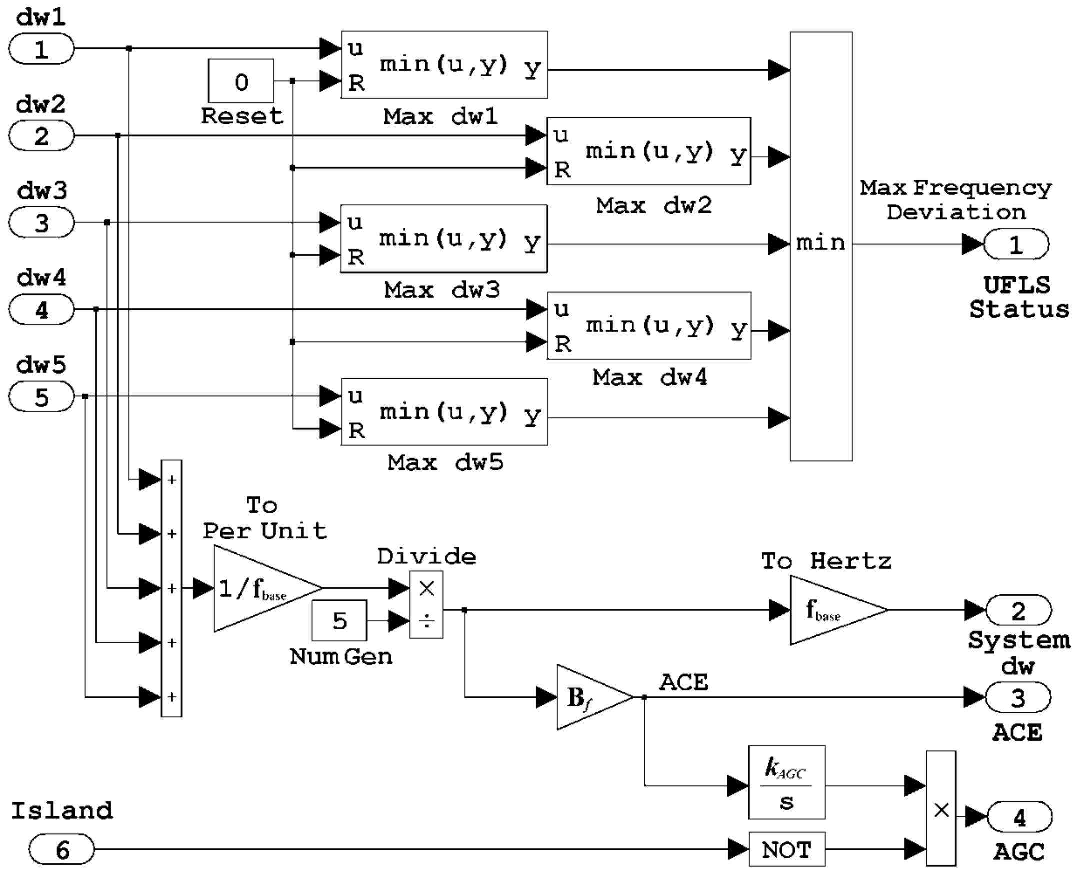


Figure 18
Simulink Model of Frequency Calculation and AGC Dispatch

The frequency bias constant B_f and the gain used for integration of the ACE signal, k_{AGC} were chosen based on the machines' speed droop constants and the per machine AGC gains used in previous versions. The system bias constant can be approximated using the generator governor droops R_i following equation:

$$\mathrm{B}_f = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + \frac{1}{R_5} \right)$$

This gave a value of $B_f = 375$ (per unit MW/Hz) where each machine has $1/R_i = 75$. The value for k_{AGC} was chosen using the per machine gain of $k_i = 10$, where each machine had the same AGC gain. The value was calculated using the assumption that the speed response of the generators is identical for any given load change. Setting the system AGC control signal equal to the sum of secondary frequency control loop signals within the generator blocks gives the following relationship between the gains:

$$k_{AGC} = \frac{5k_i}{B_f}$$

This results in a value of $k_{AGC} = 0.1\overline{3}$ to be used within the frequency calculation and AGC dispatch subsystem. To see how the two AGC implementations compare the load on bus 14 is dropped at $t = 0$ and the 5.75% decrease in load leads to a speed increase for the generators. Constant bus loads were used for both of the simulations. After the load is dropped generator governor action and AGC act to eliminate the frequency deviation in the system. The response using the system-wide AGC scheme resulted in undershoot in several generators and so the AGC gain was decreased and the final value of $k_{AGC} = 0.08$ was used. The plots in Figure 19 compare the response of the simulator using the per machine AGC control strategy with the response using system-wide AGC.

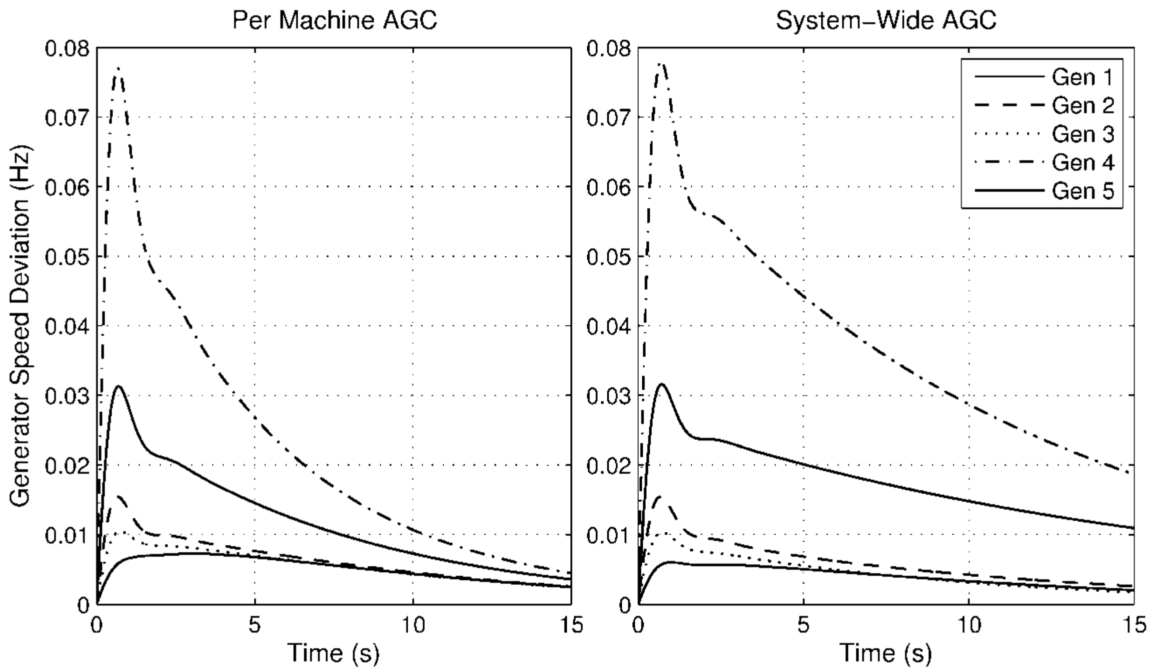


Figure 19
Comparison of Two AGC Schemes within the IEEE 14 Bus System

In both cases the speed swings are arrested within a second and the steady-state frequency error is corrected within about two minutes. At this point the machine speed deviations are essentially eliminated using the per machine AGC scheme where the deviations are less than 1.5×10^{-9} Hz. The system-side AGC scheme takes longer to settle and the generator speed deviations are within $\pm4\times10^{-5}$ Hz after two minutes.

5.1.4 Network Model

The DC power flow (DCPF) calculation that also includes the network model consisting of the transmission lines, is implemented as a MATLAB function block within the Simulink model. An island checking algorithm is included to identify electrically isolated portions of the system, or islands, and modify the power flow calculation as necessary. In addition underfrequency load shedding and line overload tripping is performed within the MATLAB function. The inputs outputs for the network model are shown in Table 21.

Table 21
Inputs and Outputs of the Network Model

User Input Machine Parameters	**Units**	**Source/Sink**	**Notation**
Underfrequency load shed enable	-	Constant block	-
V2G enable	-	Constant block	-
External Inputs			
Clock signal	Seconds	Simulink model	t
Maximum negative frequency deviation (used for UFLS)	Per unit, Hz	AGC subsystem	-
Generator rotor angles	Radians	Machine subsystems	δ
Generator status signals	-	Machine subsystems	-
Bus loads (total PHEV and non-PHEV)	Per unit, MW	Simulink model	p_{load}
Outputs			
Electrical demand on machines	Per unit, MW	Machine subsystems	p_{gen}
Load bus angles	Radians	Simulink model	δ
Islanding indicator	Hertz	AGC subsystem	-

The V2G enable signal modeled as a constant in the Simulink model, allows the user to enable the use of PHEV as a source of frequency regulation. The following sections describe the various components included in the network model and the steps used in calculating the DC power flow for the system.

5.1.4.1 Underfrequency Load Shedding

When there is a generation shortage in the power system the synchronous generators will see a decrease in speed which may lead to underspeed load tripping to protect the machines from damage. It takes hours to bring thermal generating units back online therefore underspeed generator tripping should be avoided if at all possible. Underfrequency load shedding (UFLS) is used to avoid underspeed tripping. UFLS causes portions of the load to be dropped at predetermined locations in the system using underfrequency relays.

To avoid a blackout as machines trip offline on underspeed, a UFLS scheme similar to those currently used by utilities was implemented in the 14 bus system. As discussed in Section 4.3 the UFLS program requirements set forth by the Mid-Atlantic Area Council (MAAC) were used as given in [35].[28] The MAAC criterion requires distribution companies within its region to shed 30% of their load in three 10% steps at 59.3, 58.9, and 58.5 Hz. In the IEEE 14 Bus System, UFLS was implemented using two shedding levels at 59.8 Hz and 59.7 Hz. An initial load of 259 MW was used in the IEEE 14 Bus System as implemented in [15] and within this study. A value of 400 MW was used for the peak load in the system and at the two underfrequency thresholds, 10% of the peak load (40 MW) is shed. The maximum negative frequency deviation among the generators in the 14 bus system was used to trigger UFLS in the network model. The locations of the load shedding were chosen arbitrarily and can be seen in Table 14.

Table 22
Load Shed Increments for Traditional UFLS Scheme

Bus Number	Level 1	Level 2
3	-	10 MW
4	10 MW	10 MW
5	10 MW	20 MW
9	-	10 MW
11	-	10 MW
12	10 MW	10 MW
14	10 MW	10 MW
TOTAL	**40 MW**	**80 MW**

As demonstrated in Section 4.3 the use of UFLS was able to save the IEEE 14 Bus System from blackout with an apparent 60% increase in loading following islanding.

[28] The program outlined in [35] is a legacy criterion which augments the reliability standards of Reliability*First* and is not an enforceable reliability standard.

5.1.4.2 DC Power Flow Calculation

At the beginning of the MATLAB function adjustments are made to the network model if generators are offline or underfrequency load shedding is needed (UFLS). In addition when zero-crossing detection takes place in the Simulink model, any recent changes to the network model are rolled back. Once these adjustments have been made, the power flow is calculated beginning with island checking.

A DC power flow (DCPF) was used to calculate the power flow on the transmission lines within the system and as a result the electrical demand on each of the generators in the system. The power flow calculation is a series of matrix multiplications where the dimensions of the matrices depend on the number of buses that need angle and power calculated. The knowns and unknowns at each bus will depend on the bus type and at initialization buses are identified as either load or generator buses as follows:

- Load bus: No generator connected, includes buses with $p_{load} = 0$, and
- Generator bus: Generator connected, may or may not have load.

A bus type vector is initialized in each iteration of the MATLAB function and is modified within the network model to reflect changes in the system state. Bus types will change if a generator goes offline, load is dropped, or if islands are deactivated. When islanding occurs in the system any island without load or generation is deactivated to simulate blackout within the island.

Table 23 describes the four bus types used within the network model along with the modifications to the buses after events occur in the system. In addition a static array of the original bus types (referred to as true bus types in code) is used as a reference throughout the MATLAB function. The true bus type may be generator or load and an additional bus type denoted ‘C’ is used for buses that contain both load and generation.

Table 23
Bus Types Used in Calculating the DC Power Flow

Bus Type	Normal System Operations		
	Use	Angle	Power[29]
Generator Bus (G)	Buses with generation and possibly load while generator remains online; If generator status = 0, change bus type to 'U'; In deactivated island leave generator to go offline on underspeed.	Input from Simulink model	Calculate p_{net} in DCPF, then $p_{gen} = p_{net} + p_{load}$
Known Theta Bus (T)	Generic generator bus for buses with only load which become swing buses in deactivated islands; bus is excluded from power flow calculation since isolated from system and no generation available.	$\delta = 0$	$p_{load} = 0$, and $p_{net} = p_{load} = 0$
Load Bus (L)	Buses with load and no generation; In deactivated island change bus type to 'T', add p_{load} to total dropped load.	Calculated in DCPF	p_{load} input from Simulink model, and $p_{net} = p_{load}$
Unknown Theta Bus (U)	Generic load bus for generators that have gone offline; In deactivated island change bus type to 'G' and becomes a swing bus with $\delta = 0$.	Calculated in DCPF	$p_{gen} = 0$, and $p_{net} = p_{load}$

[29] Within the Simulink model the calculated generator demand p_{gen} is output to the Simulink model where it is denoted p_e; the power injected at a bus p_{net} is the difference between the power being generated and that being absorbed by the load.

Since completion of the work reported in [15] the island checking procedure has been replaced to streamline calculations within the MATLAB function. The new island checking algorithm treats the network as an undirected graph where buses are the nodes and transmission lines are the edges. Islands are identified by determining the connected components within the graph, by iterating through the lines in the system. A first-in, first-out (FIFO) queue was coded in the function as none is provided by MATLAB. The FIFO was used to store bus numbers while identifying islands with multiple buses.

Any islands that have no load or generation are unsustainable and the island is "deactivated" by dropping all loads and lines within the island. No change is made to the generators in a deactivated island as they will go offline due to overspeed shortly after all loads are removed. To save time in computation, island checking is only performed if line or generator statuses have changed since the previous iteration. The following steps outline the island checking algorithm implemented in MATLAB:

I. Identify islands with multiple buses:
   A. Find the start of an island
      1. Begin with the next transmission line that is in service and has not been checked yet,
      2. Assign an island identifier to the line's to and from buses, and
      3. Add buses to the FIFO, and mark the line as checked.
   B. Sweep the island to identify all buses
      1. Choose the next bus in the FIFO,
      2. Identify all lines connected to that bus that are still in service,
      3. Assign all buses the same island identifier,
      4. Add the buses connected to these lines to the FIFO if not added yet, and
      5. Mark lines as checked,
      6. If more buses in FIFO to be checked return to B.1,
      7. Else if all lines have not been checked yet, return to A.1.

II. Identify single bus islands

C. Identify all buses whose island identifier is zero,

1. Assign island identifiers to all single bus islands.

III. Tabulate island statistics and deactivate non-viable islands:

D. Set island indicator to 1 for use in Simulink model,

E. Begin with the first island

1. Tabulate the total load, number of online generators, and number of buses in the island,
2. Set the island status to 1,
3. If the island contains only one bus with only load or only generation identify as an isolated bus,
4. Deactivate island if there is no load or no generators online,
    a) Set island status to 0,
    b) Load buses: Bus type set to 'T', add load to total dropped load, set $p_{load} = 0$, and $\delta = 0$,
    c) Unknown theta buses ('U'): Bus type set to 'G', $p_{gen} = 0$, and $\delta = 0$,
    d) Lines: remove from service by setting status to zero,

F. If more islands to be checked return to E.1.

Once island checking is done the DC power flow (DCFP) is calculated based on nodal equations for power injected at each of the buses. An assumption is made that the resistance of the transmission lines is negligible and the impedance is equal to the line reactance, X. Therefore the line's admittance is formed using only an X term and so the line admittance is denoted Bx. The system's admittance matrix, $\mathbf{Bx}$ is used to calculate the DC power flow and is formed using the following equations:

Diagonal elements: $Bx_{kk} = \sum_{i=1}^{n} \frac{1}{X_i}$

Off-Diagonal elements: $Bx_{ki} = -\frac{1}{X_{ki}}$

A one is placed in the diagonal of the $\mathbf{Bx}$ for any load buses in deactivated islands (now 'T' buses). Two additional vectors of the power injected at the generator buses and the generator rotor angles denoted $\mathbf{P}$ and $\mathbf{\Theta}$ respectively, are used to calculate the power flow. The matrix form of the DC power flow equations is:

$$\begin{pmatrix} p_1 \\ p_2 \\ \vdots \\ p_n \end{pmatrix} = \begin{pmatrix} Bx_{11} & Bx_{12} & \dots & Bx_{1n} \\ Bx_{21} & Bx_{22} & \dots & Bx_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Bx_{n1} & Bx_{n2} & \dots & Bx_{nn} \end{pmatrix} \cdot \begin{pmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_n \end{pmatrix}$$

The $\mathbf{P}$ and $\mathbf{\Theta}$ vectors and $\mathbf{Bx}$ are partitioned by using a vector of indices that address only the lines and columns relevant to the calculation. Angles for the load and unknown theta buses are calculated first, and then the net power injections at the generator buses are calculated. Using generator convention p_{load} will be negative and p_{net} positive so the power output of a generator is calculated as:

$$p_{gen} = p_{net} - p_{load}$$

The generator output power is output to the Simulink model for each of the machines in the system. Note that within the Simulink model p_e is used to refer to the electrical demand on a generator in place of p_{gen}. A flow chart illustrating the steps used to update the network model and then calculate the DC power flow is shown in Figure 20. The MATLAB code for the network model and power flow including V2G computations is included in Appendix B.

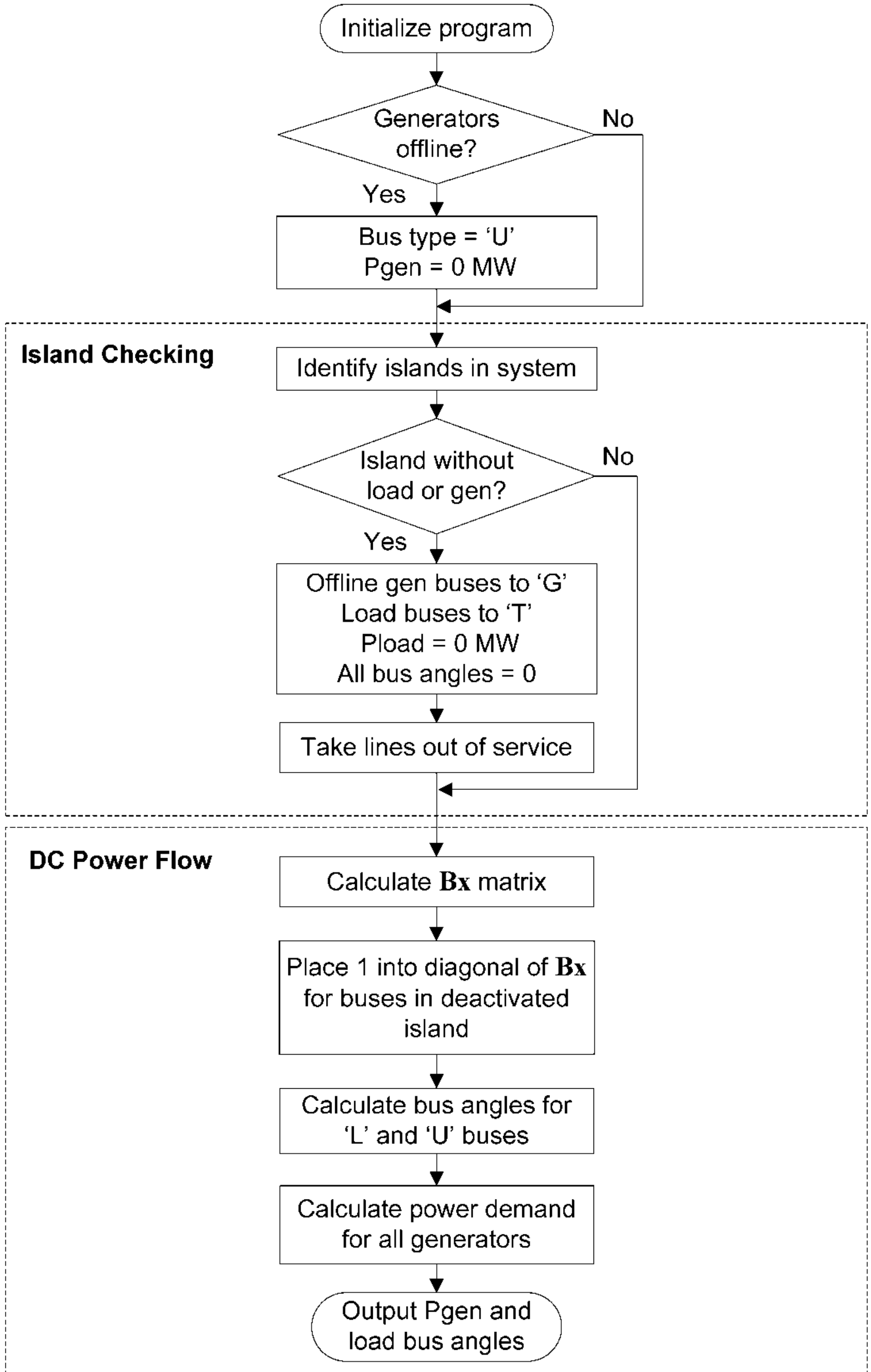


Figure 20
DC Power Flow Calculation Flow Chart

5.1.4.3 Line Overload Switching

After an angle and power injection have been calculated for all buses in the system using the DC power flow equations the line flows are also calculated using the net power injected at the bus. Each of the lines in the network has a limit on the amount of power that the line can carry and if this limit is exceeded the line would be removed from service due to overload.

To simulate overload tripping a flag is set when the flow on the line exceeds the limit initially. The overload tripping mechanism is modeled as a time-delay relay with a constant time delay for relay pickup and breaker operation. The time delay used in the simulator is 0.05 seconds so that the overload breaker takes the line out of service in three cycles. If the power flow on a line is within the limits before the breaker operates the overload flag is cleared. Additional code is included in the MATLAB function to handle zero-crossing events.

5.2 PHEV and Control Component Models

The following sections discuss the models that augment the power system simulator to represent plug-in hybrid electric vehicle (PHEV) and the control components used in vehicle-to-grid (V2G) operations. A model for the PHEV load at each of the buses represents the vehicles that are participating in distributed frequency regulation only. The size of the load is based on the non-PHEV load at each bus and assumptions regarding PHEV penetration and V2G participation. Each of the vehicles also has a V2G controller which basically tracks the charge duration, state-of-charge of the battery system, and the regulation supply state. No information about user preferences or charge interruption was incorporated into the simulator.

The PHEV coordinators track system frequency at the bus and provide the V2G controllers with a regulation control signal which combines elements of primary and secondary frequency regulation. Additional functionality was considered in the research and system design phase, but was not implemented in the base version of the simulator. More sophisticated models incorporating additional factors are left for future work.

5.2.1 Aggregate PHEV Load Model

To create PHEV load curves for the load buses the probability functions that EPRI developed based of the 2001 National Household Travel Survey were used [32]. An estimate for the number of PHEV participating in V2G at each of the eleven load buses was found and the vehicles were assigned a plug-in hour and number of miles traveled based on the cumulative probability distributions. As discussed in Section 4.1.1 it was assumed that all vehicles are plugging in at home and have an initial charge rate of 1kW. It was also assumed that all vehicles have a 10 kWh battery pack with a usable state-of-charge of 8 kWh. In the power system simulator the PEHV bus loads were implemented using Simulink‘From File’ blocks like those used to model the non-PHEV load at each bus.

The number of PHEV participating in V2G at each load bus was estimated using the following procedure:

1. Calculate the average non-PHEV bus load,
2. Using sector composition at bus determine average residential sector load,
3. Estimate the number of homes assuming an average load of 1kW per home,
4. Determine number of PHEV located at bus as a percentage of the homes, and
5. Determine number of PHEV participating in V2G at bus as a percentage of the PHEV being served through the bus.

Arbitrary values were chosen for the portion of residential load at each bus, the percentage of homes with a PHEV, and the percentage of PHEV participating in V2G. An assumption was made that the homes with a PHEV have only one PHEV. The values used were chosen arbitrarily, where the residential load proportion was chosen as 30%. Based on EIA estimates for electricity consumption within each sector, residential electricity consumption accounted for a little more than a third of delivered electricity consumption in 2005 and 2006 [18]. The percentage of homes with PHEV and PHEV participating in V2G were both arbitrarily chosen to be 30%. Within the Excel spreadsheet used to generate PHEV load curves different values may be input for each of the these three parameters for each of the buses.

The probability functions extracted from [32] were used to develop the aggregate PHEV load curves for each of the load buses. Based on the estimated number of vehicles at each bus, the vehicle population was developed by first using a uniform random number to assign a plug-in time to each vehicle. The probability of a vehicle arriving home in each hour was used to create a cumulative distribution function and the random numbers identified the hour that the vehicle plugged-in the charge at home. So that the vehicles are not all beginning to charge at the top of the hour a random number between 0 and 59 was generated to represent the minute that the vehicle plugs in.

Similarly the probability for the distance driven before plugging in at home was used to assign a mileage to each of the vehicles. The cumulative distribution function for the mileage driven was found for each hour of the day and again a uniform random number was used to determine the mileage range. The distance driven was divided into 12 categories: one for vehicles that haven't been driven, ten representing 10 mile distance ranges up to 100 miles, and one for vehicles driven more than 100 miles. The data in [32] showed that about 14% of vehicles are driven 0 miles in a day and therefore there are vehicles at each bus that will not charge during the 24-hour simulation period.

Once a mileage range was identified the average distance driven in that range during that hour was used to determine the battery's remaining state-of-charge (SOC). This was based on the assumption that all vehicles consume 0.2 kWh/mi. in their all-electric range, with a minimum SOC of 20%. The charge duration in hours when a vehicle plugs in using a charge rate of 1 kW is calculated as follows:

$$t_{charge} = \frac{10\ \text{kWh} - (10\ \text{kWh} - d \times 0.2\ \text{kWh/mi})}{1\ \text{kW}}$$

The term in parentheses represents the remaining state of charge when the vehicle plugs in, with a minimum value of 2 kWh. The plug-in time and charge duration was used to create 1-minute interval load curves for the aggregate PHEV loads at each bus. Table 24 summarizes the resultant number of homes and PHEV participating in V2G at each of the load buses along with characteristics of the aggregate PHEV load.

Table 24
Characteristics for PHEV Load Curve Development

Load	Bus	Estimated # of Homes	Estimated PHEV in V2G	Peak PHEV Load	Average PHEV Load
1	Bus 2	7,623	686	386 kW	132 kW
2	Bus 3	34,152	3,074	1,637 kW	588 kW
3	Bus 4	18,706	1,683	901 kW	319 kW
4	Bus 5	2,499	225	122 kW	42 kW
5	Bus 6	3,406	307	167 kW	58 kW
6	Bus 9	10,540	949	503 kW	176 kW
7	Bus 10	3,062	276	162 kW	55 kW
8	Bus 11	1,229	111	60 kW	21 kW
9	Bus 12	2,048	184	103 kW	36 kW
10	Bus 13	4,438	399	201 kW	73 kW
11	Bus 14	4,808	433	239 kW	81 kW
Total		**92,510**	**8,327**	**4,451 kW**	**1,582 kW**

The resulting load curve for the total PHEV bus load in the IEEE 14 Bus System is shown in Figure 21. Note that the charge cycles are looped such that those running beyond the simulated 24-hours are added in at the beginning of the simulated day.

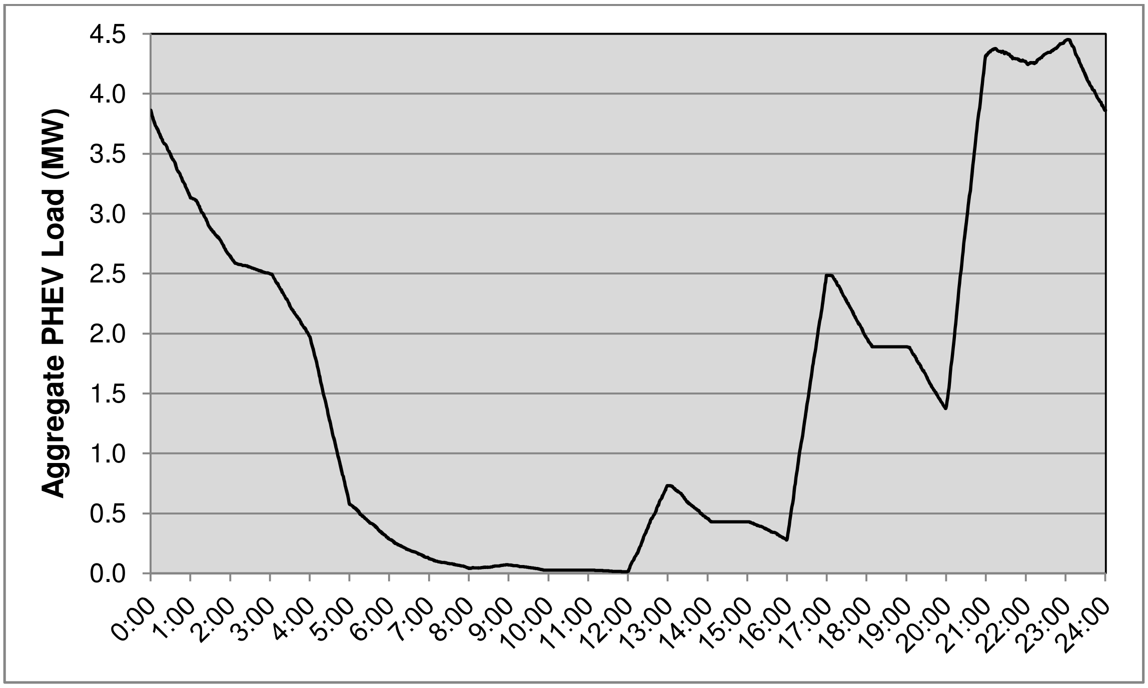


Figure 21
Aggregate PHEV Load Curve for IEEE 14 Bus System

With large increases in charge current or after completing a charge/discharge period it may be beneficial to the battery's health to allow a rest period or a ramp period. The battery load model used in this study will not include a rest or ramp period, however in the future this may be a desirable feature to add to the battery model to study the effects on supply response time and aggregate behavior.

5.2.2 V2G Controller

The V2G controller actions were implemented within a MATLAB function using the V2G regulation signals from the eleven PHEV coordinators as inputs. The V2G regulation signals represent the raise/lower amount for a single vehicle. A first implementation of V2G control was developed to test the use of PHEV as a source of regulation following a step load change in the IEEE 14 Bus System. Constant bus loads were used and 14.9 MW of load was dropped at bus 14 to see how the system responds using a centralized AGC scheme compared to the response when PHEV provide additional regulation. An assumption was made that the vehicles charging at the start of the simulation remain charging throughout the simulation. This base case was simulated over a period of several minutes. A second implementation of V2G controller actions for longer simulation periods on the order of hours is discussed in Section 6.3.

The continuous regulation signal from the PHEV coordinator is input to the MATLAB function for each of the load buses. This per vehicle regulation signal is then multiplied by the total number of vehicles on AGC supply to get the total raise/lower amount at that bus. The amount of PHEV regulation is capped based on the maximum charging power p_{max} and the minimum charging power p_{min} allowed for the vehicles. To stay within the maximum power rating for level 1 charging at home (see Table 4), a maximum allowable charge power deviation is 0.4 kW, where $p_{max} = 1.4$ kW and $p_{min} = 0.6$ kW.

After being adjusted using the charging power limits, the total bus load values are updated to reflect the amount of regulation being supplied by the PHEV at each bus. This approach was used to produce the results presented in Chapter 6.

5.2.3 PHEV Coordinator

The PHEV coordinator actions are modeled in the main Simulink file and the angles for eleven buses that have load connected are the inputs. The regulation signal is continuous and includes terms for modeling speed governor action and integral AGC action. It is assumed that all PHEV behave the same and all V2G controllers use the same logic in the first round of implementation used to produce the results in Chapter 6. In the final version the blocks which calculate the PHEV coordinator regulation signals were grouped into a masked subsystem[25] for ease of use. With the subsystem the user can enter the values for the vehicle speed droop constant R_{PHEV} and the vehicle integral gain k_{PHEV} through the mask interface without having to update the constants for each of the buses. Table 25 shows the inputs and outputs associated with the PHEV coordinators.

Table 25
Inputs and Outputs for the PHEV Coordinator

User Inputs	Units	Source/Sink	Notation
Vehicle speed droop constant	Per unit, MW/Hz	Subsystem mask	R_{PHEV}
Vehicle integral gain	-	Subsystem mask	k_{PHEV}
External Inputs			
Load bus frequency deviation	Per unit, Hz	Simulink model	$\Delta\omega$
Outputs			
AGC raise/lower signal	Per unit, MW	V2G controllers	u_{reg}

The user inputs the speed droop constant for a single vehicle and the integral gain for a single vehicle. The regulation signal is then calculated using the bus frequency deviation $\Delta\omega$ as follows:

$$u_{reg} = \Delta\omega\left(\frac{1}{R_{PHEV}} + \frac{k_{PHEV}}{s}\right)$$

The proportional term in the regulation signal represents the equivalent of generator governor action for a single PHEV. The initial vehicle speed droop constant was derived from the frequency and power limits for an individual vehicle using the following equation:

$$R_{PHEV} = \frac{\omega_{max} - \omega_{min}}{p_{max} - p_{min}}$$

Using ± 0.4 Hz with $p_{max} = 1.4$ kW and $p_{min} = 0.6$ kW results in a value of $R_{PHEV} = 1666.\overline{6}$. The vehicle integral gain k_{PHEV} is the gain used for the integral term in the regulation signal. The integral term represents secondary frequency regulation which acts to eliminate the steady-state frequency error in the system. The centralized AGC gain $k_{AGC} = 375$ which was used for the total system in the frequency calculation and AGC dispatch subsystem was scaled to determine a starting point for the vehicle gain. Using an average total load of 324 MW and an average vehicle load of 1×10^{-3} MW (1 kW) results in a scaled gain of $k_{PHEV} = 1.2\times10^{-3}$ which was used as a base. Chapter 6 follows with simulation results and a discussion of alternative methodologies that may be used for V2G frequency regulation. The MATLAB code for the network model and power flow including V2G computations is included in Appendix B.

6 RESULTS AND DISCUSSION

Three simulations were performed using the simulator described in Chapter 5. The base case uses only central generation to perform automatic generation control, the second case allows plug-in hybrid electric vehicles to contribute to primary regulation, and the third allows PHEV to supply both primary and secondary frequency regulation. The simulation scenario used to compare the system responses using the three regulation strategies is a step change in the system load. The system load is static throughout the simulation, with 14.9 MW dropped at bus 14 at $t = 1$ seconds. The initial generator powers and rotor angles, and transmission line data used in the simulations are given in Appendix A.

When the PHEV are participating in frequency regulation, the PHEV load values are adjusted at each iteration to reflect the current PHEV regulation supply amount. As a first step in testing V2G functionality within the power system simulator the PHEV bus loads were increased by a factor of ten. The higher PHEV loads made it easier to study the effectiveness of using a controllable load as a source of frequency regulation.

Note that generator convention is used when referring to regulation supplied by PHEV and where regulation up causes generators to increase their output, the PHEV will instead decrease their demand. Conversely where regulation down causes generators to decrease their output, the PHEV will instead increase their demand.

The results of the simulations are presented in Sections 6.1 and 6.2. Section 6.3 provides a discussion of alternative implementations of V2G control and next steps in modeling. Table 26 shows the parameters that were used in the final version of the simulator used to produce the results discussed in Sections 6.1 and 6.2.

Table 26
Final Simulator Parameters

Main Simulink Model	Value	Notation
Number of buses	14	-
Non-PHEV load	259 MW	$p_{non-PHEV}$
PHEV load	39 MW	p_{PHEV}
Total system load	298 MW	p_{total}
Underfrequency load shed enable	1	-
V2G enable	0/1	-
System base power	100 MW	$\mathrm{P}_{\mathrm{base}}$
Base frequency	60 Hertz	$\mathrm{f}_{\mathrm{base}}$
Synchronous Machine Subsystem		
Governor valve control time constant	0.1 s	T_g
Prime mover time constant	0.2 s	T_{ch}
Load frequency damping factor	0.001	D
Frequency Calculation and AGC Dispatch Subysystem		
Frequency bias constant, bulk system	375 per unit	B_f
Automatic generation control gain, bulk system	0.08	k_{AGC}
Plug-In Hybrid Electric Vehicles and V2G Controllers		
Number of vehicles charging	38,620	-
Base charging power	1 kW	-
Charging power limits	± 0.4 kW	p_{max}, p_{min}
PHEV Coordinators		
Vehicle speed droop constant	6×10^{-4} per unit	R_{PHEV}
Vehicle integral gain	0.0012	k_{PHEV}

6.1 Base Case: Centralized AGC Scheme

In the base simulation only centralized frequency regulation is used to eliminate the steady-state frequency error once generator governor action arrests the initial frequency swing. In this case only the synchronous machines are participating in AGC and the PHEV charge at a constant power of 1 kW. The generator speeds settle after about 93 seconds. Figure 22 shows the area control error (ACE) and the AGC control signal following the load drop at 1 second.

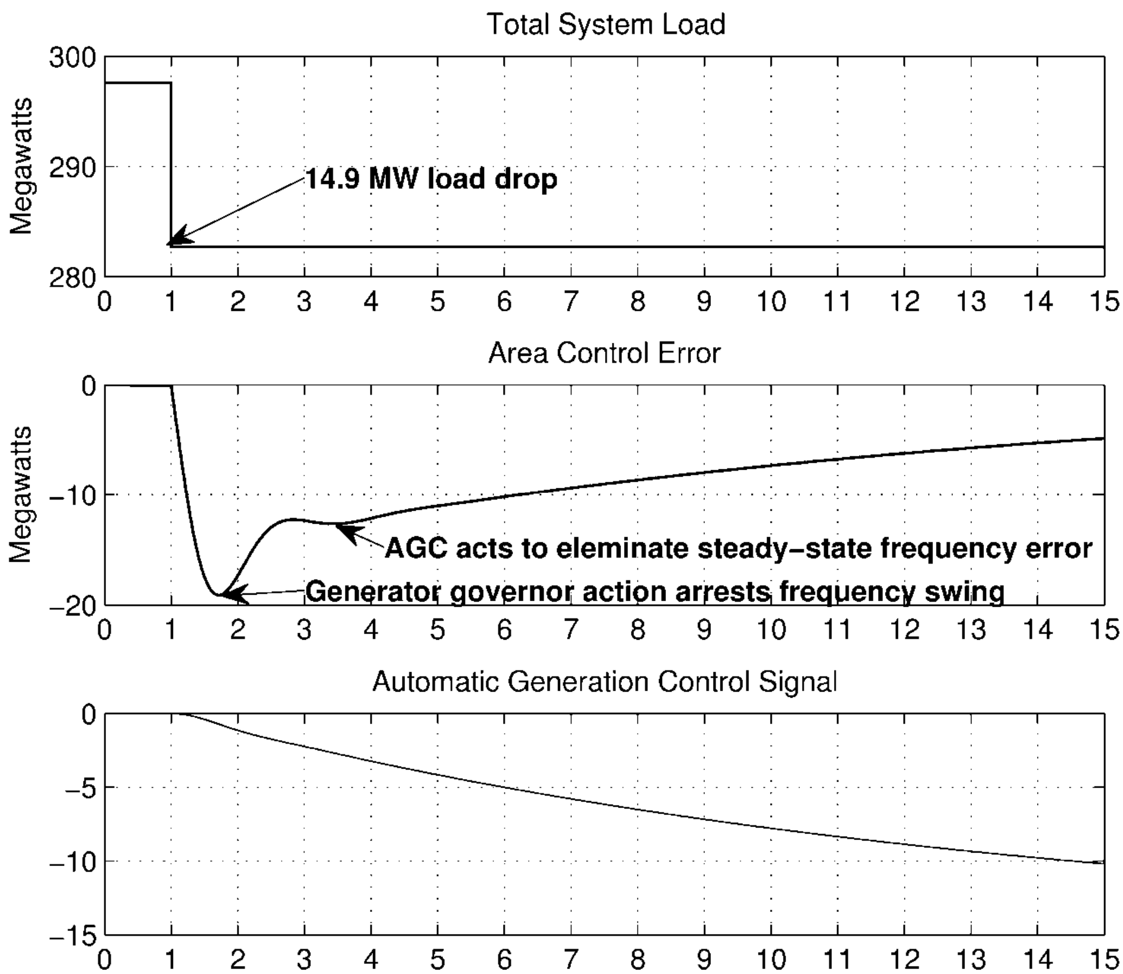


Figure 22
Plots of the ACE and AGC Control Signal in Base Case Simulation

6.2 PHEV Provide Frequency Regulation

To augment the frequency regulation provided by central generation, the effects of PHEV supplying regulation were then added to the simulation. The PHEV supply regulation along with the synchronous machines and decrease the ACE following the load drop at 1 second. The maximum and minimum charging power allowed for PHEV supplying regulation were set at $p_{max} = 1.4$ kW and $p_{min} = 0.6$ kW. The PHEV coordinators produce a regulation signal with a raise/lower amount appropriate for a single vehicle. Within the MATLAB network model function the regulation signal is multiplied by the number of vehicles on AGC supply and adjusted accordin to p_{max} and p_{min}. The final aggregate PHEV regulation supply is then subtracted from the PHEV load at each bus.

6.2.1 Case 1: Providing Only Primary Frequency Regulation

In the first case of PHEV providing regulation, the integral gain k_{PHEV} is set to zero so that each vehicle effectively had a governor response providing primary frequency regulation. The reader is referred to Section 3.2.1 for a complete discussion of primary and secondary frequency regulation. Figure 23 shows the system load after the load drop, when the PHEV supplying regulation increase their charging power to provide regulation down.

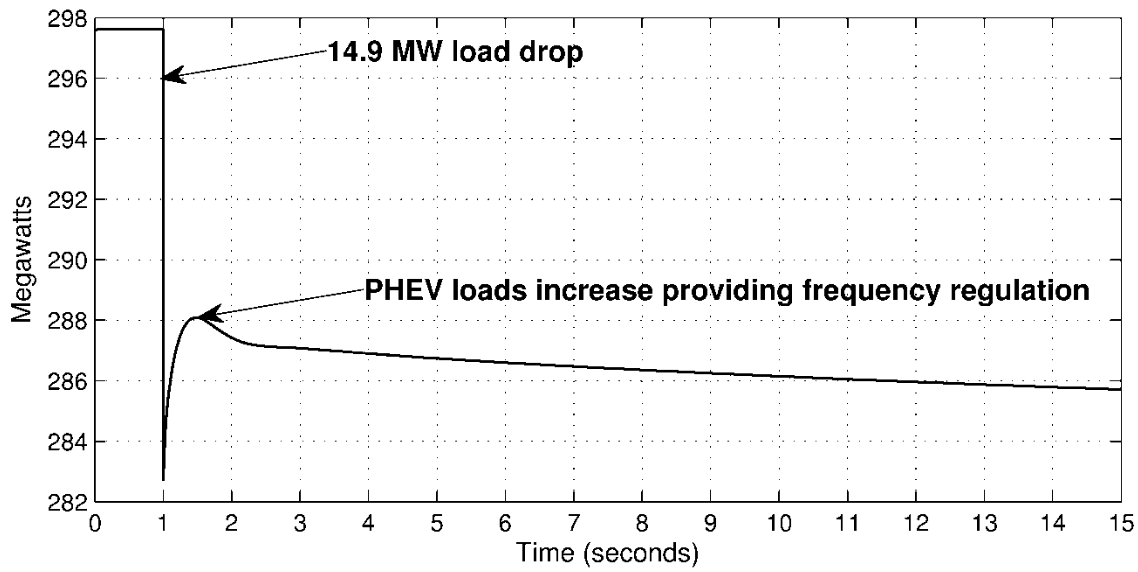


Figure 23
System Load with PHEV Providing Primary Frequency Regulation

The resulting ACE and AGC control signal which the synchronous machines must follow can be seen in Figure 24.

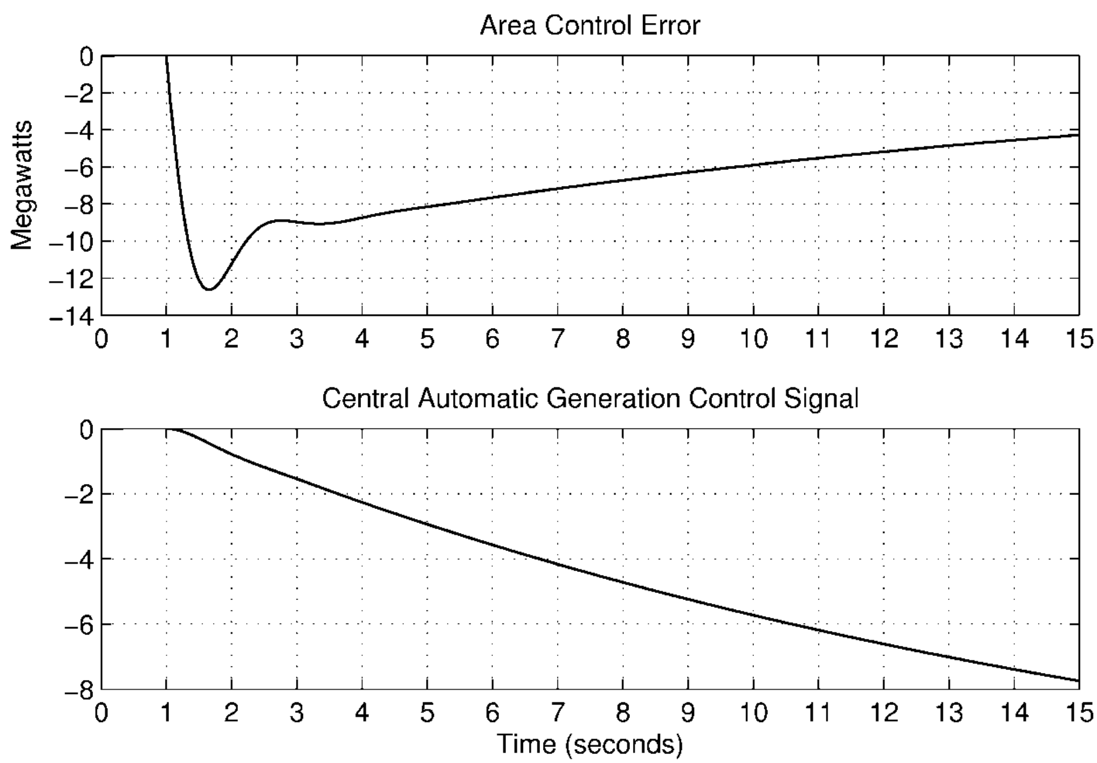


Figure 24
ACE and AGC Control Signal with PHEV Providing Primary Frequency Regulation

With PHEV contributing to regulation the generator speeds settle at about 147 seconds, slightly longer than in the base case. This is due to the fact that no additional integral control is present with the PHEV providing only primary regulation. The centralized AGC control system will continue to act until the PHEV supply is completely released which takes longer without additional integral control. Figure 25 compares the ACE during the first four seconds following the load drop using the base case and with PHEV contributing to primary frequency regulation.

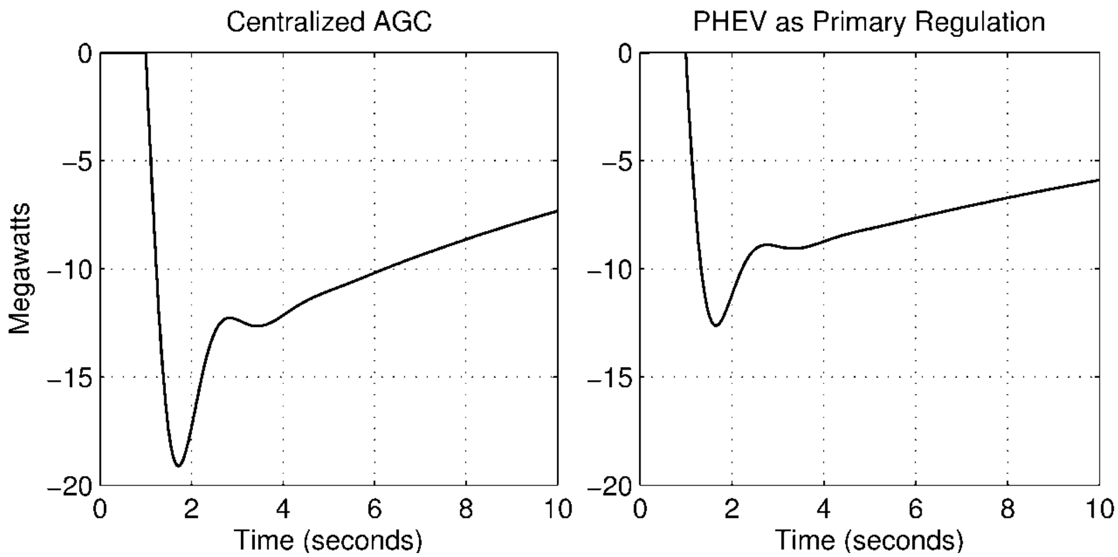


Figure 25
Comparison of the Area Control Error with only Centralized AGC and with PHEV Providing Primary Frequency Regulation

Although the system takes longer to settle the area control error is reduced considerably, and therefore the PHEV had a positive impact on the centrally dispatched AGC.

6.2.2 Case 2: Providing Primary and Secondary Frequency Regulation

Additional benefits are possible when an integral term is included in the PHEV regulation signal. The integral gain was reset to its initial value of $k_{PHEV} = 0.0012$ and the simulation was repeated. Figure 26 shows the system load after the load drop, when the PHEV supplying regulation increase their charging power to provide regulation down.

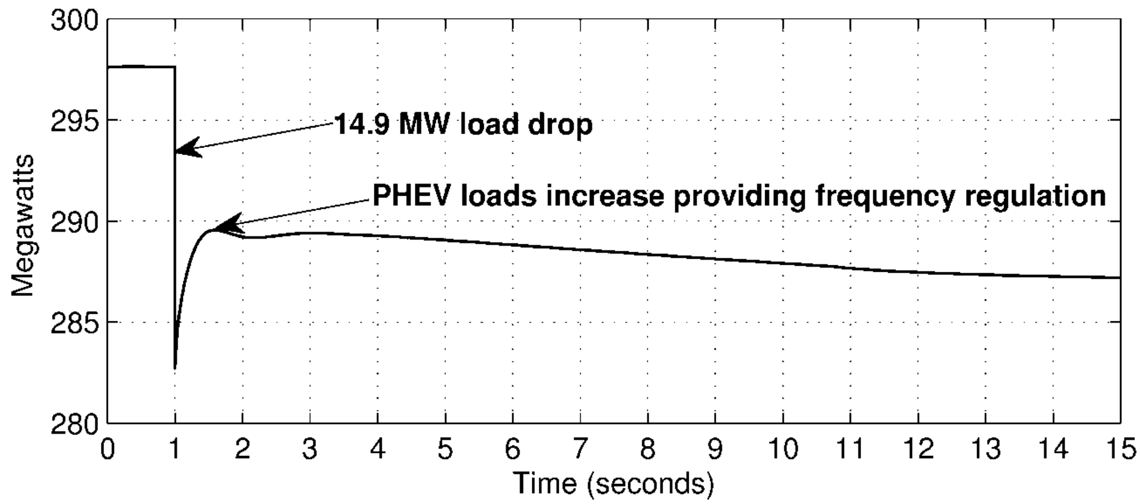


Figure 26
System Load with PHEV Providing Primary and Secondary Frequency Regulation

The decrease in load with PHEV providing primary and secondary regulation remains higher for a longer duration, compared to the load response shown in Figure 23 with PHEV providing only primary regulation. This reflects the addition of secondary frequency regulation action to the PHEV coordinator supply recommendation. The ACE and AGC control signals which the synchronous machines must follow can be seen in Figure 27.

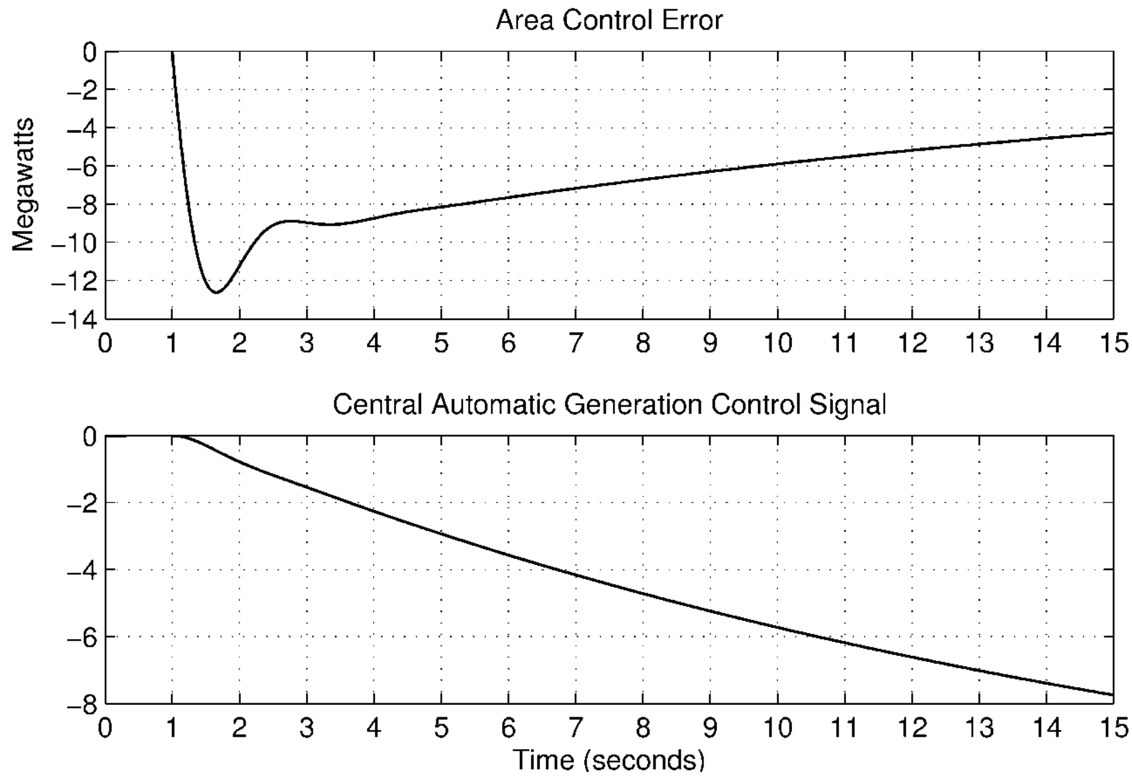


Figure 27
ACE and AGC Control Signal with PHEV Providing Primary Frequency Regulation

With PHEV contributing to both primary and secondary regulation the generator speeds settle at about 104 seconds, which is much closer to the 93 seconds settling time in the base case. This reflects the additional integral control with the PHEV contributing to secondary frequency regulation in addition to primary. Again the centralized AGC control system continues to act until the PHEV supply is completely released. With the fast acting PHEV regulation less ramping is required of the thermal generating units, which decreases the wear and tear on the units. Figure 28 compares the ACE during the first four seconds following the load drop in all three simulation scenarios.

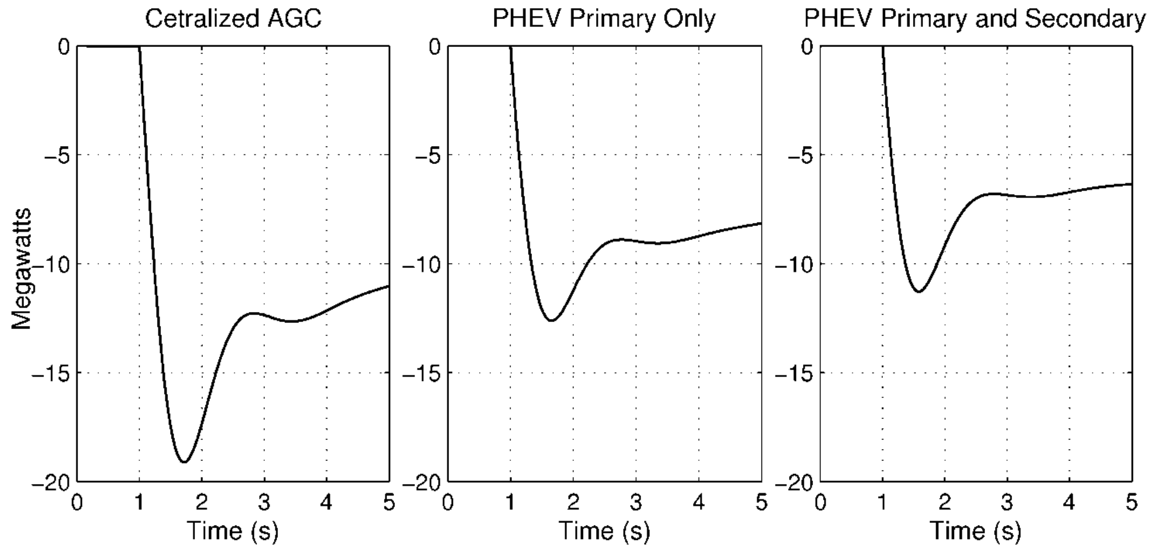


Figure 28
Comparison of the Area Control Error in the Three Simulation Scenarios

Again the ACE is reduced compared to the case where PHEV provide only primary regulation. Compared to the base case where only centralized AGC is used, the peak ACE value is reduced by about 40%. This shows that the PHEV are able to contribute significantly to frequency regulation following a step change in load. A reduction in ACE means that the central generation units are subjected to less ramping than without PHEV contributing to frequency regulation.

6.3 Discussion

A second implementation of V2G controller behavior was also developed to be used in simulations with a longer time scale, on the order of hours. In this case it is desirable for the vehicles to have a set dispatch duration along with a mechanism to prevent the vehicles from remaining at a lower power charge rate for too long.

As a starting point the regulation supply duration was set to 5 minutes and depending on the raise/lower signal at the end of a supply period a PHEV may remain in the same supply state for an additional 5 minutes. After a maximum of 10 minutes providing regulation up or down the supply state will transition to "off supply" where the vehicle is charging at 1 kW.

As a first implementation vehicles supplying regulation up (decrease PHEV load) will charge at p_{min} (kW), and those supplying regulation down (increase PHEV load) will charge at p_{max} (kW). The raise/lower signal generated by the PHEV coordinators will indicate the sign of the change in consumption that is desired. So, a raise signal tells the V2G controllers that an increase in charging power is desired.

The determination of the regulation state transition at the end of each 5-minute interval depends on: the current regulation supply state, the battery's state-of-charge (SOC), the current local raise/lower signal, and the duration at the current regulation state. Table 27 presents the logic used by the V2G controllers when making PHEV regulation supply decisions.

Table 27
V2G Controller Logic for Regulation Supply State Transitions

<table>
<tr><th>Regulation State at t_i</th><th>Local AGC Signal</th><th>State-of-Charge at t_i</th><th>Resulting Regulation State for t_{i+1}</th></tr>
<tr><td rowspan="2">Up, p_{min}</td><td>Lower</td><td>High</td><td>If Up at t_{i-1} then Off, 1 kW;
If Off at t_{i-1}, then stay Up, p_{min}</td></tr>
<tr><td>Raise</td><td>High</td><td>Off, 1 kW</td></tr>
<tr><td rowspan="2">Down, p_{max}</td><td>Lower</td><td>Don't care</td><td>Off, 1 kW</td></tr>
<tr><td>Raise</td><td>Don't care</td><td>Down, p_{max}</td></tr>
<tr><td rowspan="3">Off, 1 kW</td><td>Lower</td><td>Low</td><td>Off, 1 kW</td></tr>
<tr><td>Lower</td><td>High</td><td>Up, p_{min}</td></tr>
<tr><td>Raise</td><td>Don't care</td><td>Down, p_{max}</td></tr>
</table>

Using this implementation of V2G controller action, the PHEV coordinator only needs to supply a raise/lower signal to the vehicles. This can be accomplished using the same signals developed for the simulations discussed earlier in the chapter. Then within the

MATLAB network model and power flow function the sign of the regulation signals can be extracted for use by the V2G controllers.

6.3.1 Implementation Issues

Several limiting factors were found using Simulink and MATLAB together to model V2G regulation control. The first is the additional computational time when each V2G controller acts on its own. The appropriate data storage structure and V2G decision algorithm must be identified to study higher penetrations of vehicles. One version of the simulator with the initial 3,862 vehicles used a MATLAB function to implement the V2G control actions. To avoid iterating through each vehicle in the system, only vehicles that had been on AGC control for the 5-minute dispatch duration were checked. MATLAB allows matrices to be indexed using an array, so a single statement can be used to find a particular subset of vehicles, e.g. PHEV supplying regulation up with a low state-of-charge. Although this is an elegant way of picking out the rows that need to be updated, it is still computational expensive and slowed the simulation down considerably. To test the basic response of the PHEV providing frequency regulation, the strategy discussed earlier in the chapter was used as a starting point. Ideally to simulate the parallel behavior of a collection of unique items and object oriented programming environment should be used.

Another issue arose in using the load bus angles calculated in the MATLAB DC power flow function to find the frequency deviation at buses with only load. The angles were output to the Simulink model where the derivative was taken to be used in calculating the PHEV coordinator control signals. Following a load change in the system, the angles at buses with only load experience a step change which results in a pulse in the derivative signal. Several strategies were used to try to overcome the pulse, but no solution was found. Therefore another approach may necessary to be able to use the load bus frequencies as a control input for the PHEV coordinator’s supply recommendation.

As a next step in modeling, a noise signal can be added to the 24-hour bus load curves to simulate smaller scale load fluctuations throughout the day. Alternatively a live data stream of real-time load data could be used for the bus loads along in combination with a predictor.

Within this study the centralized AGC dispatch also acts as a load following signal for the generators. It may be desirable to separate the load following action from the AGC functionality to be applied to the generators on an hourly basis.

7 CONCLUSION

The results presented in Chapter 6 show that the use of PHEV for distributed frequency regulation decreases the amount of area control (ACE) error following a step change in system load. This reduction in ACE in turn leads to a decrease in the amount of automatic generation control (AGC) that needs to be supplied by central generating units. The balance of real power flow is closely related to financial measures such as ancillary service markets. The resulting power system and V2G simulator may be expanded to help inform a discussion on how markets for near-real time energy management services may be structured. The unique contributions resulting from this work include:

- Studied PHEV energy systems and limitations on battery charging/discharging,
- Reviewed standards for interconnection of distributed resources and electric vehicle charging [1], [2],
- Explored strategies for distributed control of PHEV charging,
- Developed controllers to accommodate PHEV regulation, and
- Developed a simulator combining a power system model and PHEV/V2G components.

7.1 Future Work

There are several ways that the simulator may be extended to include more variables, and model more sophisticated behavior including:

- Plugging in at public charging stations,
- Interruption of charging,
- Effects of varying charge duration and supply amount,
- Unique battery characteristics and V2G controllers for each PHEV, and
- Hybrid transmission-distribution system modeling.

The model can also be extended to include other forms of stationary distributed storage in place of the PHEV. It could be a battery pack placed in the garage, a flywheel providing neighborhood level storage, or any number of small scale energy storage.

In addition issues involving systems related to V2G and ancillary service supply may be considered. The following issues are particularly relevant:

- Market design,
- Inclusion of additional PHEV energy sources, e.g.. ultracapacitors,
- Investigate applicability to other ancillary, power, or energy services,
- Impacts on existing distribution design and planning.

In order to study the problem more realistically, a communications system could be overlaid with the original simulation to study the effects of communications delays and explore the use of different network implementations and protocols. In order to do this, the base simulation could be integrated with A Discrete Event System simulator (ADEVS) to simulate discrete systems such as communications and controls [37]. A joint project by Oak Ridge National Lab and the University of Minnesota combined a dynamic simulation of the IEEE 14 Bus System with a communications system [38].

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A IEEE 14 BUS SYSTEM DATA

The parameters and initial conditions for the five generators in the IEEE 14 Bus System are shown in Table 28. The AGC participation factor for a machine is denoted pf. The initial powers p_{init} and rotor angles δ_{init} used to produce the results presented in Chapter 6 are also given.

Table 28
Generator Data for IEEE 14 Bus System

Bus	p_{init} (MW)	δ_{init} (Radians)	$1/R$ (per unit)	M (per unit)	pf
1	5.400000000000005e-01	0	75	25	0.2
2	40	-2.234457429138957e-02	75	25	0.2
3	6.000000000000001e-01	-8.121376307617530e-02	75	25	0.2
6	70	6.651622308990288e-04	75	25	0.2
8	74	1.389981375408480e-01	75	25	0.2

Coefficients for continuous polynomial 24-hour bus load curves developed from the normalized 5-minute bus load data discussed in Section 5.1.2 are shown in Table 29, along with the R-squared values for the linear regression.

Table 29
Coefficients for 24-hour Polynomial Load Curves in the IEEE 14 Bus System

Bus	a_0	a_1	a_2	a_3	a_4	R^2
2	-3.26E-20	6.64E-15	-4.06E-10	6.12E-06	-2.17E-01	0.9734
3	-1.83E-19	3.67E-14	-2.20E-09	3.23E-05	-9.42E-01	0.9671
4	-4.97E-20	1.03E-14	-6.05E-10	5.86E-06	-4.78E-01	0.9450
5	-2.21E-22	1.21E-16	-8.13E-12	-9.16E-08	-7.60E-02	0.5626
6	-2.82E-20	5.44E-15	-3.26E-10	5.65E-06	-1.12E-01	0.8694
9	-5.08E-20	1.03E-14	-6.25E-10	9.30E-06	-2.95E-01	0.9574
10	-1.29E-20	2.79E-15	-1.81E-10	3.04E-06	-9.00E-02	0.9599
11	-6.70E-21	1.41E-15	-8.94E-11	1.48E-06	-3.50E-02	0.9297
12	-1.04E-20	2.12E-15	-1.31E-10	2.12E-06	-6.10E-02	0.9634
13	-2.36E-20	4.71E-15	-2.83E-10	4.52E-06	-1.35E-01	0.9682
14	-2.32E-20	4.81E-15	-3.05E-10	5.30E-06	-1.49E-01	0.9432

The line data used within the simulator is shown in Table 30.

Table 30
Transmission Line Data for the IEEE 14 Bus System

Line	From Bus	To Bus	Reactance (per unit)	Maximum Power (per unit)
1	1	2	0.05917	1.485
2	1	5	0.22304	1.6
3	2	3	0.19797	0.825
4	2	4	0.17632	0.743
5	2	5	0.17388	0.743
6	3	4	0.17103	0.412
7	4	5	0.04211	0.99
8	4	7	0.20912	0.825
9	4	9	0.22618	0.825
10	5	6	0.25202	0.825
11	6	11	0.1989	0.825
12	6	12	0.25581	0.99
13	6	13	0.13027	0.99
14	7	8	0.17615	1.32
15	7	9	0.11001	0.495
16	9	10	0.0845	0.495
17	9	14	0.27038	0.99
18	9	14	0.27038	0.99
19	10	11	0.19207	0.66
20	12	13	0.19988	0.99
21	13	14	0.34802	0.577

B NETWORK MODEL AND DC POWER FLOW CODE

```
% DCflow_IEEE14_PHEV_v8.m
% Created by Sara K. Mullen, beginning 7/2006
%
% SYSTEM: IEEE 14 Bus power system model.
% ISLAND CHECKING: Identifies islands in the system.
% POWER FLOW CALCULATION: Calculate bus injections and line flows.
% FEATURES: ZC handling, underfrequency load shedding, and line
% overload tripping.
%
% Input- vector 'u' with,
%        u(1) - u(9)  : odd inputs are generator angles
%        u(2) - u(10) : even inputs are generator statuses
%        u(11) : clock signal (current simulation time)
%        u(12) : enable underfrequency load shedding (UFLS)
%        u(13) : maximum negative frequency deviation (for UFLS)
%        u(14) - u(24): loads in per unit on 100 MW base
%
% Output- power demand for 5 gens, islanding signal, & load bus angles:
%
[Pgen(1),Pgen(2),Pgen(3),Pgen(6),Pgen(8),systemSplit,busAngle(4),busAng
le(5),busAngle(9),busAngle(10),busAngle(11),busAngle(12),busAngle(13),b
usAngle(14)];


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function Output = DCflow_IEEE14_PHEV_v4(u)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% INITIALIZATION %%%%%%%%%%%%%%%%%%%%%%%%%%

%% %%%%%%%%%%%%% Non-Static System Data and Variables%%%%%%%%%%%%%%%%%%
% DYNAMIC SIMULATION INPUTS
clock       = u(11);
UFLS        = u(12);
dwMin       = u(13);
V2G_enable  = u(36);

% BUS TYPES and LOADS
% busType:= holds bus types as they change throughout simulation.
% Initially only:'G':= generator, 'L':= load
% As bus types change also:
%   'T':= generic (gen) known theta bus used to be'L', now Pload = 0,
%          busAngle = 0, excluded from power flow calculations
%   'U':= generic (load) unknown theta bus used to be'G', now Pgen = 0,
%          busAngle = 0, bus angle calculated in power flow calculations
busType = ['G';'G';'G';'L';'L';'G';'L';'G';'L';'L';'L';'L';'L';'L'];
```

```
Pload    = [0;u(14);u(15);u(16);u(17);u(18);0;0;u(19);u(20);
           u(21);u(22);u(23);u(24)];
PHEV_coor = [0;u(25);u(26);u(27);u(28);u(29);0;0;u(30);u(31);u(32);
             u(33); u(34); u(35)];

%% %%%%%%%%%%%%%%% Static System Data and Variables %%%%%%%%%%%%%%%%%%
% INITIALIZE STATIC AND PERSISTENT VARIABLES
persistent Nlines Nbuses Ngen trueBusType
persistent counter breakerTrip fidLOG
persistent systemSplit lastTime
persistent frombus tobus xline bxLine maxflowPU alarm
persistent lineOut islLineTimeOut lastLineStatus
persistent shed1 shed2 shed1Flag shed2Flag
persistent NbusColumn NlineColOnes NlineNbus
persistent genStatus genBus busAngle Pgen Pnet genOut lastGenStatus
persistent A AT delta numVeh lastReg

if clock == 0

    % Open output file and initialize flags and counter at t=0 s.
    fidLOG = fopen('V2GLog.txt','wt');
    counter = 0;  % Iteration counter for DC power flow.
    breakerTrip = 0.05; % Time delay for relay pick-up plus breaker
                        % trip for overloaded transmission line.
    systemSplit = 0;    % Set to '1' upon islanding in system.
    newDisturbance = 0; % To indicate a log entry of contingency event.
    zcCount = 0;
    numVeh = [0; 3270; 14410; 7890; 1040; 1400; 0; 0; 4310; 1280; 500;
              840; 1660; 2020];

    % SYSTEM PARAMETERS
    Nlines = 21;
    Nbuses = 14;
    Ngen = 5;
    % trueBusType holds the original bus types
    % 'G':= generator, 'L':= load, 'C':= generator and load
    trueBusType = ['G'; 'C'; 'C'; 'L'; 'L'; 'C'; 'L'; 'G'; 'L'; 'L';
                   'L'; 'L'; 'L'; 'L'];

    % Initialize zero arrays.
    NbusColumn   = zeros(Nbuses,1);
    NlineColOnes = ones(Nlines,1);
    NlineNbus    = zeros(Nlines,Nbuses);

    % UFLS DATA
    % Flags store time when underfrequency load shedding (UFLS) occurs.
    % At first underfrequency level, shed this:
    shed1Flag = 0;
    shed1 = [ 0  0  0  0.1  0.1  0  0  0  0  0  0  0.1  0  0.1]';
    % At second underfrequency level, shed this:
    shed2Flag = 0;
    shed2 = [ 0  0  0.1  0.1  0.2  0  0  0  0.1  0  0.1  0.1  0  0.1]';
```

```
    % STATIC LINE DATA
    frombus = [ 1 1 2 2 2 3 4 4 4 5 6 6 6 7 7 9 9 9 10 12 13]';
    tobus   = [ 2 5 3 4 5 4 5 7 9 6 11 12 13 8 9 10 14 14 11 13 14]';
    xline   = [0.05917 0.22304 0.19797 0.17632 0.17388 0.17103 0.04211
               0.20912 0.55618 0.25202 0.1989 0.25581 0.13027 0.17615
               0.11001 0.0845 0.27038 0.27038 0.19207 0.19988
               0.34802]';
    bxLine  = 1./xline;
    maxflowPU = [1.485 1.6 0.825 0.743 0.743 0.412 0.99 0.825 0.825
                 0.825 0.825 0.99 0.99 1.32 0.495 0.495 0.99 0.99 0.66
                 0.99 0.577]';
    lineOut = NlineColOnes; % Overload and deactivated status changes.
    islLineTimeOut = -1e6*NlineColOnes; % Time stamp for tripping of
                                        % lines in deactivated islands.
    lastLineStatus = NlineColOnes; %Last iteration's lineStatus vector.
    alarm       = -1e6*ones(Nlines,4); % Tracks time of initial
    alarm(:,4)  = 0;                   % overload (col 1), time of
                                       % overload removal (col 2), time
                                       % line out of overload (col 3),
                                       % and relay+breaker operating
                                       % time (col 4).

    % STATIC GEN DATA
    % Initialize bus gen statuses to '0', insert gen angles from
    % dynamic model at each iteration.
    genStatus   = NbusColumn;
    lastGenStatus = genStatus; % Used to check if gens offline since
                               % last iteration.
    genBus   = find(busType == 'G'); %Holds references to gen buses.
    busAngle = NbusColumn;
    Pnet     = NbusColumn;
    Pgen     = NbusColumn;
    genOut=-1e6*ones(Nbuses,1);%Timestamp for gen trip over/underspeed.

    % STATIC POWER FLOW MATRICES
    % Build A matrix - static.
    A = NlineNbus;
    for k = 1 : Nlines
        A(k,frombus(k)) = 1;
        A(k,tobus(k)) = -1;
    end
    AT = A';
    % Delta matrix to ensure Bx_matrix is invertible for PflowPU calc.
    delta = 0.0001 * eye(Nbuses);
end

counter = counter + 1;  % Update iteration counter, used in logs.
```

```
%%%%%%%%%%%%% PHEV Regulation Dispatch and Load Update %%%%%%%%%%%%%%%%
PHEV_reg = -numVeh.*PHEV_coor;
PHEV_reg_MW = PHEV_reg*100;
PHEV_base_power_MW = 0.001.*numVeh;

PHEV_max_power_MW = 1.4*0.001.*numVeh - PHEV_base_power_MW;
PHEV_min_power_MW = -PHEV_max_power_MW;

if (V2G_enable == 0)
    Pload = Pload;
else
  for i = 1:14
    if PHEV_base_power_MW(i) ~= 0
      if (PHEV_reg_MW(i)>=0)&&(PHEV_reg_MW(i)>PHEV_max_power_MW(i))
                PHEV_reg_MW(i) = PHEV_max_power_MW(i);
      else if (PHEV_reg_MW(i)<0)&&(PHEV_reg_MW(i)<PHEV_min_power_MW(i))
                    PHEV_reg_MW(i) = PHEV_min_power_MW(i);
           end
      end
    end
  end

    PHEV_reg_MW_short = PHEV_reg_MW;
    PHEV_reg_MW_short(8) = [];
    PHEV_reg_MW_short(7) = [];
    PHEV_reg_MW_short(1) = [];

    total_reg = sum(PHEV_reg_MW);
    PHEV_reg_log = [clock,total_reg,PHEV_reg_MW_short'];
    fprintf(fidLOG,'%1.3f s : TOTAL %1.3f MW, Bus 2 %1.3f Bus 3 %1.3f
            Bus 4 %1.3f Bus 5 %1.3f Bus 6 %1.3f Bus 9 %1.3f Bus 10
            %1.3f Bus 11 %1.3f Bus 12 %1.3f Bus 13 %1.3f Bus 14
            %1.3f\n', PHEV_reg_log);

    PHEV_reg_correction = PHEV_reg_MW/100;
    Pload = Pload + PHEV_reg_correction;
end

%% %%%%%%%%%%%%%%% Zero-crossing Detection Handling %%%%%%%%%%%%%%%%%%

% LINE OVERLOAD ALARMS and TRIPPING
resetTrip = find(clock < alarm(:,2));
lineOut(resetTrip) = 1;
alarm(resetTrip,2) = -1e6;

% Reset initial alarms set during time step with zero crossing event.
resetAlarm = find(clock < alarm(:,1));
alarm(resetAlarm,1) = -1e6;

% LINES OUTAGES IN DEACTIVATED ISLANDS
resetLine = find(clock < islLineTimeOut);
lineOut(resetLine) = 1;
islLineTimeOut(resetLine) = -1e6;
```

```
 % GENERATOR OVERLOAD TIME STAMPS
resetAlarm = find(clock < genOut);
genOut(resetAlarm) = -1e6;

%% %%%%%%%%%%%%%%%%%% System State Modifications %%%%%%%%%%%%%%%%%%%%%%

%% GENERATOR VARIABLES and LINE STATUS UPDATE
genStatus(genBus)    = u(2:2:Ngen*2);
busAngle(genBus)     = u(1:2:Ngen*2);
lineStatus = lineOut;

% UPDATES FOR OFFLINE GENERATORS
offline = find((busType == 'G') & (genStatus == 0));
takeOut = find((busType == 'G') & (genStatus == 0) & (genOut < 0));
busType(offline) = 'U';  % An angle will be calculated for these buses.
Pgen(offline) = 0;       % Set gen demand to zero.
genOut(takeOut) = clock; % Store generator trip time.

%% UNDERFREQUENCY LOAD SHEDDING
if (UFLS == 1)
    % Zero-crossing handling for UFLS events.
    if(clock < shed1Flag)
        shed1Flag = 0;
    end
    if(clock < shed2Flag)
        shed2Flag = 0;
    end

    % Adjust loads for UFLS when frequency drops below 59.8 Hz.
    if (dwMin < -0.3)
        Pload = Pload + shed2;
        if (shed2Flag == 0)
            shed2Flag = clock;
        end
    elseif(dwMin < -0.2)
        Pload = Pload + shed1;
        if (shed1Flag == 0)
            shed1Flag = clock;
        end
    end
end % UFLS code

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%% ISLAND CHECKING - SKM %%%%%%%%%%%%%%%%%%%%%%%%%%

% Check for islands only if any lines were removed since last iteration
% OR if system is already islanded and gens have just gone offline.
if ((~isequal(lastLineStatus,lineStatus)) ||
((~isequal(lastGenStatus,genStatus)) && (systemSplit == 1)))

    islandID    = 0;          % Initialize to zero.
    busIsland   = NbusColumn; % Vector with island number for each bus.
    busFIFO     = NbusColumn;
    beginFIFO   = 1;          % Pointer to first element in first-in
```

```
                            % first-out(FIFO) Queue.
endFIFO      = 1;           % Pointer to last element in FIFO.
busInFIFO    = NbusColumn'; % Identifies whether bus is in the FIFO.
line         = 1;           % Holds next line to be checked.
lineDone     = ~lineStatus; % Identifies whether a line has been
                            % checked yet.
loadDrop     = 0;           % Initialize load dropped - 0 MW.

% Identify multi-bus islands.
while ((sum(lineDone) < Nlines) && (line < (Nlines+1)))
    % Find first 'IN' line to begin identifying an island.
    flag = 0;
    while((flag == 0) && (line < (Nlines+1)))
        if ((lineStatus(line) == 1) && (lineDone(line) == 0))
            islandID = islandID + 1; % Increment ID# for next isl.
            flag = 1;%First 'IN' line is found, proceed with sweep.
            busIsland(frombus(line)) = islandID;
            busIsland(tobus(line)) = islandID;
            % Add to and from bus to FIFO if not there already.
            if (busInFIFO(frombus(line)) == 0)
                busFIFO(endFIFO) = frombus(line);
                endFIFO = endFIFO + 1;
                busInFIFO(frombus(line)) = 1;
            end
            if (busInFIFO(tobus(line)) == 0)
                busFIFO(endFIFO) = tobus(line);
                endFIFO = endFIFO + 1;
                busInFIFO(tobus(line)) = 1;
            end
            lineDone(line) = 1;     % Mark line as checked.
        end
        line = line + 1;            % Increment line pointer.
    end %Find beginning of new island.

    % Island sweep - identify all buses in the island.
    while (beginFIFO ~= endFIFO)
        % Grab first bus in FIFO Queue.
        bus = busFIFO(beginFIFO);

        % Find the buses still connected to it that haven't been
        % checked, add to FIFO. Begin by identifying lines whose
        % 'frombus' = the current bus.
       lineTemp=find((frombus==bus)&(lineStatus==1)&(lineDone==0));
        for i = 1:length(lineTemp)
            if(busInFIFO(tobus(lineTemp(i))) == 0)
                busFIFO(endFIFO) = tobus(lineTemp(i));
                endFIFO = endFIFO + 1;
                busInFIFO(tobus(lineTemp(i))) = 1;
            end
            busIsland(tobus(lineTemp(i))) = busIsland(bus);
        end
        lineDone(lineTemp) = 1;     % Mark lines as checked.
        %  Next identify lines whose 'tobus' = the current bus.
        lineTemp2=find((tobus==bus)&(lineStatus==1)&(lineDone==0));
```

```
        for i = 1:length(lineTemp2)
            if(busInFIFO(frombus(lineTemp2(i))) == 0)
                busFIFO(endFIFO) = frombus(lineTemp2(i));
                endFIFO = endFIFO + 1;
                busInFIFO(frombus(lineTemp2(i))) = 1;
            end
            busIsland(frombus(lineTemp2(i))) = busIsland(bus);
        end
        lineDone(lineTemp2) = 1;     % Mark lines as checked.
        beginFIFO = beginFIFO + 1;   % Increment pointer to
                                     % beginning of FIFO.
    end %Island Sweep

end %Multi-bus island identification.

% Assign island IDs to single bus islands.
noIsland = find(busIsland == 0);
busIsland(noIsland) = (islandID+1):(islandID+length(noIsland));
islandID = islandID + length(noIsland);

% Get stats for each island, deactivate those without load or
% generation.
islandStats=zeros(islandID,5);%Each row holds stats for an island.
if (islandID > 1)
    systemSplit = 1;

    for isl = 1:islandID
        % Island statistics.
        members = find(busIsland == isl);
        islandStats(isl,1) = abs(100*sum(Pload(members)));% Total
                                                          % MW load.
        islandStats(isl,2) = sum(genStatus(members)); % Total # of
                                                      % generators online.
        islandStats(isl,3) = 1;      % Island status - initially 1.
        islandStats(isl,4) = length(members);  % Number of buses.

        if ((islandStats(isl,4)==1) && (trueBusType(members)~='C'))
            islandStats(isl,5) = 1;
       % Set to '1': Isolated bus that only has load or generation.
       % Default '0': Multiple-buses or single-bus island with
       %              load and gen connected (trueBusType = `C')
       %              even if gen offline and/or all load has been
       %              dropped.
        end

        % Deactivate islands without load or generation.
        if ((islandStats(isl,1) == 0) || (islandStats(isl,2) == 0)
        % No gen or load.
            islandStats(isl,3) = 0;  % Island status to zero.
             % Loads dropped, and become swing buses, angle 0.
            drop = find(busType(members) == 'L');
            busType(drop) = 'T'; % Change to generic known theta
                           % bus, excluded from power flow calc.
            loadDrop = loadDrop + islandStats(isl,1);
```

```
                % Drop loads on all buses in deactivated island.
                Pload(members) = 0;
                busAngle(drop) = 0;
                % Any gens offline now become swing buses, angle 0.
                newSwing = find((busIsland == isl) & (busType == 'U'));
                busType(newSwing) = 'G';
                busAngle(newSwing) = 0;
                % Take lines in island out of service.
             islLines =find((lineStatus==1)&(busIsland(frombus)==isl));
                lineStatus(islLines) = 0;
                lineOut(islLines) = 0;
                islLineTimeOut(islLines) = clock;
            end
        end % Island stats calculation.
    end % Island identification.

end %ISLAND CHECKING.

% Used in next iteration to check for status changes.
lastLineStatus = lineStatus;


%% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%% POWER FLOW CALCULATION %%%%%%%%%%%%%%%%%%%%%%%%

% BLACKOUT CHECK and REPORTING
% Will cause simulation to halt with error message.
if ((sum(genStatus)==0) || (sum(lineStatus) == 0) || (sum(Pload) == 0))
    % Throw error in Simulink simulation when system blacks out.
    fprintf(fidLOG,' *$@$*$@$*$@$*$@$*$@$*$@$*$@$*$@$*$@$*$@$*$@$* \n');
    fprintf(fidLOG,'*$@$* BLACKOUT, at %1.3f seconds *$@$*\n', clock);
    fprintf(fidLOG,' *$@$*$@$*$@$*$@$*$@$*$@$*$@$*$@$*$@$*$@$*$@$* \n');
    error('*$@$* B L A C K O U T *$@$* B L A C K O U T *$@$*);
end

% CALCULATION OF Bx MATRIX
lineB = bxLine.*lineStatus;
AoutBline = diag(lineB);
Bx_matrix = (AT*AoutBline*A);
% Place 1 into diagonal for buses in deactivated islands.
comp = find(diag(Bx_matrix) == 0);
for i = 1:length(comp)
    Bx_matrix(comp(i),comp(i)) = 1;
end

% CALCULATE ANGLES AND POWER DEMANDS.
PbusRow = find((busType == 'L') | (busType == 'U'));
PbusCol = PbusRow';
TbusRow = find(busType == 'G');
TbusCol = TbusRow';

% Bus angle calculated for load and deactivated generator buses.
busAngle(PbusRow,1) = Bx_matrix(PbusRow,PbusCol)\(Pload(PbusRow,1) -
                      Bx_matrix(PbusRow,TbusCol)*busAngle(TbusRow,1));
```

```
Pnet(TbusRow,1)      = Bx_matrix(TbusRow,PbusCol)*busAngle(PbusRow,1) +
                       Bx_matrix(TbusRow,TbusCol)*busAngle(TbusRow,1);

Pgen(TbusRow,1)      = Pnet(TbusRow,1) - Pload(TbusRow,1);

% CALCULATE LINE FLOWS
nonGen = find((busType == 'L') | (busType == 'U') | (busType == 'T'));
Pnet(nonGen,1) = Pload(nonGen,1);
PflowPU = abs(AoutBline*A*inv(Bx_matrix + delta)*Pnet);
lineLoad = 100*PflowPU./maxflowPU;

%% SET LINE OVERLOAD ALARMS and TRIP PERSISTENTLY OVERLOADED LINES
%  Use: ti = alarm(:,1) initial overload time;
%       tu = alarm(:,3) time no longer overloaded;
%       tr = alarm(:,2) time line removed after breaker acts;

% OVERLOADED LINES BACK IN LIMITS: Reset initial alarm timestamp.
%  Reset initial timestamp to negative of initial overload, ti = -ti.
%  Then init overload time still there if need after zero-crossing.
%  Set time out of overloading, tu = clock, to use after zero-corssing
%  to restart timer on overloaded line, instead of setting as initial
% overload again.
inLimit = find((PflowPU <= maxflowPU) & (alarm(:,1) > 0) & (alarm(:,2)
< 0));
alarm(inLimit,1) = -alarm(inLimit,1);    % Unset breaker countdown, ti.
alarm(inLimit,3) = clock;                % Set time out of overload, tu.


% ZERO CROSSING CLOCK SETBACK:
% Check lines that previously came OUT of overloading.
%  Lines without active removal timer, ti < 0.
%  Lines no longer overloaded, ti=-(ti), negative of initial over time.
%  Lines that haven't come out of overloading, ti = -1000000.


%  Case 1: Clock has stepped back to before line came out of
%          overloading but after time of initial overloading.
%          |ti| < clock < tu
restartAlarm = find((PflowPU > maxflowPU) & (alarm(:,1) < 0) &
(alarm(:,1) > -1000000) & (clock < (alarm(:,3))) & (clock >
abs(alarm(:,1))) );
alarm(restartAlarm,1) = -alarm(restartAlarm,1); % Restart initial
overload timer, ti.


%  Case 2: Clock has stepped back to before line was initially
%          overloaded last time (and consequently before came out of
%          overloading). (clock < tu) & (clock < |ti|)
resetAlarm = find((PflowPU>maxflowPU) & (alarm(:,1)<0) & (alarm(:,1)>-
1000000) & (clock<(alarm(:,3))) & (clock<abs(alarm(:,1))) );
alarm(resetAlarm,1)=clock;%Reset initial over timer ti,to current time.
alarm(resetAlarm,3)=-1e6;%Reset time out of overload tu, to init value.
```

```
%  Case 3: Clock has stepped back but is AFTER initial overload time,
%          AND AFTER line came out of inital overloading, but WITHIN
%          breaker trip time of initial overloading.
%           (|ti| < clock) & (tu < clock) & (clock - |ti| < breakerTrip)
restartAlarm = find((PflowPU > maxflowPU) & (alarm(:,1) < 0) &
(alarm(:,1) > -1000000) & ((clock + alarm(:,1)) < breakerTrip) );
alarm(restartAlarm,1) = -alarm(restartAlarm,1); % Restart initial
overload timer, ti.

% For lines operating over limits for first time:
%  Set initial overload time stamp for first time overloads.
newOver = find((PflowPU > maxflowPU) & (alarm(:,1) < 0));
alarm(newOver) = clock;
% Now, all overloaded lines have their initial alarm time set.

% Recalculate the overload timer for all lines that are over.
% Represents the combined relay+breaker operation time.
alarm((PflowPU > maxflowPU),4) = clock - alarm((PflowPU >
maxflowPU),1);
% Find indices of those ready to trip out that haven't been already.
takeOut = find((alarm(:,4) > breakerTrip) & (alarm(:,2) < 0));
alarm(takeOut,2) = clock;
lineOut(takeOut) = 0;

%% CLEAN UP and OUTPUT
% Used in next iteration to check for zc detection and status changes.
lastTime = clock; % Save time to check for zero-crossing detection.
lastGenStatus = genStatus;

Output  =
[Pgen(1),Pgen(2),Pgen(3),Pgen(6),Pgen(8),systemSplit,busAngle(4),
 busAngle(5),busAngle(9),busAngle(10),busAngle(11),busAngle(12),
 busAngle(13),busAngle(14)];

end %DCflow_IEEE14.m
```

C AGENTS

Table 31 and Table 32 define agents in the local electric power system (Local EPS) and the PHEV energy transfer system (ETS). These agents are based on the multiagent system outlined in [33] (M. Amin, "Toward Self-Healing Infrastructure Systems", *IEEE Computer, 2000).*

Table 31
Local Electric Power System (EPS) Agents

Agent	Layer	Inputs and Basic Functionality
Point of common coupling (PCC) monitor	Reactive	• Inputs: System frequency (high-side of substation), voltage at the PCC • Threshold detection per IEEE 1547's Area EPS frequency and voltage requirements [2] • Notify ETS to cease energizing upon abnormal conditions in Area EPS
Local EPS state determination	Deliberative	• Inputs: Data from local sensors, Area EPS, and ETS states • Determine state of the Local EPS
Model management	Coordination	• With ETS state update, or plug-and-play notification of new ETS node • Keep track of recommendations and ETS demand/supply levels • Validate Local EPS model status and ETS demand/supply changes
Local demand/supply recommendation	Deliberative	• Inputs: Local EPS state • Determine ± recommendation, ongoing • Broadcast request to local PHEV ETS if supply/demand is favorable, i.e. (Real time LMP – Day ahead LMP) > Price Threshold

Table 32
PHEV Energy Transfer System (ETS) Agents

Agent	Layer	Inputs and Basic Functionality
Plug-and-play agent	Coordination	• Notify local PHEV Coordinator (within Local EPS) of existence • Include information needed to update Local EPS model
Battery model management	Coordination	• With demand monitor updates, ETS state determination, demand/supply determination, supply release, etc. update battery model as necessary
Electric vehicle supply equipment (EVSE) model management	Coordination	• With ETS state determination update EVSE model as necessary
Demand monitor, DR connection	Deliberative	• Inputs: Battery state, user inputs (may include daily schedule) • Track PHEV demand • Forecast demand profile and availability • Determine allowable demand/supply range and duration (± kW, 10 min.)
ETS state determination (ongoing or at change?)	Deliberative	• Inputs: Local EPS state, premises level sensing and measurement data, battery system data, EVSE data, and user inputs • Determine general ETS state (PHEV plus the EVSE)
Demand/supply determination	Deliberation	• Inputs: ETS state, results from demand monitor, Local EPS state, and the local demand/supply recommendation • Determine 1) best contribution to frequency control, OR 2) new charge rate after supply is released
Supply release agent	Coordination (Command interpretation agent)	• Input: Notification to cease supply or release control from PCC monitor • Stop discharging, • Else if charging trigger demand/supply determination for new charge rate (this may be initial charge rate or modified to repay energy supplied)