Plug-In Hybrid Electric Vehicle's Impact on Primary and Secondary Frequency Regulation

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ABSTRACT

Plug-in hybrid electric vehicles (PHEV), while they are plugged-in, support the grid a distributed storage. With the advent of smart grid along with the developed communications related with it, PHEV could contribute to ancillary services such as frequency adjustment. An excellent service for PHEV is frequency regulation supply as the duration of supply is short. Moreover, with regard to the fact that frequency regulation is the highest priced ancillary service, the owners of vehicles benefit from PHEV financially. A reliable frequency measurements can be achieved by the coordinators of the system that can drive the trustworthy local automatic generation control (AGC) signals for vehicles which are participating in vehicle-to-grid (V2G) operation. A V2G controller as well as PHEV coordinator are extra controllers which estimate the battery state, recommended level of supply, and user preferences for V2G participation. The simulation part uses three sequences of cases for regulation supply when a sudden change in loading is detected: Providing frequency regulation using central generating units, using aggregate PHEVs storage as a contribution to primary regulation, and finally utilizing the storage as a contribution to primary as well as secondary regulation.

Keywords: Plug-In Hybrid Electric Vehicle, Frequency Regulation, Automatic Generation Control, Area Control Error.

ÖZ

Şarj edilebilir hibrid elektrikli araçlar (PHEV) küçük çapta dağıtılmış enerji deposu olarak kullanılabilir. İlgili iletişim ve ölçüm sistemleriyle akıllı şebekenin gelişmesiyle PHEV frekans kontrolu için yardımcı kaynak görevi yapabilir. Frekans kontrolu, dakikalarla ölçülen kısa bir süreç olduğundan PHEV için ideal bir görev alanıdır. Frekans düzenlemesinin en pahalı yan servis olduğu bir piyasada araç sahipleri için de bir mali kazanç sağlamaktadır. Bu sistemde, üst katmanlarda yer alan ve güvenilir frekans ölçümlerine erişimi olan PHEV koordinatörü vardır. Bunun görevi V2G'ye katkı yapan araçlara yerel olan bir otomatik üretim artır/azalt kontrol işareti göndermektir. Her araçta ise, akü durumu, tavsiye edilen tedarik seviyesi ve kullanıcı tercihlerini dikkate alarak düzenleme tedarik kararları veren bir V2G denetleyicisi bulunmaktadır. Sistemin, yükte ani değişim ile üç durum için benzetimleri yapılmıştır: Merkezi üretim birimlerini kullanarak frekans düzenlemesi; PHEVyi birincil düzenlemeye (hız idarecisi kontrolu) katkı yapması durumunda; PHEVnin, kontrol işaretinde fazladan bir integral terimi bulunmak suretiyle, birincil ve ikincil düzenlemeye katkı yapması durumunda.

Anahtar sözcükler: Şarj-edilebilir hybrid elektrikli araçlar, Frekans düzenlemesi, Otomatik Üretim Kontrolu, Alan Kontrol Hatası.

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LIST OF SYMBOLS/ABBREVIATION

ACE	Area Control Error
B_f	Frequency Bias Constant
f_{syn}	Nominal System Frequency
k_{AGC}	Local Automatic Generation Control Gain
pf	AGC Participation Factor
p_{veh}	Charge Rate in Kilowatts
T_{ch}	Prime Mover Time Constant
t_{full}	Expected End Time of Charging
T_g	Governor Time Constant
u_{AGC}	AGC Dispatch Signal
u_{reg}	Regulation Signal
β	Local Area Frequency Response Characteristic
δ	Generator Rotor Angle
AER	All-Electric Range
AGC	Automatic Generation Control
CD	Charge-Depleting
CDF	Cumulative Distributed Function
CI/CV	Constant Current/Constant Voltage
CS	Charge-Sustaining
CV	Conventional Vehicles
DCPF	DC Power Flow
DOD	Depth of Discharge of Battery
DR	Distributed Resources

EMS	Energy Management System
EPS	Area Power System
EPRI	Electric Power Research Institute’s
ETS	Energy Transfer Systems
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
ICE	Internal Combustion Engine
LI-ION	Lithium-Ion
PCC	Point of Common Coupling
PHEV	Plug-in hybrid Electric Vehicles
ROCOF	Rate of Change of Frequency
SAE	Society of Automotive Engineer
SOC	State-Of Charge
SOH	Battery State of Health
SCIB	Supper Charge Ion Batteries
TLR	Transmission Loading Relief
V2G	Vehicle-to Grid.

Chapter 1

INTRODUCTION

1.1 Introduction

In thesis the application of PHEVs as a contribution to the frequency regulation is explored. Our main concern is the applicability of the PHEVS, first proposed by Mullen on September 2009 in [3]. Fundamentally, plug-in hybrid electric vehicles (PHEVs) are similar to the today's hybrid gasoline electric vehicles, but including a bigger battery cord for charging. Hence, providing a higher energy storage, we can drive PHEV for miles using only electrical energy. Using the combustion engine and regenerative breaking (s. g, electric vehicles and hybrid vehicles can recover some of the kinetic energy, while pressing break in a hybrid electric vehicle, such that the electric motor mode changes to generator mode. Subsequently, the kinetic energy transfers to the generator through wheels with the aid of drivetrain. The generator finally converts some part of kinetic energy to electricity which is used in a high-voltage battery as a storage), the battery cannot be fully recharged anymore as a result of raised energy storage of the battery. In comparison to conventional vehicles (CV)[1], PHEVs have many benefits such as the following:

- Lower operating and maintenance costs
- Fewer sensitivity to changeable fuel prices and reduced oil dependency

[1] Conventional vehicles are vehicles that use internal combustion engine for providing required energy and power based on gasoline.

- Reduction in vehicle noise and driving in a quitter condition
- Convenience (home charging for all-electric and plug-in hybrid vehicles)
- Decrement in the greenhouse gases emissions
- Increased energy efficiency

Major automakers have tried the most to commercialize electric vehicles (EVs) with a little end outcome, for instance the EV invented in the early 1990's by the General Motors. Nevertheless, raising environmental concerns, increasing gasoline prices, and yearning to decrease oil consumption are the leading reasons in the ongoing attempts to commercialize PHEVs and the healthy electric vehicles. Furthermore, a vehicle needs a big battery system in order to utilize just electrical energy in consideration of supplying the necessary power and energy.

1.2 Motivation

Recently, distributed energy resources (DER) have gained lots of considerations in the power industry as the units of generation and energy storage which are in several size and shapes and might be owned by the system operator, utilities, or utility customer. There are plenty of approaches in which DER can contribute to both the normal and abnormal grid operation, for instance by handing over spinning reserves[2] and smoothing renewable energy resources. Recently, to simplify the interconnection of these resources, there are attempts in progress with the advanced modification of transmission, distribution system, and consumer services. Communicating from control center down to all parts of the power grid, involving homes, and vice versa is one of the most compelling modifications related to the infrastructure in the power grid.

[2] Spinning reserve refers to unused online generation capacity, employed to contribute to generation and transmission shortages when necessary

Moreover, digital electronics are progressively being applied in control as well as monitoring devices throughout the grid. These distributed processors facilitate the advent of complicated computational adequacies and intelligence all over the system. These facilitations result a smart grid in which plug-in hybrid electric vehicles could be charged optimally in order to supply the system [1].

Conversion to the smart grid makes the capability all over the system enlarged beside the unification of the DER improved with aims of having more reliability and stability. In order to control PHEV's charging, the smart grid would provide required means to simply postpone its charging to the high demand period. Assuming that the grid can provide necessary charging for the vehicles, the advantages of distributed storage bring into the question: what are the vehicles advantages? The non-stationary storage would be the answer.

1.3 Objectives and Organization

With the abundant penetration of PHEVs, the following problems must be considered:

1. For the system operator, it is not possible to dispatch services over exclusive vehicles, hence the service must be dispatched locally.

2. Ancillary service requirements must be driven dependent on the local operating conditions since the state of the entire system is not known by local controllers.

Because of the consumer disinterest in vehicle to grid (V2G) participation, V2G might not be accomplished. Whereas, the acting of PHEV could also be compensated by the other distributed storages such as rooftop solar panels. Since PHEV is a certain kind of battery storage when can be distributed, their upsides can be definitely outweighed by other storages that may be convenient for frequency adjustment.

In this study, we explore how PHEVs possibly and efficiently supply distributed frequency control. The important questions relevant to the practical implementation of PHEVs clarify the objective of this study:

- What is the effect of PHEV on the design and planning of the distributed system?
- What are the local operating parameters necessary to bring out what the PHEVs should supply, although not having enough knowledge of the entire system?

This thesis addresses these questions by:

- Driving the proper power magnitude and duration which helps the system in a general way.

- Depending on that power, huge PHEV regulation supply is defined.

Chapter 2 introduces the concept of PHEVs including battery system, battery management system, and energy transfer system. Chapter 3 discusses the concept of vehicle-to-grid, the interconnection of vehicles with the system, and the role of PHEVs as an energy source. Chapter 4 mentions system design as well as supplementary components. Chapter 5 involves power system simulator. In chapter 6, simulation results, conclusion, and future work are defined.

Chapter 2

PLUG-IN HYBRID ELECTRIC VEHICLE

2.1 PHEV Definition

Plug-in hybrid electric vehicles (PHEVs) are hybrid vehicles with high capacity batteries that can be charged by plugging them into an electrical outlet or charging station. PHEVs can properly store adequate electricity from the power grid to significantly reduce their petroleum consumption. PHEVs need large batteries for energy storage which affect vehicle weight, cost, and performance. Many investigations have been carried out for different vehicle design in term of all-electric-range (AER), especially ones that can be driven 0, 20, and 60 miles [2], [3]. A plug-in hybrid all-electric range is designated by PHEV-YY where YY represents the distance the vehicle can travel on the battery power alone. For instance, a PHEV-40 can travel 40 miles or about 64 kilometers without using its internal combustion engine.

The PHEV's battery can operate in one of the two modes: charge-sustaining (CS) or charge-depleting (CD) mode as illustrated in the Figure 2.1. Considering an approximately full battery, they will consume only electrical energy in charge-depleting mode whenever requested till the battery charge range reaches to a conventional point for charge-sustaining mode that can be expressed as (20-50) % state-of charge (SOC). In charge-sustaining mode the energy management operation will be such that SOC remains as much as possible close to the threshold point. At low

SOC, electric energy is recovered with combustion engine or slightly regenerative breaking and can be utilized as power boost when the speed is increasing.

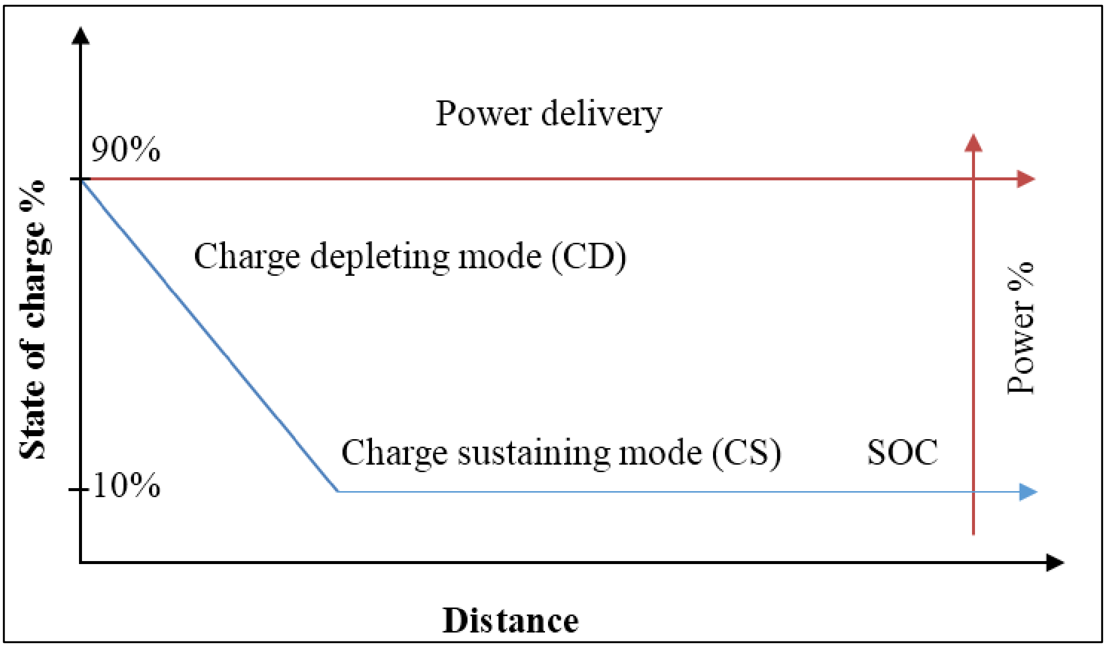

Figure 2.1: Illustration of typical PHEV discharge cycle

In practice, for the sake of both safety and battery life time the battery maximum SOC may be restricted to less than 100% and the minimum SOC might be limited to more than 0%.

In charge-depleting mode, blended operation can be also considered such that the PHEV uses electricity and gasoline to power the vehicle from the engine and battery blended together. In this design the YY stands for the mile that a vehicle is supposed to be driven in CD mode. In comparison to the hybrid electric and conventional vehicles, PHEVs saving in both renewable and non-renewable energy has gained lots of attentions. The Table 2.1 shows the different types of vehicles performance.

Table 2.1: PHEV saving with comparison to CV counterpart [2], [3]

Vehicle class	Primary energy saving		Fuel cost saving	
	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%

Plenty of reasons cause PHEV being highly efficient in the areas of fuel cost and consumption. But above all of them, the advantage of electric motor compared with internal combustion engine (ICE) makes the differences more and more visible. In a CV's, in order to operate properly under all driving conditions the ICE is immensely implemented outside of its effectiveness rate to respond sufficiently to the power needs. Whereas, a PHEV uses both the engine together with the battery simultaneously and the engine is used mostly as a base power. The mentioned reasons indicate that the engine can be operated considerably near its optimal efficiency point so that the battery improves the slack. Moreover, reduced gears are required which simplify the vehicle drive system. At present, the primary concern between power grid and PHEV is battery charging while the vehicles are stopped and plugged in. There are two adaptable ways of charging:

- Dumb charging
- Smart charging

Under the dumb charging scheme, a PHEV starts charging as soon as plugged in until it is fully charged or unplugged (V0G). Smart charging, on the other hand, controls starting point of charging and interrupting point by means of communication from utility to PHEV (V1G). The vehicle charging can be controlled in the smart charging by means of external sources such as vehicle owner conventional rules for charging, third party checking a group of PHEVs, or utility postponing charging based on demand response program.

One-way communication has its own disadvantages as there is no way of knowing the corresponding response. For instance, considering the case that the utility wants to reduce system loading and, hence they distribute signal to cease charging, but how much energy actually has been saved without round way communication path? The ability of two way communication and energy flow, as the smart grid progresses, introduce the other option for the control of charging denoted as vehicle to grid (V2G). V2G allows vehicles to provide a number of services for the grid admitting PHEVs to supply power back to the system. In the following sections, PHEV battery system and energy transfer system (ETS) will be discussed.

2.2 Battery System

PHEV battery system consists of two major parts, the battery pack and battery management system (BMS). The BMS provide a way for interaction between the battery and the other part of the vehicle such as engine management and the onboard charger. The BMS tracks the state of the battery, prolongs its life time and keeps it ready to deliver full power when needed. In addition, the BMS depends on vital energy and power for the drive train, when driving, examines management of the energy.

2.2.1 Lithium-Ion Battery Pack

A battery pack is composed of series and parallel cells constructing interconnected battery modules. In recent past, nickel metal hydride (NiMH) batteries have been mostly the chemistry heart of the batteries until lithium-ion (Li-Ion) batteries due to their energy and power density efficiency have gained lots of attention. The viable superiority of Li-Ion batteries is their weight and size which are considerably comparable with the similar HEVs and conventional vehicles. Besides, in order to provide the same voltage, lesser cells are required that means breaking down the complexity of the battery design. Furthermore, Li-Ion batteries are not affected by the memory difficulties and have a very low self-discharge value of about 6% in a month when comparing to the other batteries which might be 0.9% in a day.

Another advantage of the Li-Ion batteries is the greater energy density per unit volume which indicates lighter and smaller battery pack in comparison to NiMH batteries. Finally, the battery temperature and charge rate do not considerably influence the charging and discharging effectiveness of the Li-Batteries especially in the CD mode where opposing with a highly variable power demand and a rapid charging. The battery pack size is considerably based on the necessary energy for operating in the AER. Figure 2.2 shows the energy storage needed for 4 class of PHEV with 20 and 60 miles in AER.

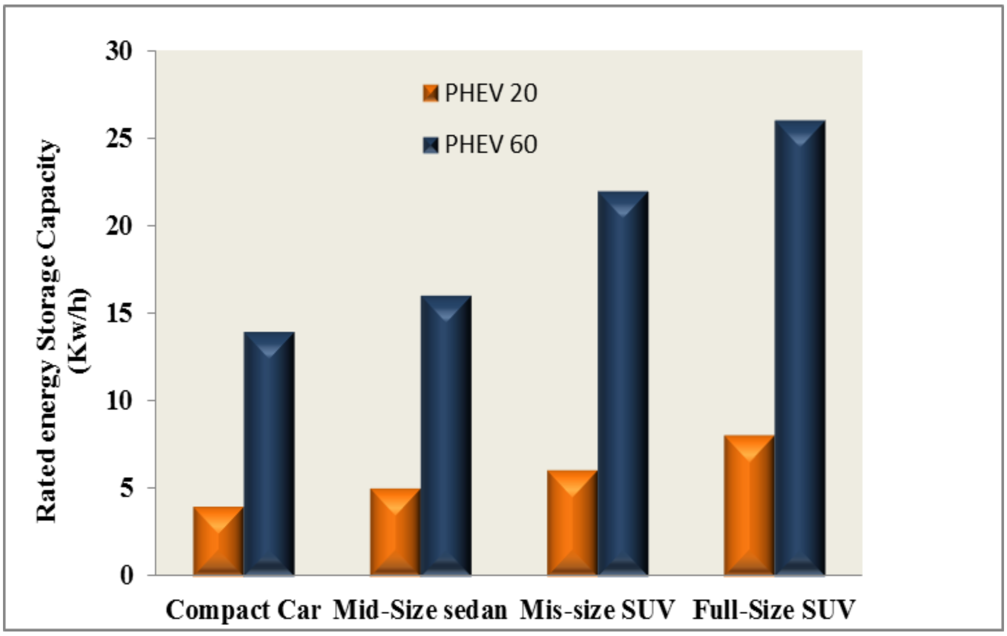

Figure 2.2: Total energy capacity of battery system in all electric range for different vehicle class [2] [3]

In consideration of battery health and restricting probable future damage to it, there is a permissible state-of-charge (SOC). The rated value between minimum and maximum state-of-charge is considered as usable state-of-charge which is about 50% to 80% dependent on the battery and the vehicle design.

A deep cycle would be considered as consuming usable state-of-charge in a CD mode in terms of charge/discharge cycles. Current battery systems are constructed for 3,000 deep cycles and more. In this case, a battery should be able to be implemented for approximately 10 years or more if a vehicle consumes every day all its electric range and charged completely overnight. Li-ion batteries development is keeping on with the advanced materials for the anode as well as cathode and in particular using nanotechnology approaches [4]. For example, Supper Charge Ion Batteries (SCIB^{TM}) that in less than 5 minutes can be recharged up to 90% of a full capacity and particularly has a deep cycle life of 6000 cycles[3]. The details about chemistry of Li-Ion battery are more explained in [4].

2.2.2 Battery Life Time

Cycles and years are the features providing the being's existence of a battery, but in this report it is in terms of the services they can provide as energy supply of the vehicle. SOC and power efficiency is a usual measure of the end life of batteries so that bellowing 80% of the rated value indicates the end lifetime of them. The most important factors affecting the life of the batteries can be considered as: temperature of the charge/discharge, real drive cycles, temperature of the storage, beyond charging, the style of owner driving. In practice, vehicle batteries are designed for working up to 10-15 years, including the impact of deep cycling CD mode and shallow cycling in CS mode. Analysis of PHEV's life time regarding deep and shallow cycles has been done by many organizations [4].Calendar life and cycle life time for PHEV batteries is illustrated in the Table 2.2.

Table 2.2: PHEV battery life time comparison, table 2 [4]

Lifetime Metric	**USABC**		**MIT**	**EPRI**	
Charge Depleting Range	10 miles	40 miles	30	20 miles	60 miles
Calendar Life	15 years	15 years	15 years	10 years	10 years
Deep Cycles	5,000	5,000	2,500	2400	1400
Shallow Cycles	300,000	300,000	175,000	<200,000	<200,000

[3] These battery qualifications are upon on laboratory and might differ from application

The cost relevant to batteries can be hugely reduced when repurposing them in stationary storage application at the moment of not being applicable for utilizing in a PHEV. In this case, many attempts have been carried out to evaluate the possibility of repurposing PHEV batteries including Sandia National Labs in 2003 [5] .The study found that they can be conveniently used as a transmission support and commercial and residential applications.

2.2.3 BMS

Generally, the battery management system (BMS) observes the battery's current condition and interacts with the other vehicles or energy management system (EMS) when appropriate. For this study battery state and corresponding energy characteristic will be reviewed. Table 2.3 states different parameters tracked by the BMS. Furthermore, developed methods such as Neural Networks and Kalman Filters might be used for determination of SOC. Table 2.3 shows diverse parameters determined by EMS.

Table 2.3: Battery system important parameters

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

2.2.4 Behavior of Charging

Controlling the battery charging is of a particular interest, since the required power to charge the PHEV would alter dependent on the particular pack of battery and equipment for charging. Usual charging system provides maximum existent current [6]. Nevertheless, the practical functions in Society of Automotive Engineers (SAE J2293-1) makes controlled charging possible and further allows assigning restriction on charging through load management system [7]. Li-Ion batteries are mainly charged by using a mixture of constant voltage and constant current denoted by CI/CV. At the beginning, the battery voltage increases till the voltage remains constant to keep the battery healthy. The charge current will start to fall down while voltage is constant till reaching to the fully state of charge. Lastly, at a minimum threshold for current, for example 3% of the rated current, charging will be ceased as demonstrated in the Figure 2.3. Maximum charge limit is mainly 4 volts for a single cell and several hundred for the entire battery pack.

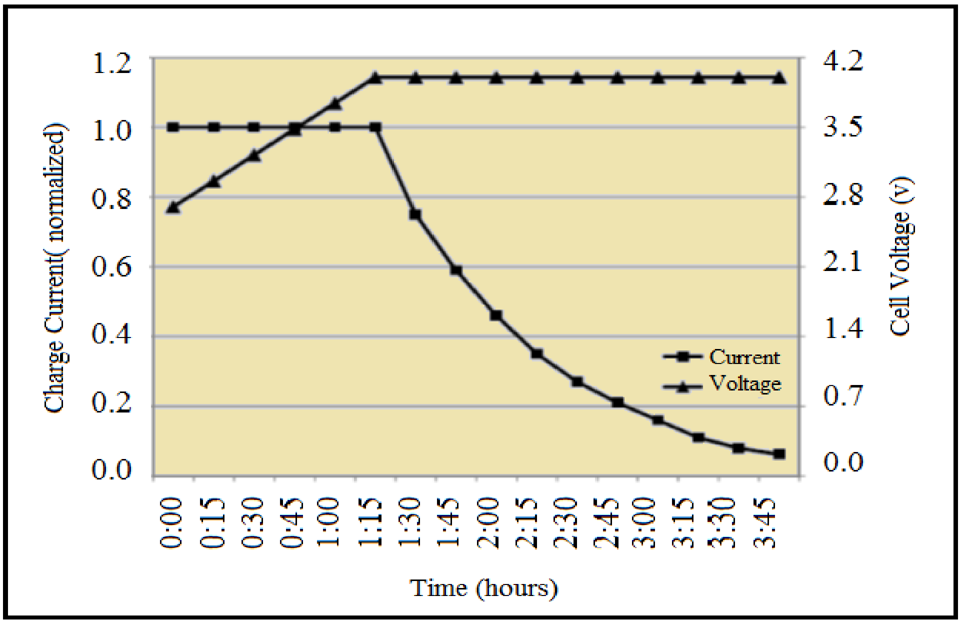

Figure 2.3: Indication of charge behavior for Li-Ion batteries [6].

The power of the battery pack alters considerably correspond to the fact that the driving needs of the vehicle alter continuously. As a result, the charge controller may rest in the meanwhile between charging and discharging to give a chance for chemical relaxation and thermal equilibration in order to attenuate effects on battery pack. It will be possible with the persistent development in the Lithium-Ion batteries to have an analogous charge management during driving the vehicle with a lesser influence on the battery life.

2.3 Energy Transfer System

The electric vehicle together with its supply equipment (EVSE) are the components of ETS. Energy transfer system requirements and system architecture can be summarized in SAE j2293-1 [7]. The physical connection and path between ETS and utility service point is shown in the Figure 2.4.

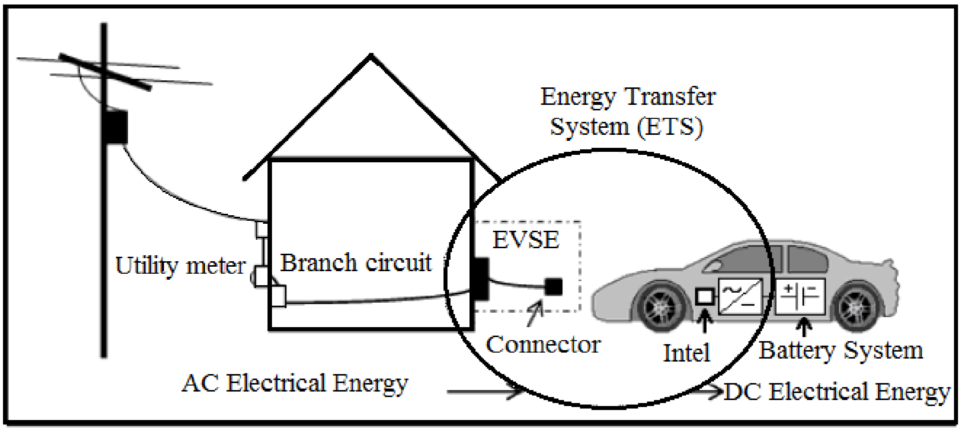

Figure 2.4: Diagram of ETS for Electric vehicles figure 1 in [7]

ETS indicates when EVSE and the vehicle are capable of transferring energy, handles the energy transferred to the vehicle, and switches and converts AC power to DC [7].

2.4 Impacts on the Power Grid

PHEV effects on the distribution system is of a primary concerns. System loading is one of the significant factors in designing distribution system. Load characteristics and future change in it are the important means for designing the system. With the contribution of these factors one can actuate the capacity of feeding lines as well as distribution transformers rating values. Smart charging allows charging to be postponed during of the peak periods and improves employment of generation constituents overnight.

Chapter 3

VEHICLE TO GRID (V2G)

3.1 V2G Definition

Vehicle-to-grid (V2G) is generally defined as a possibility to have two-way energy transformation and communication among the utility and the vehicle. Smart charging handled by the third party, for example V2Green[4] , is one of the most viable features of the integration of vehicles into the grid. Extra software and/or hardware might also bring into the PHEV and EVSE for allowing V2G abilities. EVSE could be a charge coupler and a standard grand outlet or even can be a charging station.

3.2 Role of PHEV in Form of an Energy Source

PHEVs are movable dispersed capacity which are able to operate as both a source of energy and a controllable load. As a source of energy they can be utilized in the following applications:

1. Peak shaving,
2. Smooth out load,
3. Backup power supply, and
4. Smoothing output of alternative generation

[4] V2Green is an inventor in plug-in electric vehicle management system used for determining standards for electric vehicles with the power grid interfacing.

In light of power and accuracy needs, employing distributed energy resources outweigh using huge generation unit. For example, because distributed resources are not so far from the load and distributed generation (DG) management system, they can properly be incorporated into both DG and load management system without being concerned of communicating with the system operator. Hence, the presence of big storage and generating units will be unnecessary which means improved utilization and cost saving. Indeed, locally serving of many energy and power services is more suitable.

3.2.1 Building[5] Supply Capacity Potential

In case of minimizing cost, smoothing out load, or handling peak signals PHEV can be used as both adjustable load and origin of the energy. The dynamic range of the PHEV power is from several hundred to several thousand watts. To give an example, residential electricity customers of Minnesota were 2,267,167 in 2007 with a residential retail electricity sales of 22,646 GWh [8] .So an average of 27 kWh depletion each day means PHEV can be perfectly used as recovery supply following loss of electrical service.

3.2.2 Aggregate Supply Capacity Potential

The power and energy capacity are the most significant factors in defining suitable service storage. At a specific power level, the period of time that the storage is able to supply energy drives by the rate of the energy capacity over the power. The following example figures out the duration of PHEV as an energy supply. In 2007 about 4.7 million vehicles were encountered in Minnesota [9]. Considering 5 percent of them to

[5] Commercial and household building

be PHEV, each including 10 kWh fully charged battery with 80% allowable energy capacity, total storage capacity can be calculated as:

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

For Three levels of AC charging system stated in SAE J1715ee level [10] total power rating and duration of storage is shown in the table 3.1.

Table 3.1: Total power and storage duration of PHEV in Minnesota

Charger Class	Power Level	Total Power	Total Energy	Storage Duration13
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

Values in Table 3.1 demonstrate efficiency of PHEV as a supplement for services with the usual order of minutes to hours. As a result, PHEVs are excellent for supplying services with the duration of minutes to hours, although they cannot be ideal as a base-load power supply.

3.3 Generation and Load Equilibrium

Balancing load and generation is gained by using many generation dispatching and regulating services for a large system load. One of the particular concerns in power system is applying the storage for the aims of regulation reserve that can be prepared hugely with PHEV Li-Ion battery system. The rest of this chapter discusses the use of PHEV as a regulation supply, traditionally frequency regulation, and automatic generation control (AGC) signal.

3.3.1 Typical Frequency Regulation

At present, controlling and regulating of the frequency is applied to catch balance between generation and load system. Two frequency regulation steps are:

1. Primary: Eliminate frequency deviations by response of generator governor.
2. Secondary: take system frequency back to its nominal 60 Hz using AGC signal.

Following load disturbance, the system frequency will modify so that it rises when generation is more than load and falls down when load is more than generation. Noticing frequency deviation, generator governor catches the excursion in a few seconds and reacts so as to restore load/generation balance and the frequency goes to a new steady-state value which results in a new frequency error. Subsequently, AGC is applied to correct this error and return frequency to 60 Hz in an order of several minutes.

AGC signals are computed from an area control error (ACE) which is the instantaneous difference between the actual net and scheduled interchange. Receiving negative ACE indicates overloading and units participating in AGC increases their output for providing regulation up. In contrast, following a positive ACE indicates generation increment and units reduce their output and aid to regulation down. Generally, AGC units reply to ACE signals in a minute or even less with recovering time of few minutes. Regulation reserves might be fixed up several times in a day in comparison to the contingency reserves such as spinning reserve that might be fixed up one or two times in a year [11].

3.3.2 Amalgamate PHEV into Regulation

System operator examines total load and generation, and at the point of service electric meter as well as home smart grid determines power demand and energy consumption. Control strategies integration for the sake of the frequency regulation needs to be taken just as generator governor response has leaded to steady-state frequency error after disturbance in the system. Load curve is a continuous curve with usually 2 peaks at the morning and evening, when people are getting ready to go or come back from the work, and differs in some extant based on locations, seasons, etc. Load forecasting on an hourly basis for a system is done to simplify the system preparation and design. Because of unreliable frequency measurements on the consumer part of the system, Load forecasting is required in condition of applying regulation in a distributed manner.

A study [12] discovered the efficiency of fast regulating resources that cause decrement in the amount of AGC signals that generators must respond. The accessible storage in PHEV is perfect for Supplying fast regulation. Table 3.2 shows the impact of PHEV on regulation and needs of frequency regulation by AGC unit.

Table 3.2: PHEV operation method for regulation

Service	**Regulation up**	**Regulation down**
Condition in area EPS	Load > generation	Load < generation
Charge Tate	Decrease; alleviate regulation provided by central generation	Increase; alleviate regulation provided by central generation
Discharge rate	Increase; transfer regulation provided by central generation	Decrease; transfer provided by central generation

With the presence of accumulated PHEV, using a controller is required to coordinate ETS and operate as a connection between PHEV and V2G controllers and the system operator. Unique Characteristics of PHEVs can be summarized as follow:

1. point of consumption is the same a supplying point
2. power-frequency independence
3. Mobile capacity
4. Operating as both an adjustable load and a source itself

Employing PHEV for regulation leads to the following benefits:

1. Reduction in CO_2,
2. Reduction in losses of transmission and distribution,
3. ancillary service,
4. Saving of Fuel, and

It is more beneficial to use PHEV while charging during peak times since the market revenue for providing energy might be higher and in contrast, the energy price will considerably be lower than the off peak.

3.4 Interconnection

For the interconnection two of IEEE Std 1547™ Standards will be considered. [13]

IEEE Std 1547™-2003: Standard for Distributed Resources Interconnected with Electric Power Systems

IEEE Std 1547™ standard at the moment defines the standards for interconnection of electric power systems and distributed resources such as DG, fuel cells [13]. For the sake of this study two of them will be investigated. These standards analyze the differences between area power system EPS and Local area power system. Area EPS referred to the bulk power system whereas Local EPS referred to a building or buildings with one or more DR units. Point of common coupling (PCC) is connecting point of Local EPS and Area EPS. This standard provides testing and technical needs for connection of DR with total capacity of 10 MVA or less [13]. The PCC for interconnection of PHEV is the point that buildings are joined to the grid, and PHEV is regarded as DR. Figure 3.1 demonstrates interrelationship among Area EPS and DR units stated by the IEEE std 1547.

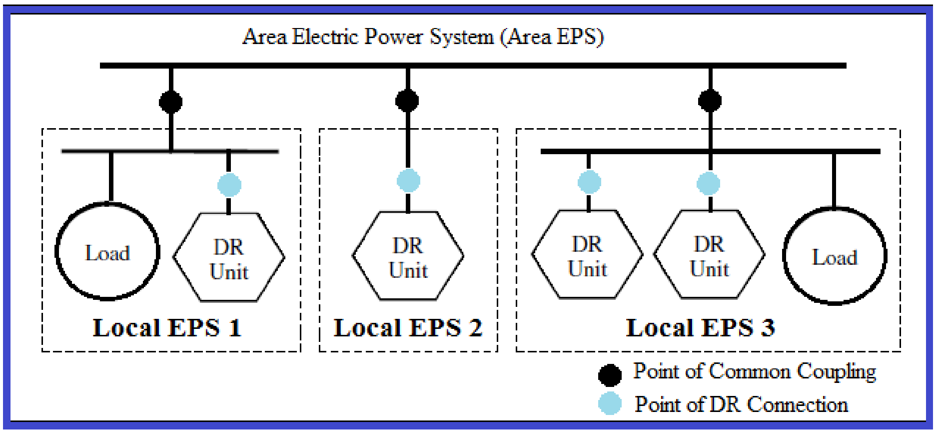

Figure 3.1: Diagram of Distributed Resources Interconnection [13] , [14]

DR unit reaction during unexpected operating situation in the Area EPS is a matter of special affection. DR must stop and supply the Area EPS within the clearing time[6].

[6] Time between presence of abnormal condition and distributed resources reaction to energize is referred to as clearing time.

The required maximum clearing time for installation of beyond 30 kW and more than 30 kW in case of system frequency disturbance is demonstrated in the table 3.3.

Table 3.3: DR Clearing Time in Response to Frequency deviation [13]

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

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

The required monitoring and data exchange instruction between DR and Area EPS' stakeholders are provided by this standard [14]. PHEV owner has an important role since he/she is considered as DR owner, maintainer, and operator. The data exchange path DR units, DR controllers, and concerned parties is shown in the figure 3.2.

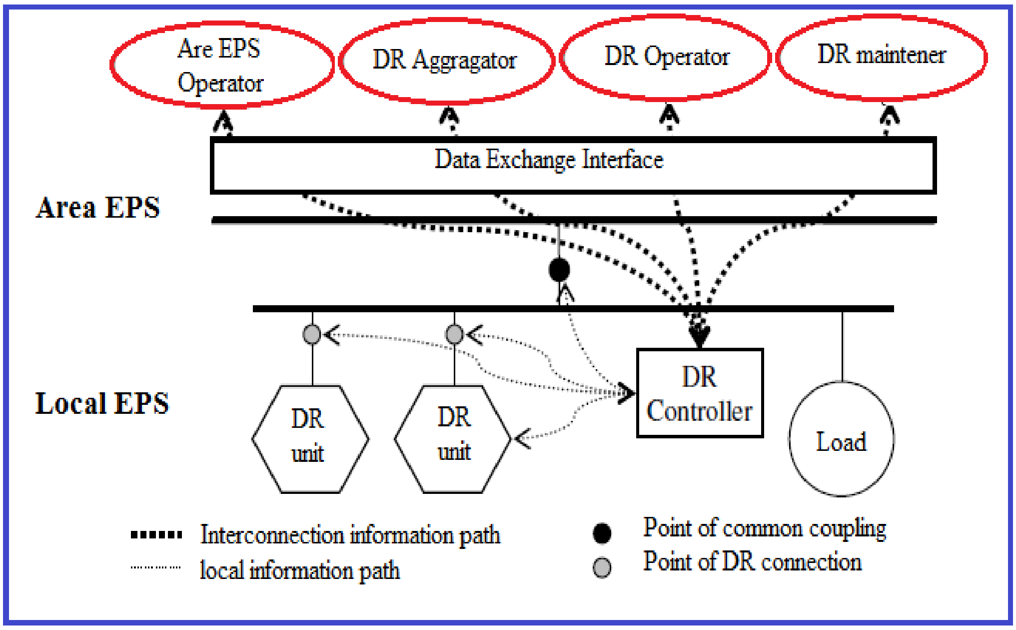

Figure 3.2: Path of data exchange between controllers, DR units, and Stakeholders

Chapter 4

SYSTEM DESIGN

4.1 Structure of the System

Behavior of a distinct level of the power system must be considered when studying the effect of PHEV charging in addition to distributed controllers. All of the power system elements have their own controlling and monitoring systems to operate conveniently together with the different elements of the system. Common components, stakeholders, control and monitoring systems are shown in the Table 4.1

Table 4.1: Different level of power grid Components, Controls, Stakeholders

Level	**Physical system**	**Monitoring and Controls**	**Stakeholders**
Bulk Transmission System	High Voltage Lines, Transformers, Central generation, Protection elements	SCADA/EMS, Load shedding, Switching, Protection and compensation equipment	Transmission owner, Maintainers, Operators Generation owners, Market Participants, Regulators
Distribution Systems	Transformers, Protection Elements, Primary and secondary Feeders, Distributed Resources	SCADA/EMS, Load shedding, Switching, Protection and compensation equipment	Distribution System Owners, Customers, regulators, Operators and Maintainers
Home or Business	Breakers and Fuses, Mains, Appliances, All other end uses	Utility revenue meter, Switching, Overcurrent protection	Building Owner and Maintainer, Utility, Regulators, Occupants

Thinking out of the behavior of the system from the transmission level to the point of consumption gives a complete system model which is not indeed considered in this study and instead, employing a full 3-phase power flow in whole system is examined. In spite of the fact that plug-in hybrid electric vehicles are connected at the distribution level, the impact of them must be regarded as the bulk system point of view. This is particularly because of the incorporation of the speed response of the central generation units with AGC signal.

4.2 Supplementary Components

The most important factor is the physical modeling of the action of the battery system. Moreover, to handle charging and supervise the behavior of the PHEVs as DR there is a need for a vehicle-to-grid (V2G) controller. Deviation from 60 Hz is the major variable for investigating whether load and generation are balanced or not. Besides a PHEV coordinator controller will be used to watch the operation of several PHEVs and monitor system situations, and make orders for energy supply to the local PHEVs. The extension of the Table 4.1 is the Table 4.2 that indicates where additional components fit into to the system.

The following sections discuss operation and necessity of these components in details as well as the important roles that they can play it the distributed level of the today power system.

Table 4.2: Extra components to improve power system model

System Level	New Components	Operations, Monitoring, and Controls	Stakeholders
Distribution	PHEV Coordinator	• Monitor system frequency. • Define supply recommendation for local PHEV • Communicate local participation (aggregate PHEV supply) to the system.	Transmission System Operators, DS, Operators and maintainers, equipment owner
Home or Business	PHEV Battery model	• Rated energy capacity. • Vehicle plug in time. • Remaining SOC. • Desired Charge/Discharge profile.	Vehicle Owner, utility.
	V2G Controller	• Control battery charge current. • Track battery state. • Forecast load curve. • Determine available storage power and duration • Summarize services provided, etc. for owner.	Vehicle Owner, utility.
	Electric Vehicle Supply Equipment	• Communication portal between PHEV and the rest of power system. • Allow user to opt utility control.	Vehicle Owner, EVSE owner.

The specification in monitoring and control strategies in table 4.2 is to carry out load smoothing and frequency control.

4.2.1 Plug-In Hybrid Electric Vehicle

As a first step in implementation, a 120 VAC outlet is dealt for the beginning point of modeling. The ETS is Comprised of V2G controller and the battery system.

4.2.1.1 Battery System Modeling

To begin, all batteries have the similar model and almost appear as mid-size sedans. PHEVs modeled for this study based on EPRI are expected fairly to be PHEV 40 with the consumption of 0.2kWh/mi in the all-electric range. Charging will be assumed to be at home with 120 VAC, 12 Amps correspond to the level 1 AC charging [11] with the power upper bound of 1.44 kW. The battery system total storage capacity will be 10 kWh with SOC of 80% along with the following characteristics:

- SOC; remained charge
- t_{full}; time for being fully charged
- p_{veh}; charge value

The probability function for the numbers of vehicles that arrive home during daily hours and the distances they have traveled was gathered by EPRI [15]. With these two data and an approximated average of 12,000 mi/year per vehicle, they found the expected number of vehicles as indicated in the Table 4.3. Depending on the sample group's expected number of vehicles, 14% of them drive 0 mile during a given day.

Table 4.3: Summary of Vehicle features [15]

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 during travel day	38 mi/vehicle
Total expected number of vehicles	33,597 vehicle
Vehicle driven ≤ 20 miles per day	50%
Vehicle driven ≤ 40 miles per day	73%
Vehicle driven ≤60 miles per day	85%

Further assumption for simplifications is that for a desired full charge duration vehicles remain plugged in as they receive home. In addition, constant charging will be employed. The expected time of having full charge can be derived using the number of miles traveled (*d*) and current time (t) as follow:

$$t_{full} = t + d * \frac{0.2\ kW\ h/m\ i}{p_{veh}} \tag{4.1}$$

Monitoring and controlling vehicle charging by V2G controllers, frequency measurements as well as supply recommendation by the PHEV coordinator are discussed in details in the following sections.

4.2.1.2 V2G Controller

The determination of the battery system's energy and power available for frequency regulation as well as supervising battery behavior are the applications of the V2G controller. The typical method of charging is to start charging at a mid-range, 1kW, as there is an allowance to raise or lower charging. Figure 4.1 shows the algorithm of the V2G controller based on SOC for defining the regulation signal sign and magnitude.

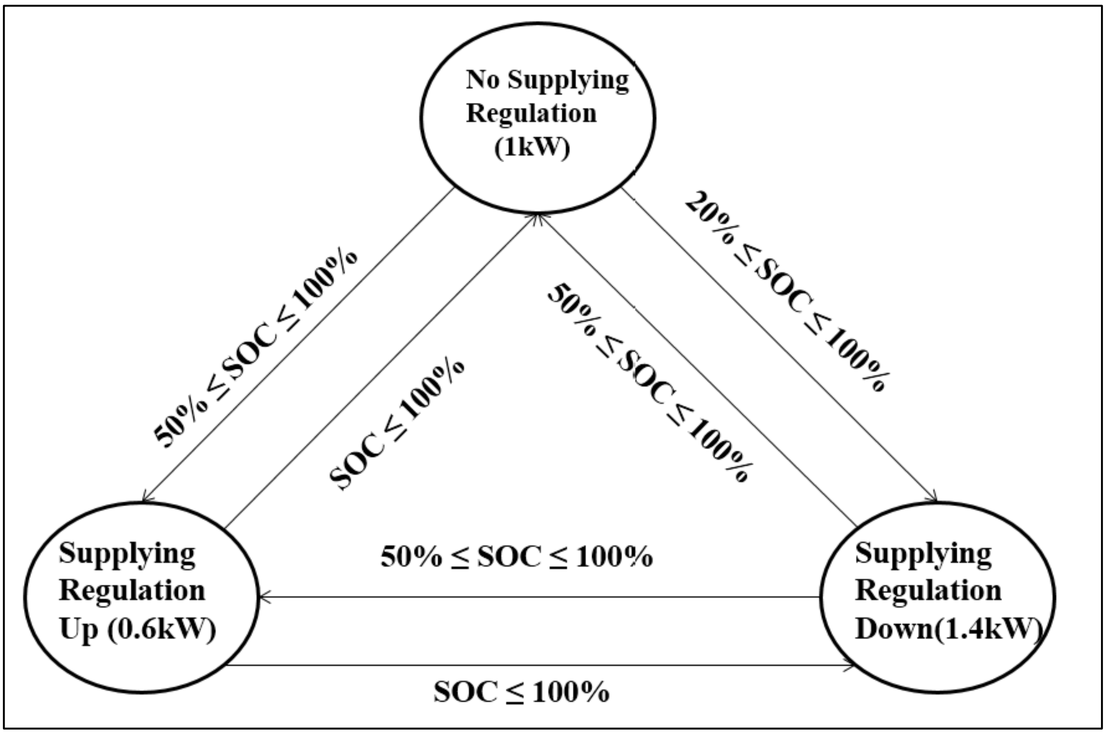

Figure 4.1**:** Regulation signal dependency on SOC [3]

4.2.2 PHEV Coordinator

V2G controllers depend completely on local information and are not exclusively capable of performing regulation of frequency since its quantities are not purely exact at the customer service location. To outweigh this drawback, PHEV coordinators will be applied and located at the high side of distribution substation transformers where actual frequency measurements could be found. Also, they can coordinate local PHEV attending in V2G. In fact PHEV coordinators will be a bridge between the area EPS and local EPS. Moreover, PHEV coordinators to do their duties are required to interact with other measurement devices along with the system operator, neighboring PHEV coordinators, and V2G controllers. Table 4.4 demonstrates the interaction of the coordinator with the other devices.

Table 4.4: Coordinator interaction with other devices

External System	**Interaction**
System Operator/central AGC control	Send updates on local regulation supply
	Receive signals to cease local regulation supply
Local V2G controllers	Send updates of supply recommendation
	notify to de-energize with abnormal system frequency
Neighboring PHEV coordinators	Exchange frequency and rate of change of frequency data

4.2.2.1 Supply Recommendation

System frequency deviation from 60 Hz, and its derivative are the major inputs. The magnitude of the recommendation will be defined by using information of the accumulated load and the available supply/demand for regulation. Factors for defining supply recommendations are demonstrated in the Table 4.5.

Table 4.5: Variables in determination of supply recommendation

Parameter	**Symbol**	**Units**	**Source**
Bus frequency deviation	Δf	Hz	Measured
ROCOF 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 AGC gain	k_{AGC}	-	Constant, tuned during simulation development
Current aggregate PHEV load	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	

General approach of supply recommendation determination steps are:

1) Estimation of ACE using Δf , $\Delta f'$, and β
2) Determination of AGC using ACE, k_{AGC}, and neglecting tie-line power flow
3) AGC recommendation updates with V2G controllers
4) Controller updates their regulation supply status with PHEV coordinators
5) Update system with coordinator signal to alter AGC

Chapter 5

SIMULATION DESIGN

5.1 Design of the Simulation

Possessing sufficient power in the response to the necessary power by the system is the most important concern in today power system. Many factors examine the ongoing condition of the system such as matched power, voltage performance, and in particular financial revenue. In order to simulate PHEVs application in frequency regulation, PHEV load, power grid characteristics, and supplementary controllers must be considered [16].

To understand the system behavior for the sake of this study a dynamic generator model in addition to computations of the area control error are necessary. Therefore, a transmission system simulator is used to simulate the operation of the system created at the University of Minnesota [17].

In the first place the simulation model examines the speed response of the whole generators in the system following changes in the load. The AGC dispatch signal is computed from the ACE is the most predominant term in this study since we would prefer to check out how it will be influenced when using battery storage to supply regulation. The IEEE 14-bus system, involving 5 generators and 11 busses with load attached to them will be employed as a testing structure, is shown in the Figure 5.1.

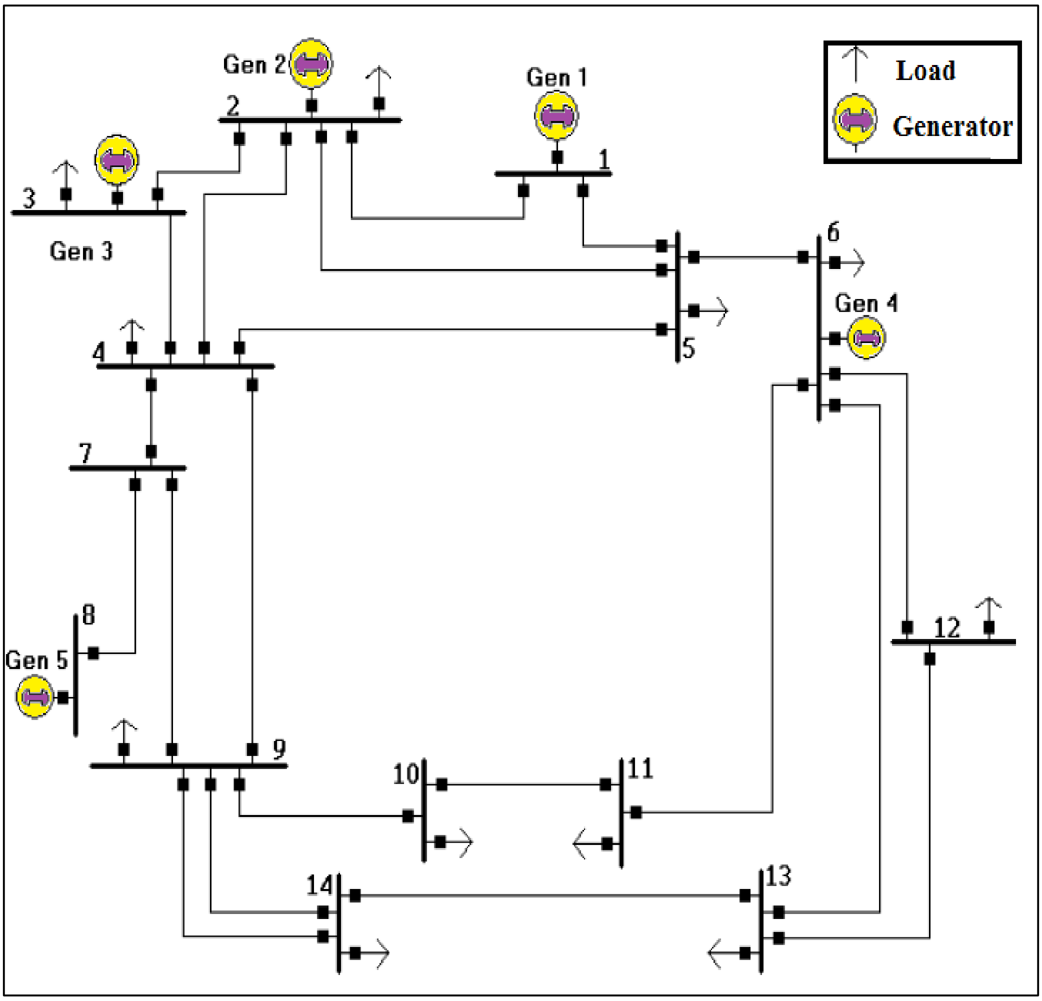

Figure 5.1: Online diagram of IEEE 14 bus system

To explore the behavior of the PHEVs when they are plugged in to the power system grid, an accumulated PHEV load attached to each load buss with their own PHEV coordinator is illustrated in the Figure 5.2.

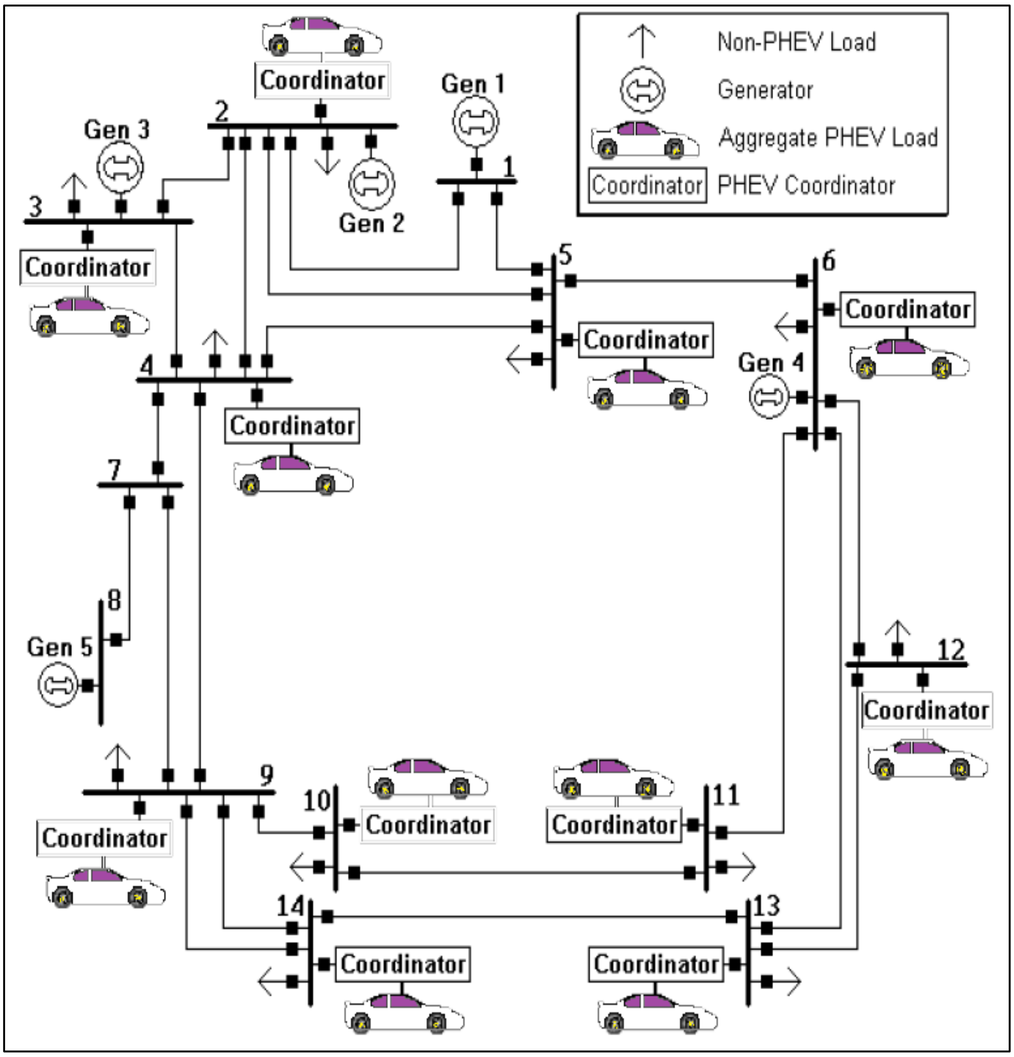

Figure 5.2:14 bus system with aggregate PHEV load [3]

As shown in the figure 5.2, PHEV coordinator is connected to the bus with a breaker which represents interruption of the V2G service for the safety and abnormal issues. The following table 5.1 shows the parameters for the whole system involving simulator and extra components.

Table 5.1: 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	295 MW	P_{init}
Initial PHEV load	39 MW	P_{PHEV}
Nominal system frequency	60 Hz	f_{syn} , ω_{syn}
Initial total load	298 Mw	$P_{total,init}$
Peak total load	382 MW	-
Frequency bias constant	375 per unit	B_f
Automatic generation control gain	0.08	k_{AGC}
System base power	100 MW	P_{base}
Base frequency	60 Hz	f_{base}

83,270 vehicles are considered to participate in the V2G while having charge range of 1kW when arriving home. Communications systems methods as well as its performance are not reviewed in this study. Standards for communication are an ongoing project and is being developed as smart grid topologies progresses. The upcoming sections talk about the operation of the simulator including power system simulator, PHEV load modeling, generators model, and additional models such as frequency and AGC dispatch.

5.2 Simulation of Power System

The power system simulator includes 5 generators operated as synchronous machines which are zipped as a MATLAB subsystem block, frequency calculation and AGC dispatch subsystem block, system load modeling, and MATLAB function block for power flow calculation and the network model [17]. The examination of the speed response of the thermal generating units is carried out. Unexpected behavior of the system load as well as simplifying advanced control technics for matching the generation and load are the backbone of this simulink implementation study.

Some of the important properties of the model can be accounted as follow:

1. The speed of the generators is dependent on the variation in the load.
2. Using average generators bus frequency deviation, the system ACE will be computed.
3. Viewing the machine speed swings as well as mechanical power in response to load changes, using scope at each generator.
4. Additional scopes to watch extra system dynamics as necessary
5. Control the Simulink behavior through a MATLAB File Editor

The connection between different components of the system model is shown in the figure 5.3.

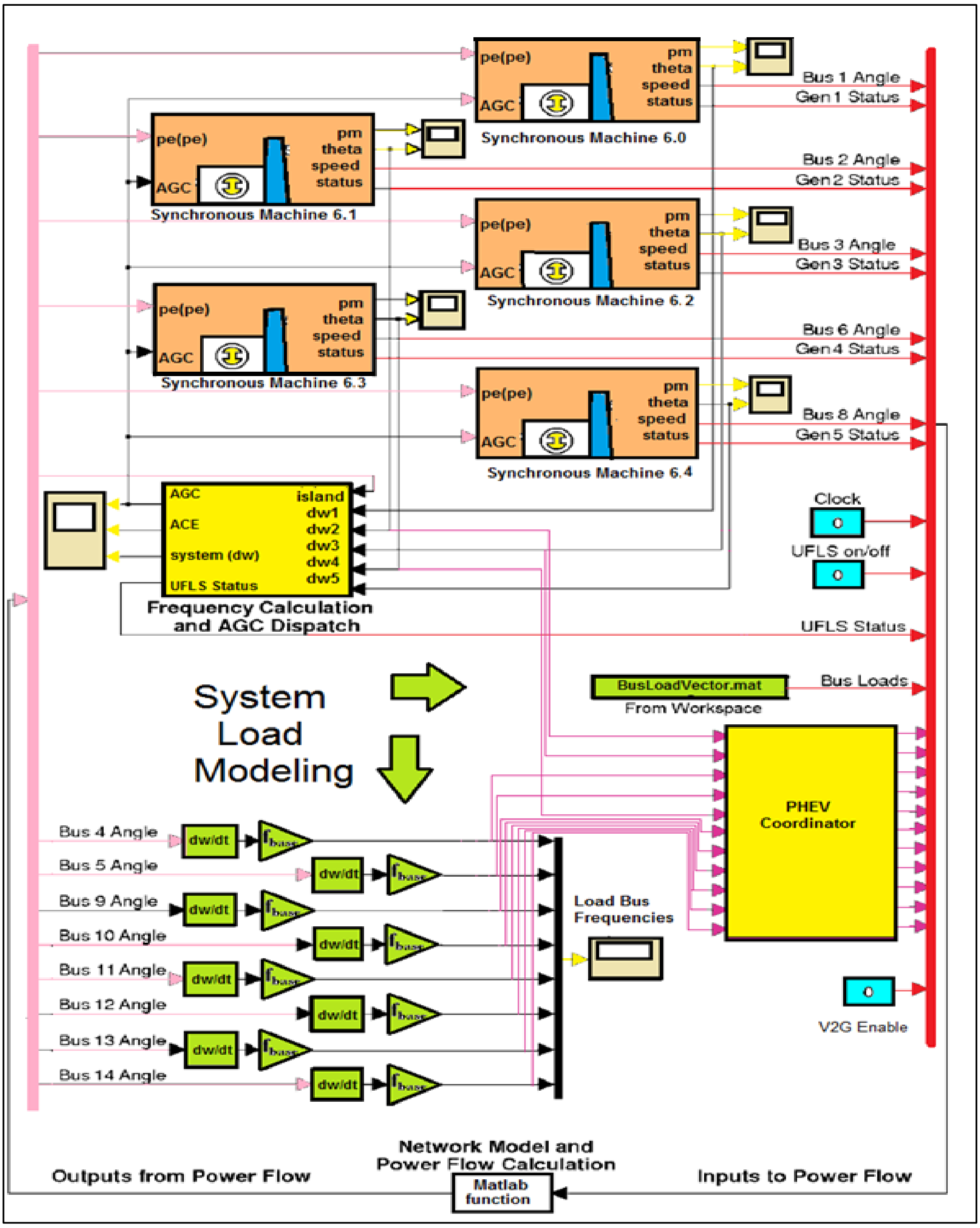

Figure 5.3: Simulink model of IEEE 14 bus system [3]

5.2.1 Synchronous Generator Model

Synchronous machines are comprised of a rotating mass, governor, non-reheat turbines. In addition, all machines in order to correct steady-state frequency error have an integrator loop clarifying automatic generation control application. The data correspond to the synchronous machines are illustrated in the Table 5.2.

Table 5.2: Synchronous machine inputs and outputs

User Input Machine Parameters	**Units**	**Source**	**Notation**
Governor speed drop	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}
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	-

u_{AGC} is an input performing integral feedback and depends on the speed deviations. The AGC participation factor (pf) is used for distributing u_{AGC} through all generators such that $\sum_i pf_i = 1$. Electrical demand Δp_e is the other input representing significant changes in the system. Total mechanical output is calculated as the summation of the initial power rates and the differences of real mechanical power from the steady-state operating point. The machine subsystem Simulink model is shown in the figure 5.4.

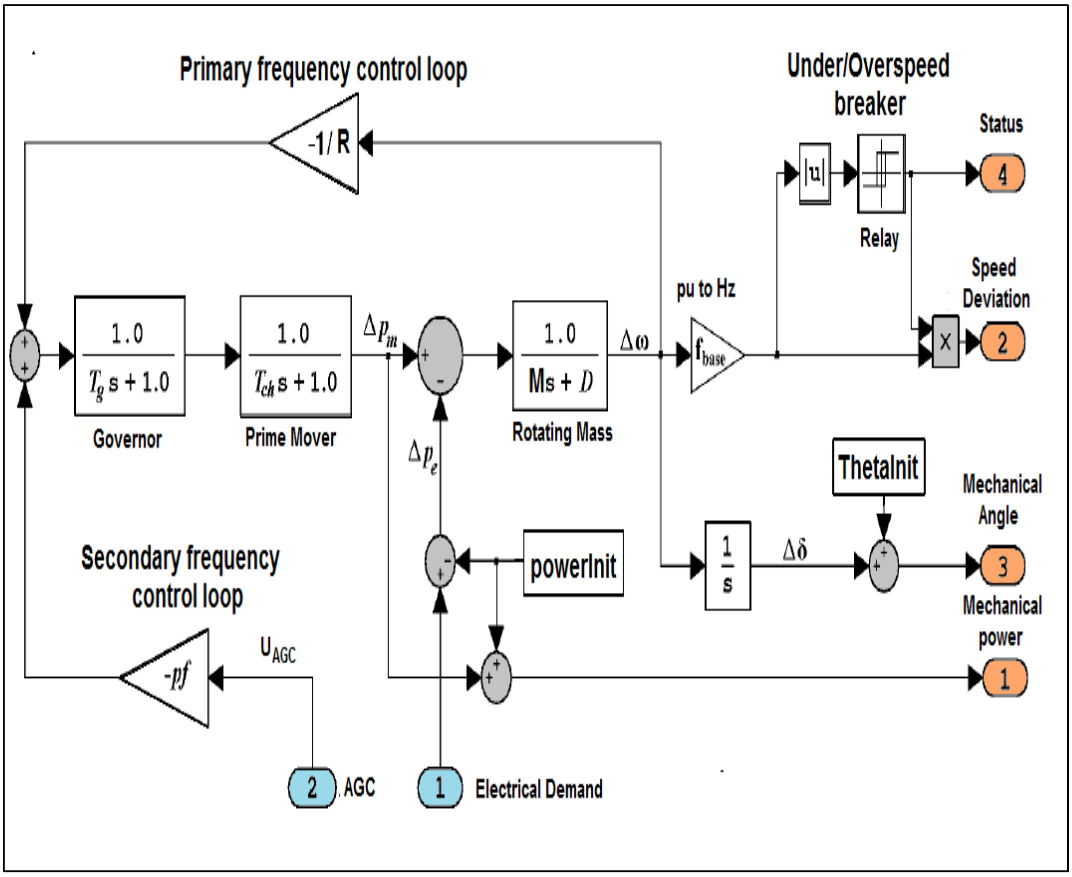

Figure 5.4: Simulink model of the synchronous generator [3]

The generator dynamic state space equation is [3]:

$$\begin{bmatrix} \Delta\dot{\omega} \\ \Delta\dot{p_m} \\ \Delta\ddot{p_m} \end{bmatrix} = \begin{bmatrix} \frac{D}{M} & \frac{1}{M} & 0 \\ 0 & 0 & 1 \\ \frac{-1}{T_{ch}T_gR} & \frac{-1}{T_{ch}T_g} & \frac{-(T_{ch}+T_g)}{T_{ch}T_gR} \end{bmatrix} . \begin{bmatrix} \Delta\omega \\ \Delta p_m \\ \Delta\dot{p_m} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{-pf}{T_{ch}T_g} \end{bmatrix} . u_{AGC} + \begin{bmatrix} \frac{-1}{M} \\ 0 \\ \frac{-pf}{T_{ch}T_g} \end{bmatrix} . \Delta p_e$$

$$y = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta\omega \\ \Delta p_m \\ \Delta\dot{p_m} \end{bmatrix} \qquad (5.1)$$

where:

T_{ch} : Prime mover time constant and is considered as 0.2 based on typical value.

T_g : Governor time constant and is considered as 0.1 based on typical value.

D : Damping factor representing frequency dependence of the system load.

Δp_e: Deviation of the electrical output power from the initial steady-state

Δp_m: Deviation of the mechanical output power from the initial steady-state

$\Delta\omega$: Speed deviation from 60 Hz

Parameters used for the five machines are illustrated in the Table 5.3.

Table 5.3: The IEEE 14 Bus System Generator Parameters

Generator	Bus	P_{init} (MW)	$1/R$ (Per unit)	M(Per unit)	AGC participation factor
1	Bus	54	75	25	0.2
2	Bus	40	75	25	0.2
3	Bus	60	75	25	0.2
4	Bus	70	75	25	0.2
5	Bus	74	75	25	0.2

To concentrate on the power shortcoming and frequency as well as saving computational time, the voltage magnitude is not considered. Moreover, exciters for checking voltage performance fix the voltage disturbance in an extremely short time in comparison with the governor acting in the order of seconds. Consequently, we can consider voltage stationary as 1 per unit. Hence, machine rotor angle can be conveniently equal voltage angle and used for power flow calculation.

5.2.1 System Load Model

Non-PHEV bus loads are data from July 9th, 2009 [18]. Total load for July 9th is depicted in Figure 5.5.

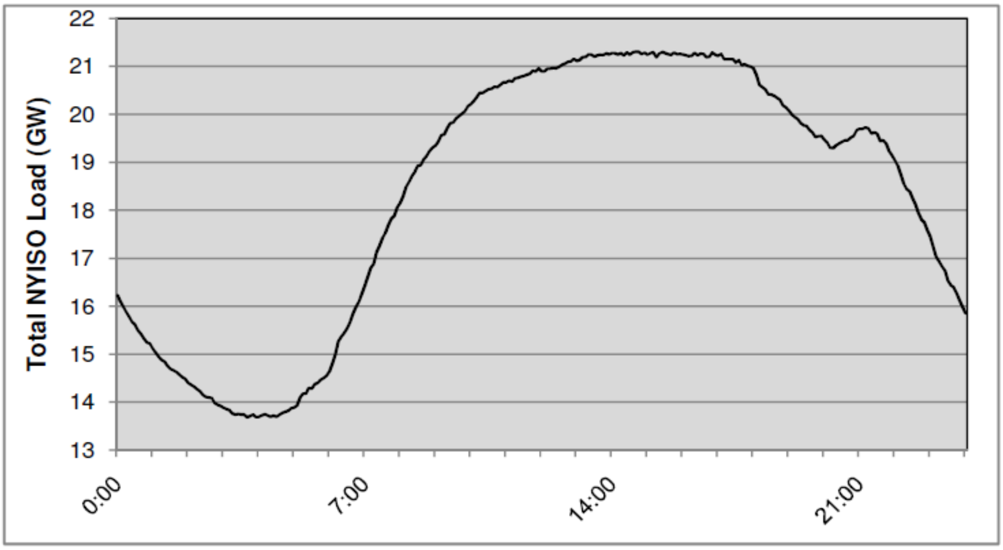

Figure 5.5: 5-Minute for Total System 5-Minute Real-Time Load Data from NYISO [18]

The load data and corresponding time are considered for from workspace block, which is a vector of eleven bus loads required for the power flow calculation. The process of integrating the load model for the aim of V2G is stated in the later sections. Bus non-PHEV load properties are illustrated in the Table 5.4.

Table 5.4: Load characteristic of non PHEV Bus

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**

5.2.2 Automatic Generation Control

Keeping system frequency and tie lines power flow at an adjusted rate is one of the main matters in the power system. In other word, the system frequency plays an important role in the power system since it is a guide to catch whether there is a load/generation balance or not. The Synchronous machines decelerate as the load increases and accelerate as the load decreases. Typically, as mentioned earlier there are two levels of frequency regulation as follow:

- Primary: related to the governor response.
- Secondary: related to the AGC implementation.

To begin, following a disturbance in the load the generators speed will alter and the generator governor arrest this deviation in a few seconds and bring the system frequency to a new steady-state which is different from nominal 60 Hz. It is at this point that generators, specified for AGC, come to the system and bring the frequency back to the nominal 60 Hz in an order of several minutes. They will receive a periodic signal in a base of MW whether to rise their output after load increase for providing regulation down and in contrast lower their output after load depletion for providing regulation up. Finally, governor action will be stopped for starting to respond to AGC and generators that are not attending in AGC are brought back to the initial rate. The system frequency data are illustrated in the Table 5.5.

Table 5.5: System Frequency Dispatch Model data

User input machine parameters	**Units**	**Source**	**Notation**
Frequency bias constant, bulk system	Per unit, MW/Hz	Subsystem	B_f
Automatic generation control gain	-	Subsystem	k_{AGC}
External inputs			
Speed deviation of the machines	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 area control error can be calculated as follow:

$$\text{ACE} = B_f \times \Delta\omega_{sys} \tag{5.2}$$

The total automatic generation control signal is computed as follow:

$$u_{AGC} = -k_{AGC} \int ACE \ dt \tag{5.3}$$

This signal is the output of the AGC system as well as input to the machine's block. It parses among the generators using the AGC participation factor of the machines where $\sum_i pf_i = 1$. Using the generator governor droop R_i, the system bias constant is derived as follow [3]:

$$B_f = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + \frac{1}{R_5}\right) \tag{5.4}$$

Which gives a value $B_f = 375$, if $\frac{1}{R_i} = 75.$ k_{AGC} is determined with each machine gain of $k_i = 10$. Setting the sum of secondary frequency control loop signals within the generator blocks equal to the system AGC control signal gives the value of k_{AGC}, here it is set to 0.08. The subsystem block with its interconnections is demonstrated in the figure 5.6

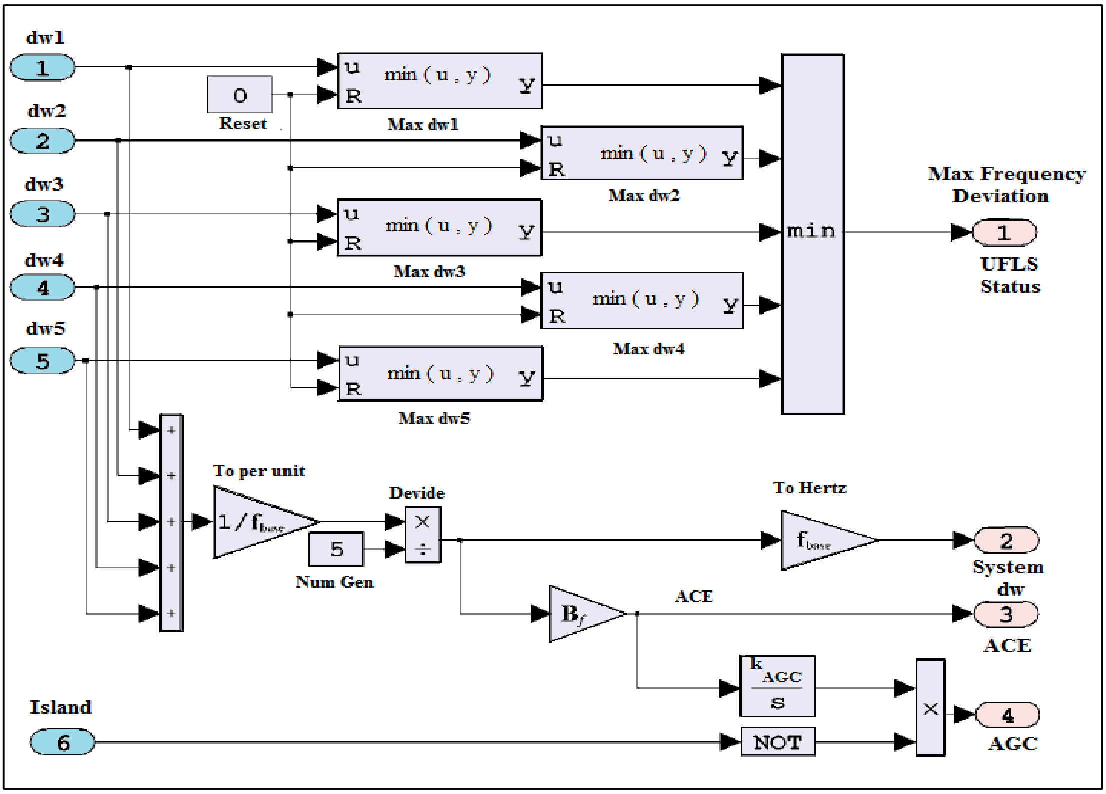

Figure 5.6: Frequency Calculation and AGC Dispatch Simulink Model [3]

5.2.3 Network model

The DC power flow (DCPF) calculation is done in the MATLAB function block within the Simulink model. The model of the network inputs/outputs are illustrated in Table 5.6.

Table 5.6: Network model inputs and outputs

User input machine parameters	**Units**	**Source**	**Notation**
Under frequency load shed enable	-	Constant block	-
V2G enable	-	Constant block	-
External inputs			
Clock signal	seconds	Simulink model	t
Maximum negative frequency deviation	per unit Hz	AGC Subsystem	-
Generator rotor angle	Radians	Machine subsystems	δ
Generator status signals	-	Machine subsystems	-
Bus loads	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	-

5.2.3.1 Power Flow Calculation

In order to derive the power flow (PF) on the transmission lines, the DC-PF is used. It is assumed that that the transmission lines resistances are insignificant and as a result the impedance is going to be the line reactance X only. So, the line admittance, denoted by BX, is used to calculate DC power flow as fallow:

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

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

The DC power flow equations matrix is as fallow:

$$\begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ p_n \end{bmatrix} = \begin{bmatrix} Bx_{11} & Bx_{12} & \cdots & Bx_{1n} \\ Bx_{21} & Bx_{22} & \cdots & Bx_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Bx_{n1} & Bx_{n2} & \cdots & Bx_{nn} \end{bmatrix} \cdot \begin{bmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_n \end{bmatrix} \tag{5.6}$$

where

p_i : is the generator buses power

θ_i : is the angles of generator rotor

At first, angles correspond to the load and undefined theta buses are derived. Secondly, the P_{net} at the buses involving the generator are derived. Finally, power output of a generator according to generator convention,P_{load} is negative and P_{net} is positive, is computed as follow:

$$P_{gen} = P_{load} + P_{net} \tag{5.7}$$

where

P_{net} : The difference of the generated and consumed power.

5.2.4 Model of PHEV and Extra Components

On the coming section, the development of power system simulator including PHEV and extra components will be discussed.

5.2.4.1 Accumulated PHEV Load

The data from the 2001 National Household Travel Survey is used to construct the PHEV load at the each load bus [6]. Residential load is randomly estimated thirty percent, and similarly thirty percent for both homes including PHEV and interested in participation for V2G. To construct a cumulative distributed function (CDF) for the plugged-in hour at home, the probability of a PHEV that arrives home in every hour is employed and a random numbers is considered for each vehicle. In a similar way, to construct CDF for the range of miles traveled before plugging in for charging, the probability of kilometers travelled before plugging in is used and a random number is considered. Hence, with the charge rate assumption of 1kW, the duration of charge while plugging in is derived in equation (5.8). Then, accumulated PHEV loads data at any load buses is calculated based on the duration of charge and time of plugging in as indicated in the Table 5.7.

$$t_{charge} = \frac{10\ kWH-(10\ kWH-d\times 0.2\ kWH/mi)}{1\ kW} \tag{5.8}$$

Table 5.7: PHEV load characteristics

Load	Bus	Estimated # of homes	Estimated PHEV in V2G	Peak PHEV Load	Aggregate PHEV Load
1	Bus2	7623	686	386 kW	132 kW
2	Bus3	34152	3074	1637 kW	588 kW
3	Bus4	18706	1683	901 kW	319 kW
4	Bus5	2499	225	122 kW	42 kW
5	Bus6	3406	307	167 kW	58 kW
6	Bus9	10540	949	503 kW	176 kW
7	Bus10	3062	276	162 kW	55 kW
8	Bus11	1229	111	60 kW	21 kW
9	Bus12	2048	184	103 kW	36 kW
10	Bus13	4438	399	201 kW	73 kW
11	Bus14	4808	433	239 kW	81 kW
Total		92,510	8,327	4,451 kW	1,582 kW

5.2.5 PHEV Controller

Employing the V2G signals from the 11 coordinators, the V2G controller action is implemented within the MATLAB function block. Total raise/lower values at each bus are computed form the multiplication of the consistent regulation signals that come from PHEV coordinators by the total number of the vehicles. The values of $P_{max} = 1.4\ kW$ and $P_{min} = 0.6\ kW$ is considered to stay with the maximum power rate of level 1.

5.2.6 PHEV Coordinator

In in the main Simulink file, the PHEV coordinator actions with the angles for the 11 buses that possess load connected as the inputs are modeled. Table 5.8 depicts the PHEV coordinators' related data.

Table 5.8: PHEV coordinator inputs and outputs

User input machine parameters	**Units**	**Source**	**Notation**
Vehicle speed drop constant	Per unit MW/Hz	Subsystem mask	R_{PHEV}
Vehicle integral gain	-	Subsystem mask	k_{PHEV}
External inputs			
Load bus frequency deviation	Per unit Hertz	Simulink model	$\Delta\omega$
Outputs			
AGC raise/lower signal	Per unit MW	V2G controllers	u_{reg}

The integral gain as well as the speed droop constant for a single vehicle can be inputted manually by the users. The u_{reg} is computed as follow

$$u_{reg} = \Delta\omega \left(\frac{1}{R_{PHEV}} + \frac{k_{PHEV}}{S}\right) \tag{5.9}$$

In the regulation signal, the proportional term represents the similar action of the governor for a single PHEV.

On the other hand, the R_{PHEV} initial value is computed from the power and frequency limits for each vehicle with $R_{PHEV} = \frac{\omega_{max} - \omega_{min}}{P_{min} - P_{min}}$.

Using minimum of -0.4 Hz and maximum of $+0.4$ gives $R_{PHEV} = \overline{0.0006}$. This value is then reduced and $R_{PHEV} = \overline{0.0005}$ is used in the Simulink. The value of k_{PHEV} is considered as 0.001.

Chapter 6

RESULTS

6.1 Simulation Results

The simulation compares three steps of frequency regulation following sudden load changes. We consider a constant system load when 14.9 MW of the load drops at t=140s at bus 14. We have typical AGC using central generation units, enabling V2G for a primary regulation contribution, and enabling V2G for both primary and secondary regulation. Finalized parameters used for simulation are stated in table 6.1

Table 6.1: Final simulator parameter

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 loads	296 MW	P_{total}
UFLS enable	1	-
V2G enable	0/1	-
System base power	100 MW	P_{base}
Base frequency	60 hertz	f_{base}
Synchronous machine subsystem		
Governor value 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 subsystem		
Frequency bias constant, bulk system	375 per unit	B_f
Automatic generation control, bulk system	0.08	k_{AGC}
PHEV and V2G controllers		
Number of vehicle charging	38620	-
Base charging power	1 kW	-
Charging power limits	± 0.4 kW	$P_{max,min}$
PHEV coordinator		
Vehicle speed drop constant	0.0005 per unit	R_{PHEV}
Vehicle integral gain	0.001	K_{PHEV}

6.2 Central Generation Method

In this method, generators are used only in AGC and PHEVs are charged at 1 kW. Centralized AGC units are used to get rid of the steady state frequency error at t=149 s. Note that the generator speeds are approximately settled after 94 seconds. Figures 6.1 and 6.2 show the resulted AGC and ACE signals.

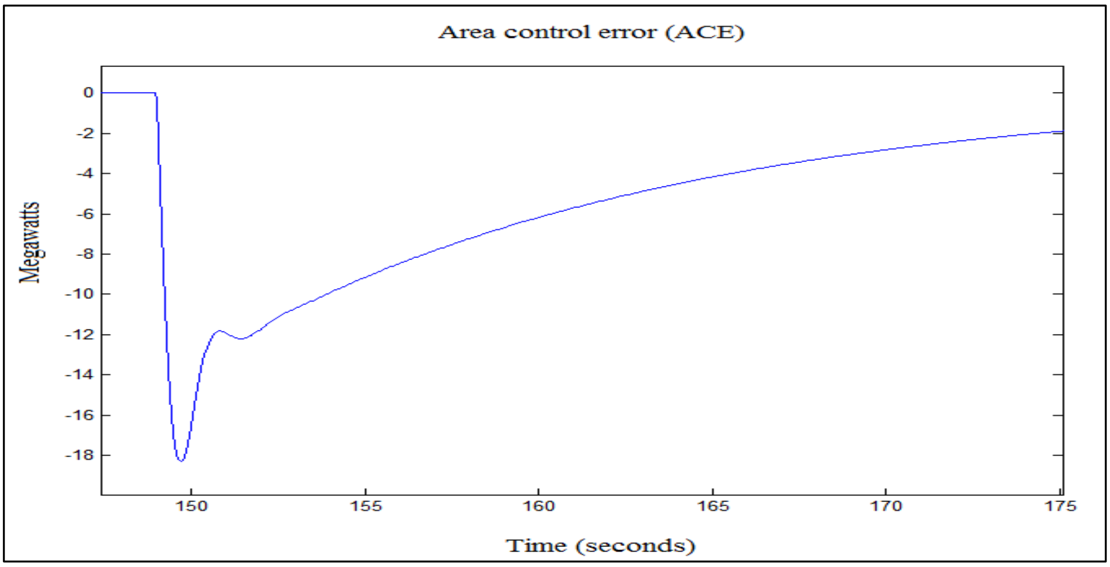

Figure 6.1: Area control error using centralized generation

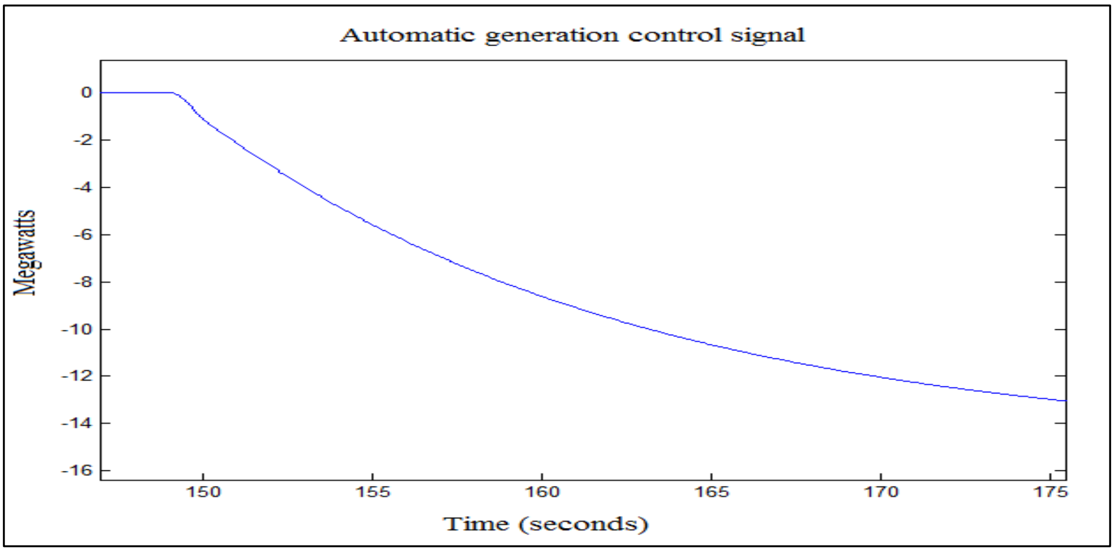

Figure 6.2: Automatic generation control signal using centralized generation

The impacts of the PHEVs on the primary frequency regulation are examined in this step. PHEV coordinators create a raise/lower regulating signal proper for a single vehicle. Then, it is multiplied by the amount of the vehicles integrating on automatic generation control and adjusted based on the $P_{max,min}$. At the end, PHEV load of each bus is subtracted from the final accumulated supply.

6.2.1 PHEV as a Contribution of Only Primary Frequency Regulation

In this case, the integral gain is considered as zero, $K_{PHEV} = 0$, such that each vehicle plays the role of the governor to provide regulation up following a drop in the load by increasing its own charging power amount. Note that the generator speeds are approximately settled after 148 seconds which is longer than using the first scheme. This is because the centralized action will pursue till PHEV supply is thoroughly consumed due to the lack of additional integral control. Figures 6.3 and 6.4 show the resulted AGC and ACE.

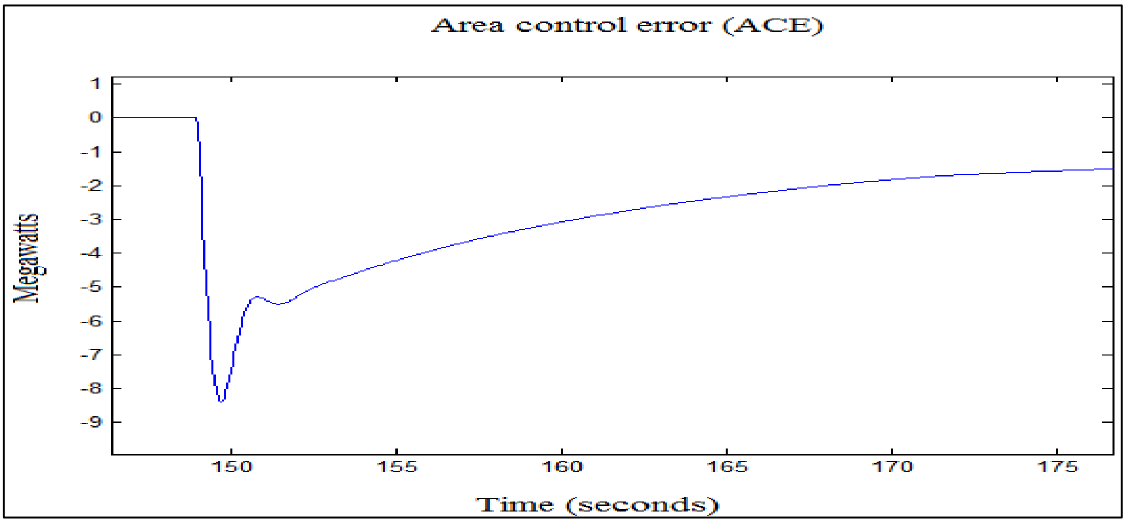

Figure 6.3: Area control error using PHEV for primary frequency regulation

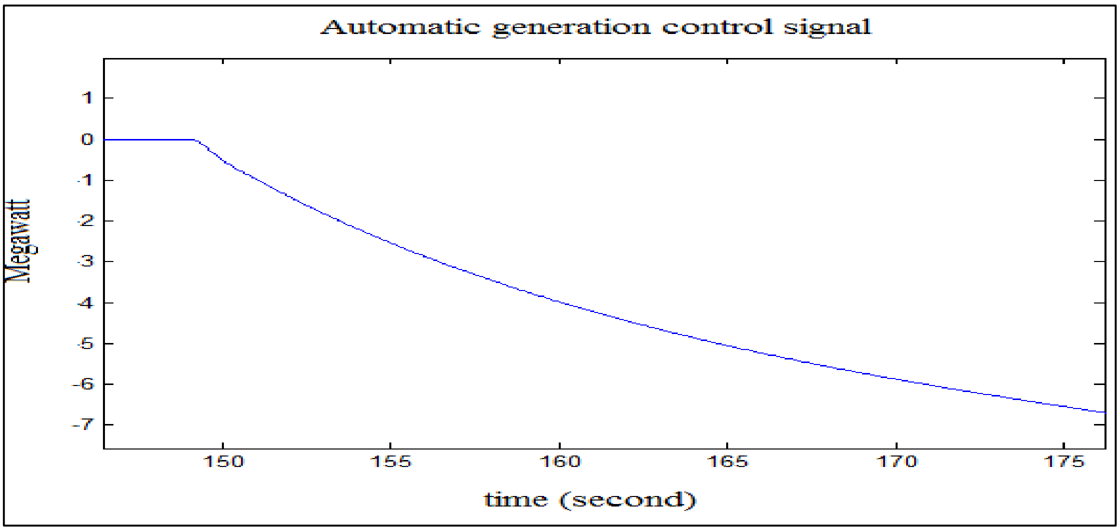

Figure 6.4: AGC using PHEV for primary frequency regulation

The comparison of both schemes is shown in the Figure 6.5.

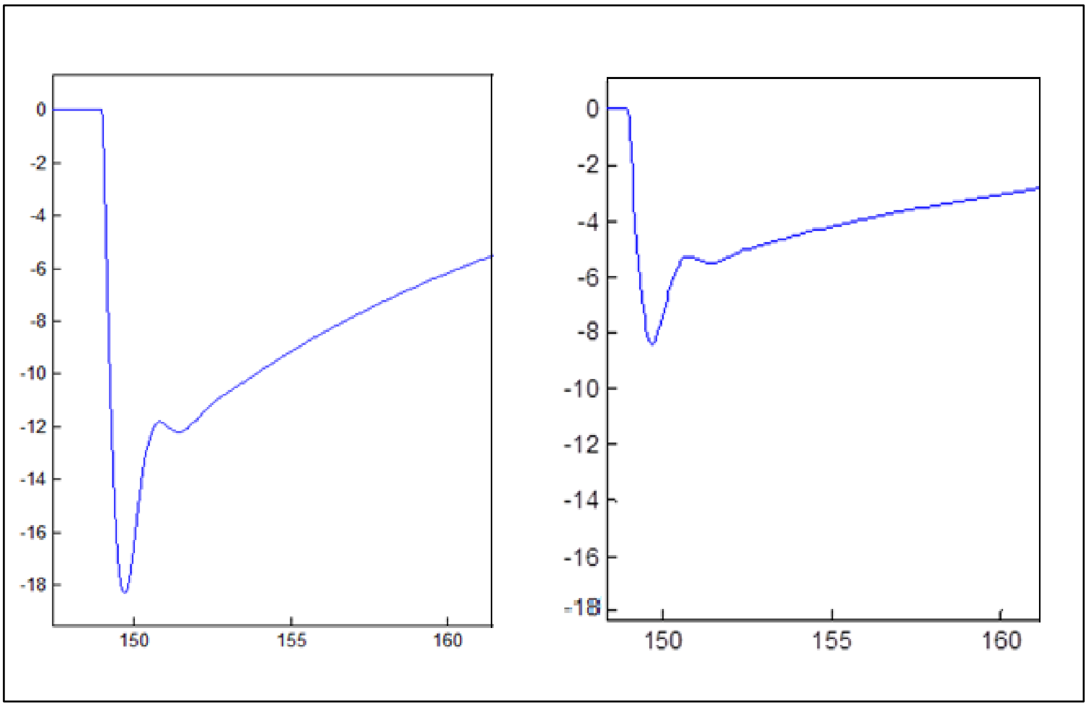

Figure 6.5: Comparison of area control error using generation units and PHEV for primary frequency regulation

6.2.2 PHEV as a Contribution of Both Primary and Secondary Frequency Regulation and Future Work

In this case, the integral gain is different from zero and will be considered as $K_{PHEV} = 0.001$. Hence, for a longer time the decrease in the load considering PHEV will be smaller than the second scheme which contribute to the recovery time. The generator speeds are approximately settled after 102 seconds which is a little longer than using the first scheme. Figures 6.6 and 6.7 illustrate the resulted AGC and ACE.

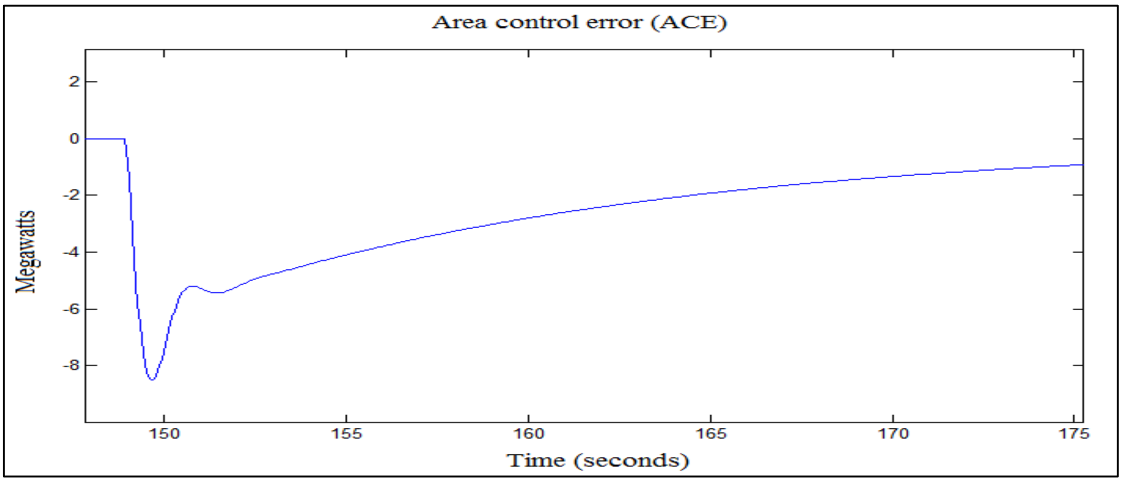

Figure 6.6: ACE using PHEV for both primary and secondary frequency regulation

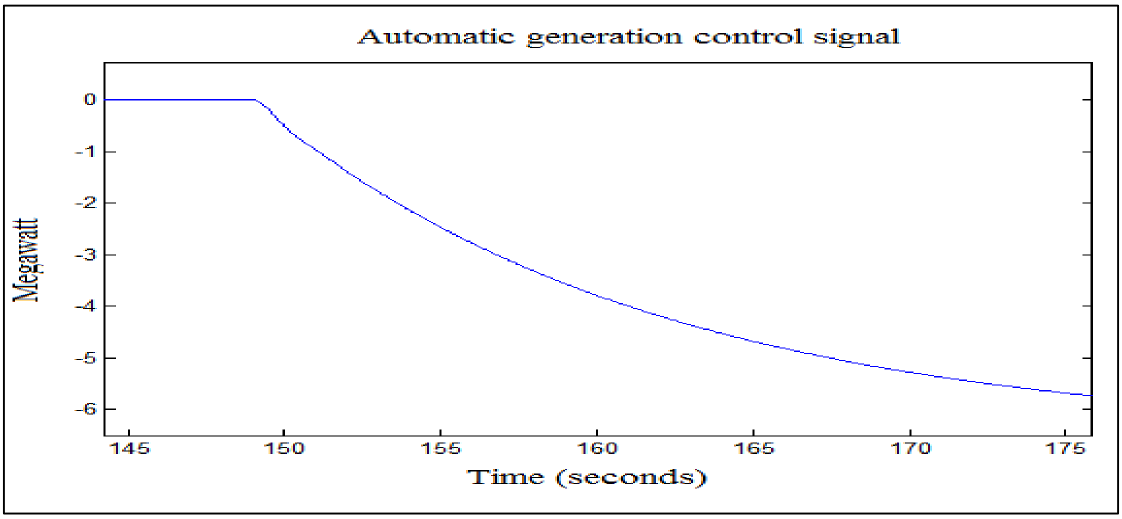

Figure 6.7: AGC using PHEV for both primary and secondary frequency regulation

These results indicate that PHEV are able to significantly impact on the frequency regulation by reducing the area control error range approximately 50%. As a result of the reduced ACE, the generation units are appose to a less ramping which means less damage on them. The comparison of the three schemes is illustrated in the figure 6.8

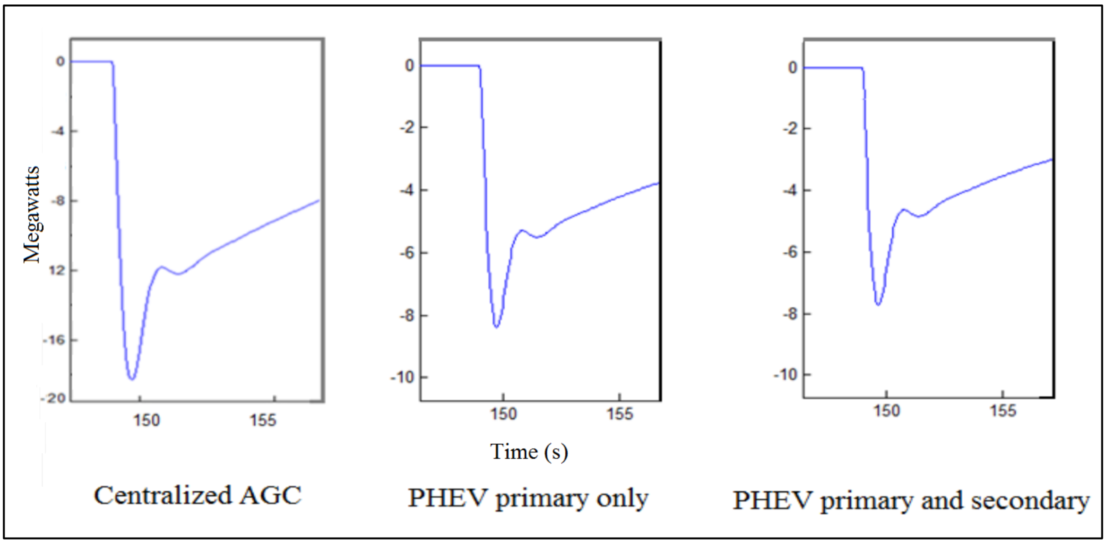

Figure 6.8: Comparison of the three centralized AGC, PHEV primary only, and PHEV secondary frequency regulations schemes.

Considering system frequency 50 Hz causes an increase in the settling time of the speed of the generators but the peak ACE slightly increase. The use of PHEVs for the primary frequency regulation with system frequency of 50 Hz is shown in the Figure 6.9.

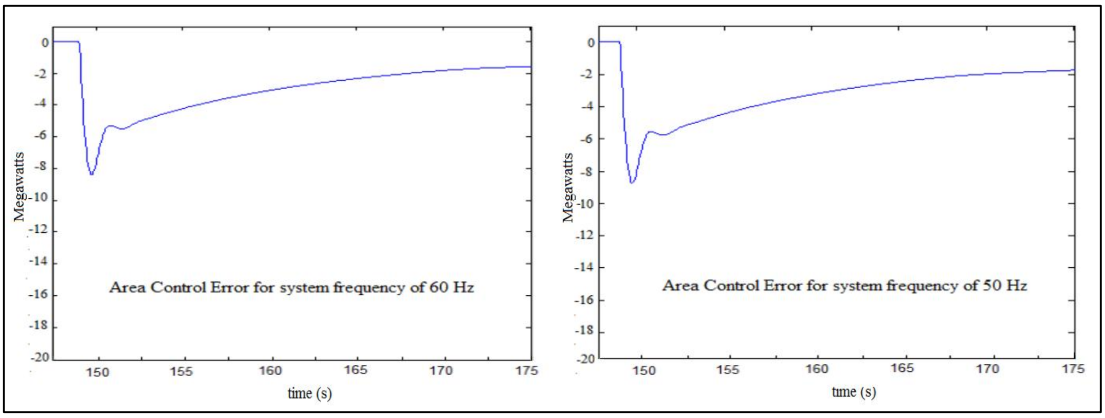

Figure 6.9: Comparison of the ACE signal for different system frequencies.

We examined the system response by decreasing the vehicle speed droop constant which causes a decrease in the recovery time of the speed of the generators. Figure 6.10 compares the ACE signal for different values of the speed droop constant of the vehicle.

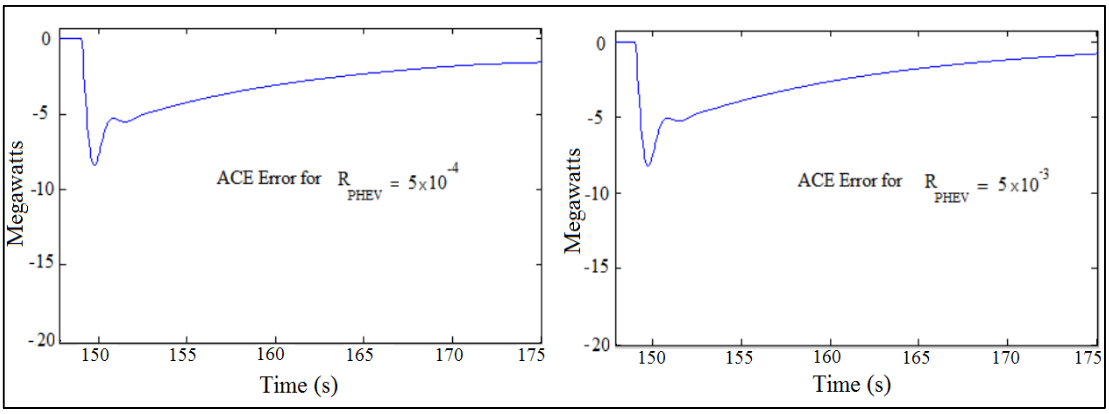

Figure 6.10: Comparison of the ACE signal for different vehicle speed droops

Furthermore, we explored the system response when increasing the vehicle integral gain which causes an increase in the peak ACE, and the settling time remains almost the same. Figure 6.11 compare the ACE error for different values of the vehicle integral gain.

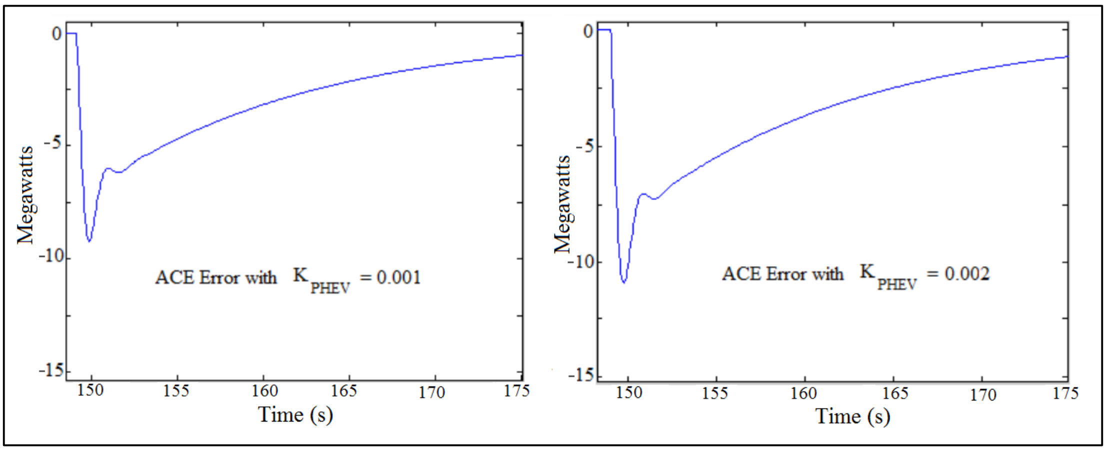

Figure 6.11: Comparison of the ACE signal for different integral gains.

Chapter 7

CONCLUSION

4.1 Conclusion and Future Work

This work is concerned with using the plug-In hybrid electric vehicles as a contribution to the both primary and secondary frequency regulation. The applicability of the PHEVS, first proposed by Mullen on September 2009 in [3]. We explored the speed response of the generators in the IEEE 14 bus system when a fault happens in the system load. In this thesis the main objective is to derive the proper amount and the duration of the power which helps to the system in a general way.

We study the effect of PHEVs on the frequency regulation by examining the area control error which gives us the automatic generation control signal. The AGC signal defines the magnitude and duration of the power that generators must provide in order to avoid under frequency load shedding when an imbalance occurs between load and generation. The main interest is to investigate the capability of integrating aggregated PHEVs storage into the frequency regulation.

In this study, we consider two additional controller for coordinating the aggregated vehicles and Monitoring the system frequency, and communicating with PHEVs which participate into the frequency regulation. We estimated the area control error and then based on this error we derived the AGC control signal. Subsequently, we updated the AGC control signal with V2G controller to derive the amount ant the duration of the supply that PHEVs can supply to the system.

We have observed that with the use of PHEVs as a contribution to the frequency regulation the system response considerably improved. Although the recovery time slightly increased, the peak area control error has significantly reduced which means that the central generation units are subjected to less ramping than without PHEV contributing to frequency regulation. Furthermore, we examined the system response for the system frequency of 50 Hz which lead to a further increase in the settling time of the speed of the generators. We increased the speed droop constant of the vehicles and noticed that as we increase further the recovery time is decreased. In addition we explored the system response when increasing the vehicle integral gain which caused the peak ACE increase as we increase more.

As a future work several extensions of the simulator may be considered such as interrupting while charging, integrating the battery system model into the system, or considering fuzzy logic controllers as a controller of the system or at least part of the system.

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APPENDIX

Appendix A: System data including :(pf , P_{init} , δ_{init}, $1/R$,and M , for the result of the chapter 6 are given in the table A.1).

Table A 1: Final generator data

Bus	P_{init} **(MW)**	δ_{init} **(Radian)**	$1/R$ **(Per unit)**	**M (Per unit)**	pf
1	54	0	75	25	0.2
2	40	-2.234e-02	75	25	0.2
3	60	-8.123e-02	75	25	0.2
6	70	+6.655e-04	75	25	0.2
8	74	+1.378e-01	75	25	0.2

Data for lines used in the Simulink are given in the table A 2.

Table A 2: Final data of the transmission line

Line	**From Bus**	**To Bus**	**Reactance (per unit)**	**Maximum power (per unit)**
1	1	2	0.05	1.48
2	1	5	0.22	1.60
3	2	3	0.19	0.82
4	2	4	0.17	0.74
5	2	5	0.17	0.74
6	3	4	0.17	0.41
7	4	5	0.04	0.99
8	4	7	0.24	0.82
9	4	9	0.22	0.82
10	5	6	0.25	0.82
11	6	11	0.19	0.82
12	6	12	0.25	0.99
13	6	13	0.13	0.99
14	7	8	0.17	1.32
15	7	9	0.11	0.49
16	9	10	0.06	0.49
17	9	14	0.27	0.99
18	9	14	0.27	0.99
19	10	11	0.19	0.66
20	12	13	0.19	0.99
21	13	14	0.23	0.57