CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

V-2-G

(Vehicle-to-Grid)

A graduate project submitted in partial fulfillment of the requirements
For the degree of Master of Science in Electrical Engineering

By

Nattee Cheeweewattanakoon

May 2014

The graduate project of Nattee Cheeweewattanakoon is approved:

Dr. Ali Amini | Date

Dr. Xiyi Hang | Date

Dr. Bruno Osorno, Chair | Date

California State University, Northridge

Acknowledgement

First and foremost, I would like to thank to my supervisor of this project, Professor Bruno Osorno for the valuable guidance and advice. He inspired me greatly work in this project. Moreover, I would like to appreciate to Professor Ali Amini and Professor Xiyi Hang whose knowledge, support, encouragement made this study successful. I also would like to thank the California State University Northridge for providing me with a good environment and facilities to complete this project. Without helps of the particular that mentioned above, I would face many difficulties while doing this.

Table of Contents

List of Tables

List of Figures

ABSTRACT

V-2-G
(Electric Vehicle-to-Grid)

By

Nattee Cheeweewattanakoon

Master of Science in Electrical & Computer Engineering

Electric vehicle (EV) is one of the most important keys which could solve energy crisis (gasoline) and environmental problem (green house gas) in the future. The advantage of EV is not only to use green energy (electricity) and provide zero emission, but also be able to help expansion of wind power. The U.S. nation focuses on renewable energy, especially the wind generation and it will be highly increased in the near future. The penetration of wind generations which unpredicted the wind strength affects on power distribution systems. The fluctuation of energy output from the generations degrades the quality of systems. Integration of EVs can mitigate those problems. However, EVs could have disruptive impact on the power distribution system because odd harmonics that are generated from EV charging devices. Then some managements and controlling such as economic operation and harmonic treatment are going to be stated to eliminate or mitigate those problems.

CHAPTER 1

Introduction

The impacts of energy crisis and environmental problems lead people to find several solutions that can mitigate or solve all of the problems. Electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) are one of the keys that can help people to solve those problems in the near future. As we know that general vehicles consume gasoline and emit carbon dioxide to the air. However, EVs consume electricity and PHEVs consume both electricity and gasoline which have zero or less carbon dioxide emission when compared with general vehicles.

Recently, renewable energy such as, solar energy, tidal power, geothermal energy, wind power, hydropower and etc play an important role in generating electricity on the grids. The projections of the amount of EVs, and electric generation (renewable energy) in the U.S. are made for illustration the direction of the design power distribution system in the future. In 2050, around half of the U.S. vehicle which more than 100 million cars will become electric cars.[19] This massive amount of EVs will increase the load in the system around 2900 GWh which have a lot of effect in the power systems. [19] Moreover, the expansions of wind generation and solar generation will be highly increased in the near future. In 2040, renewable generation capacity will account for nearly 20% of total generating capacity which the wind generation is the biggest portion of renewable generations. [21] This resource has low reliability because it depends on the weather conditions which are unstable. To solve this problem, we use EVs to mitigate the fluctuation of wind energy. If vehicle to grid (V2G) is deployed, EVs and PHEVs could enhance the reliability and power quality because the batteries that are used in EVs and PHEVs could be charged and inject the energy as needed into the distributed power system network [1]. In addition, EVs are able to be considered as an intelligent load that consumes when is required. On the other hand, some factors such as battery technologies, charging profile, market mechanism, policies and operating limits limit the ability of spreading out levels of EVs and PHEVs which is different from the ability of spreading out of distribution power systems [1][2]. Even some studies show that charging EVs and PHEVs at the grid during off-peak hours have less effect to the system [1][2][3]. However, standard EV charging devices are needed because of the harmonic issue. The harmonic from EV charging devices affect on the power quality of the system. To eliminate this issue, the harmonic treatment method is needed.[31] We still need a particular analysis to understand each network when is connected to EVs and PHEVs as much as possible for increasing efficiency and safety because each network has different characteristics [1].

Vehicle to Microgrid (V2M) is a case study that is used as an early stage to figure out the impact of EVs on the distribution networks. We need to study and analyze about how the massive EVs impact on grids, necessary control, possible service and charging [1]. These issues will be evaluated and used to demonstrate plants in the future.

CHAPTER 2

Electric Vehicles (EVs)

Electric vehicles (EVs) are a technology that was introduced in the mid-19th century. The ease of operation and a level of comfort are provided by using motor propulsion that cannot find in the combusion cars[4]. Recently, EVs are introduced to solve pollution problems and energy crisis. Instead of using only gasoline, EVs use electricity or combination between electricity and gasoline which have zero or less cabon dioxide emission. For this reason, EV is a key to solve those problems in the near future.

2.1 Differences between Electric and Traditional Vehicles

- **Electric motor**

There are two types of motors that are used in Electric vehicles (EVs) which are direct current motors (DC motor) and alternating current motors (AC motor)

- **DC motor**

“A DC motor is a mechanically commutated electric motor powered from direct current (DC). The stator is stationary in space by definition and therefore the current in the rotor is switched by the commutator to also be stationary in space. This is how the relative angle between the stator and rotor magnetic flux is maintained near 90 degrees, which generates the maximum torque. There are several kinds of DC motor.” [29]

Series-wound motors : “This type of motor speed varies automatically with the load, increasing as the load decreases. The series motor provides the starting torque required for moving large loads such as crane hoists. Traction motors used to drive trains are series motors that provide the required torque and horsepower to get massive amounts of weight moving.” [27]

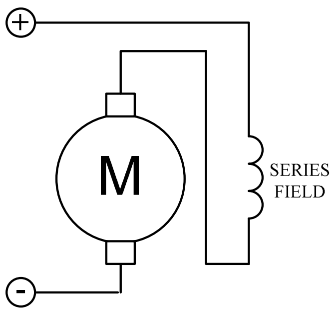


Figure 1. Series-wound motors design [26]

Shunt-wound motors : “This type of motor runs practically constant speed, regardless of the load. It is the type generally used in commercial practice and is usually recommended where starting conditions are not usually severs. It commonly used in machine shop lathes, and industry process lines where speed and tension control are critical.” [27]

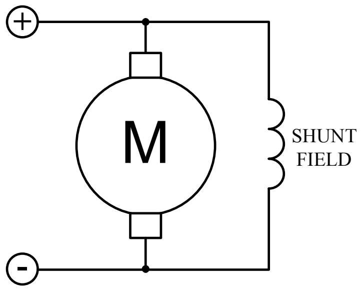


Figure 2. Shunt-wound motors design [26]

Compound-wound motors : "This type of motor is a combination of series and shunt wound types. This type is use for starting a heavy load with constant speed. The series field of this motor can response to the load change because we can controll its torque and speed by increasing the current to the field coil. If we disconnect the series field, it will work as shunt motor. Most of shelf motor is compound motors. If it needs more torque and speed, the series field will be connected into the motor. [27] "Compound motors can be connected two ways, cumulatively and differentially. When connected cumulatively, the series field is connected to aid the shunt field, providing faster response than a straight shunt motor. When connected differentially, the series field opposes the shunt field. Differentially connected compound motors are sometimes referred to as "suicide motors," because of their penchant for self-destruction." [27]

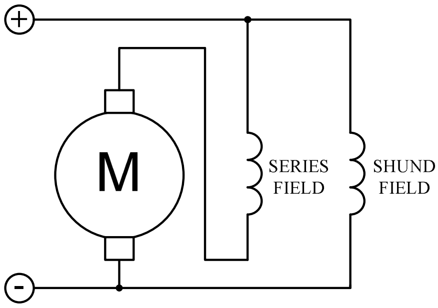


Figure 3. Compound-wound motors design [26]

Permanent magnet motors : "A permanent magnet motor (PM motor) does not have a field winding on the stator frame, instead relying on PMs to provide the magnetic field against which the rotor field interacts to produce torque. Compensating windings in series with the armature may be used on large motors to improve commutation under load. Because this field is fixed, it cannot be adjusted for speed control. PM fields (stators) are convenient in miniature motors to eliminate the power consumption of the field winding." [27]

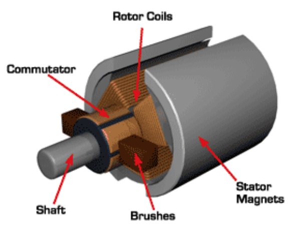


Figure 4. Permanent Magnet DC motor [26]

Brushless DC motors : **“**This type of motor does not have any carbon brushes. The stationary part consists of electromagnets which parallel to the armature and the rotating part consists of permanent magnets. This type of motor is one of synchronous motor which can avoid “slip” because frequency of magnetic field is equal to frequency of stator. BLDC motors are higher efficiency than DC motors with brush.” [28]

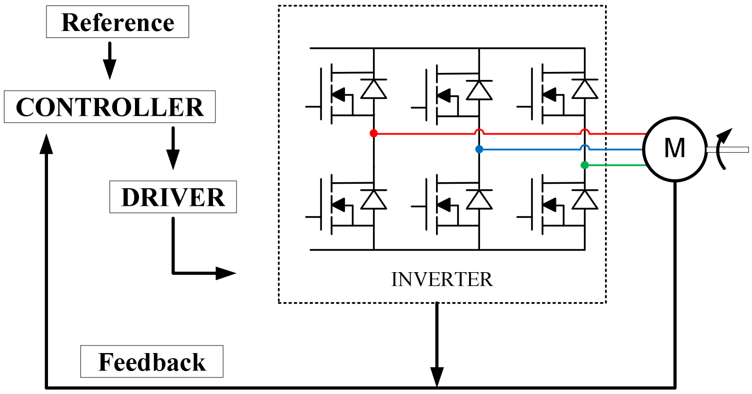


Figure 5. Block diagram for a brushless DC mortor [28]

- **AC motor**

This type of motor consists of stationary stator and rotating rotor. The rotating magnetic field is produced by the flowing of AC current in the coil of stator. The rotor produces a torque by the rotating field which the rotor is attached to the shaft. [26]

Induction motor

“Induction motors use shorted wire loops on a rotating armature and obtain their torque from currents induced in these loops by the changing magnetic field produced in the stator (stationary) coils. At the moment illustrated, the current in the stator coil is in the direction shown and increasing. The induced voltage in the coil shown drives current and results in a clockwise torque. Note that this simplified motor will turn once it is started in motion, but has no starting torque. Various techniques are used to produce some asymmetry in the fields to give the motor a starting torque.” [30]

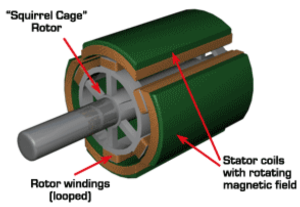


Figure 6. AC induction motor [26]

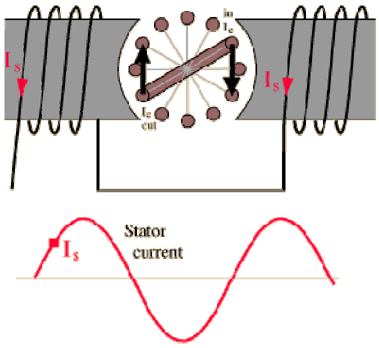


Figure 7. Induction motor action [30]

Rotor magnetic field production

Squirrel cage rotor

“When stator’s moving magnetic field cuts across the rotor’s conductor bars, it induces voltage in them. This voltage produces current, which circulate through the bars and around the rotor end ring. This current in turn produces magnetic field around each rotor bar the continuous changing stator magnetic field results in a continuously changing rotor field. The rotor becomes an electromagnet with continuously alternating poles, which interact with stator’s poles.” [26]

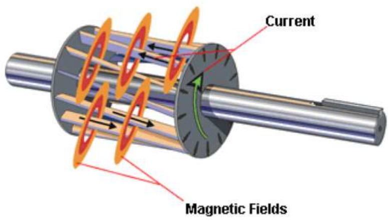


Figure 8. Squirrel cage rotor diagram [28]

Slip

“There must be difference in speed between the rotor and the rotating magnetic field in a squirrel cage motor. If the rotor and the field turned at the same speed no lines of flux would be cut, and no voltage would be induced in the rotor. The difference in speed is called slip. Slip is load dependent and is necessary to produce motor torque. An increase in load will cause the rotor to slow down, that is, increase the slip. A decrease in load will decrease slip. Slip can be expressed as:” [26]

$$\%\text{Slip} = \frac{N_S - N_R}{N_S} \times 100$$

Where N_S is the synchronous speed

N_R is the rotor speed at full load.

Synchronous Motor

"Synchronous motors are not induction motors, though they may use induction for starting. Small horsepower synchronous motors often have permanent magnet rotors. These motors neither require DC power to operate, nor use induction for starting. There is another type of synchronous motor that does require a DC power supply. It uses induction starting, and has rotor bars similar to a squirrel cage in addition to coil windings. On start, AC is applied to the stator, initiating the rotating field. The rotor starts in a manner similar to a squirrel cage rotor. After maximum speed is reached, DC is applied to rotor coils. This produces a strong and constant field that locks in step with the stator field, so the motor runs a synchronous speed. In other words, there is no slip with this type of motor." [26]

Two types of motors that are used in electric vehicle. One of them is DC Brushless motor and another type is Induction motor [5] . DC These motors have similar stators and use 3-phase modulating inverters [5]. The differences between them are rotors and the inverter's controls. The DC brushless has higher peak point efficiency and the cooling system of the rotor is easy to manage because the DC brushless motor generates lower rotor heat than the Induction motor [5]. Moreover, with the digital controllers, the control code of DC brushless drives require absolute position sensor but the control code of the Induction drives require only speed sensor [5].

- **Motor calculation** [26]

Motor efficiency

Electrical motor efficiency (η_m) is the ratio between the shaft output power and electrical input power. If power output is measured in watt (W) efficiency can be calculated as:

$$\eta_m = \frac{P_{out}}{P_{in}}$$

Where η_m is the motor efficiency

P_{out} is the shaft power out (Watt, W)

P_{in} is the electric power into the motor (Watt, W)

Power in the rotational motion (P_{out})

Power in rotational motion (P_{out}) can be written as

$$P_{out} = \tau \bullet \omega$$

Where τ is the torque (moment)

ω is the rotational speed or angular velocity

Electrical power (P_{in})

Electric power (P_{in}) can be written as

$$P_{in} = V \times I$$

Where P_{in} is the power input (W) (DC)

V is the voltage (V)

I is the current (A)

If there is AC, look also at the power factor *PF* = cosφ, where φ = power factor angle (phase angle) between voltage and current.

DC motors speed control

Speed of the DC motor is directly proportional to armature supply

$$n \approx \frac{60E_a}{Z\Phi}$$

Where n is the speed of rotor (r/min)

E_a is the armature voltage (V)

Z is the total number of armature conductors

Φ is the magnetic flux per pole

AC motors speed control

$$n = n_0(1 - s) = \frac{f(1 - s)}{p}$$

$$n_0 = \frac{120f}{p}$$

Where n_0 is the synchronous speed (r/min)

s is the slip

f is the AC current frequency, Hz

p is the number of pairs of poles

- **Internal Combustion Engine (ICE)**

  Most of PHEVs and HEVs use an engine and a motor as the primary source and the secondary source of power respectively. For this reason, the ICE of EVs is smaller than the ICE of gasoline vehicle [6]. ICE is able to recharge the batter or to power the PHEVs and HEVs while their batteries run out [6].

- **The motor's controller**

The energy from battery is drawn by the controller and the controller and sends to the motor. A pair of potentiometers (variable resistors) is connected to the accelerator pedal. These potentiometers determine the amount of power that the controller should deliver. When the car is stopped, the controller will deliver the zero power. When the driver floors the accelerator pedal, the controller will deliver full power or any power level in between. There are two types of controller. One is the DC controller and another one AC controller. [25]

- **DC Controller**

We can control the DC motor of EV by push and pull the accelerator pedal. This accelerator pedal is connected to the potentiometer. The signal from potentiometer is sent to the DC controller after we push or pull the pedal. The controller delivers the voltage from the battery to the motor (in this case is 96 volts). The controller will react to the pedal. It will "chop" the voltage thousand of time per second to create the voltage which depend on the position of the pedal. If we do not push pedal the controller will deliver 0 volts but if we fully push the pedal the controller will deliver 96 volts. If we push and pull between the minimum and the maximum point the controller will deliver the average voltage somewhere between 0 and 96 volts. [25]

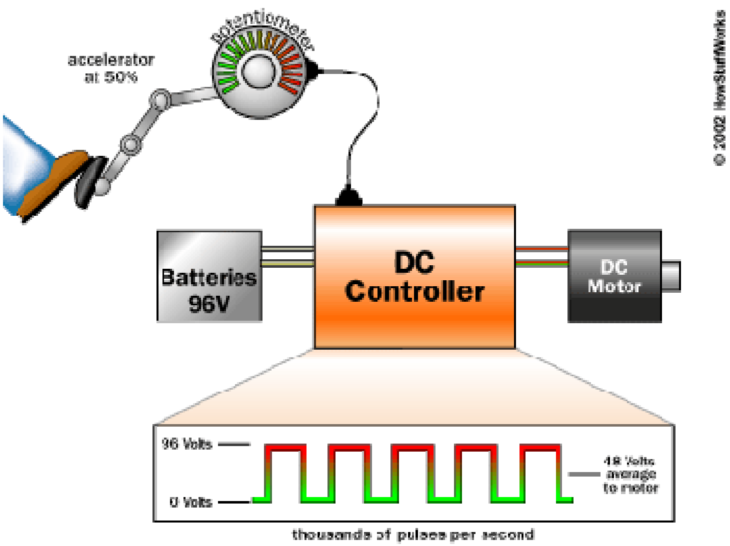


Figure 9. The diagram of the DC controller with 96V battery [25]

- **AC Controller**

"The controlling AC motor in EV is different from the controlling DC motor. In this case, one second, the polarity will be flipped 60 times. When we push the accelerator pedal which connected to the controller, the controller will change 300 volts to be AC 3 phase, 240 volts by switching it. To do this, we two set of transistors for one phase which one of them pulse the voltage and another one reveres the polarity. The controller additionally provides a charging system for batteries, and a DC-to-DC converter to recharge the 12-volt accessory battery." [25]

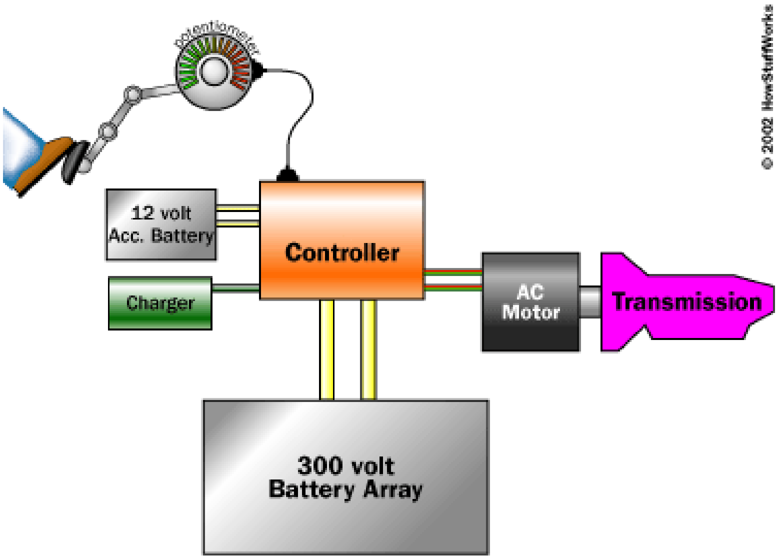


Figure 10. The diagram of the AC controller with 300V battery array [25]

- **Energy storage (Battery)**

  Energy storage or we know as a battery is the most important part of EVs because the battery used in EVs has a lot of limitations such as lifetime, weight and cost. This topic is going to discuss in the next chapter.

2.2 Type of electric vehicles.

We can consider any kind of vehicle which is able to equip with electric powertrain [4] to be an electric vehicle. There are different ways to classify electric vehicle. We can classify them as Plug-in Electric Vehicle (PEVs), Plug-in Hybrids Electric Vehicles (PHEVs) and Hybrid Electric Vehicle (HEVs).

A) Plug-in Electric Vehicles (PEVs)

Plug-in Electric Vehicles (PEVs), also called Battery Electric Vehicles (BEVs) or all Electric Vehicles (EVs) are powered by only a battery and an electric motor. The battery of this type is larger than PHEVs and does not have the gasoline engine. When PEVs have low power, they have to be plugged into an external source of electricity such as charging station, to recharge their batteries [6].

Figure 11. PEV model [7]

Advantages of PEVs

- "Zero tailpipe emissions.
- Use of cleaner energy.
- Reduce the amount of imported petroleum.
- Reduce loss from braking by using regenerative braking.
- Lower fuel and operation costs.
- Possible use in secondary markets for used batteries and reduced waste." [7]

B) Plug-in Hybrids Electric Vehicles (PHEVs)

Plug-in Hybrid Electric Vehicles (PHEVs) have both an electric motor and a gasoline engine like other HEVs but they have larger battery than HEVs and a charge port for charging their battery from external source when they are in resting state. This type can drive from 10-40 miles by using electricity and switch to use the internal combustion engine before the battery runs out [6].

Figure 12. PHEV model [7]

Advantages of PHEVs

- “Reduced fuel consumption and tailpipe emissions.
- Optimized fuel efficiency and performance.
- Lower fueling costs.
- Recovered energy from regenerative braking.
- Uses the existing gas station infrastructure.
- Uses the cleaner energy.
- Grid connection potential.
- “Home base” battery charging at a fraction of the cost of petroleum equivalent.
- Pure zero emission capability.
- Possible use in secondary markets for used batteries and reduced waste.” [7]

C) Hybrid Electric Vehicles (HEVs)

Hybrid Electric Vehicles (HEVs), generally called Hybrid, are powered by an electric motor and the internal combustion engine. The electric motor use energy from battery and generator. The battery can be charged by conversing power from ICE by generator. Moreover, HEVs could increase distance when driving in the city and stop-and-go traffic by employing regenerative braking. HEVs have different types which are considered the primary source of power. In all case, the using motor in EV can reduce the size of engine which affects on energy consumption, the total weight and the amount of emission. [6]

Figure 13. HEV model [7]

Advantages of HEVs

- “Reduced fuel consumption and tailpipe emissions.
- Optimized fuel efficiency and performance.
- Lower fueling costs.
- Recovered energy from regenerative braking.
- Uses the existing gas station infrastructure.” [7]

Table 1. The example of Plug-in Electric Vehicles (PEVs) (All-Electric Vehicles) in the market [8]

Brand / Model	**Price ($)**	**City/Highway (MPGe*)**	**Body type**	**Picture**
Nissan / Leaf	28,000	129/102	Hatchback	
Toyota / RAV4 EV	49,000	78/74	SUV	
Tesla / Model S	57,000	88/90	Sedan	
Ford / Focus Electric	39,200	110/99	Sedan	
Mitsubishi / iMiEV	29,100	125/99	Coupe	

* **MPGe** In order to compare the fuel efficiency of various vehicles, MPGe had to be introduced [8]. Burning one gallon of gasoline creates 115,000BTU which is equal to 33.7 kWh in the electrical. Therefore, the distance an electric vehicle can travel on 33.7 kWh of electricity is comparable to how far a conventional internal combustion vehicle can travel on one gallon of gasoline [8].

Table 2. The example of Plug-in Electric Hybrid Vehicles (PHEVs) in the market [8]

Brand / Model	Price ($)	City/Highway (MPG)	MPGe (AVG)	Body type	Picture
Ford / C-Max Energi	32,900	44/41	100	Sedan	
Toyota / Prius Plug-in Hybrid	32,000	51/49	95	Sedan	
Chevrolet / Volt	39,100	35/40	98	Sedan	
Fisker / Karma	111,000	20/21	52	Coupe	

Table 3. The example of Hybrid Electric Vehicles (HEVs) in the market [8]

Brand / Model	**Price ($)**	**City/Highway (MPGe)**	**Body type**	**Picture**
Toyota / Pius Liftback	24,200	51/48	Sedan	
Toyota / Camry Hybrid	26,140	43/38	Sedan	
Ford / Fusion Hybrid	27,200	47/47	Sedan	
Chevrolet / Malibu Eco	25,200	25/37	Sedan	
Kia / Optima Hybrid	25,700	34/39	Sedan	

CHAPTER 3

EVs Energy storage (Traction battery)

As we know that the EVs have several advantages such as high energy efficiency, environmentally friendly, performance benefits and reduce energy dependence; however, EVs have some limitations such as Recharge time, Battery cost and Bulk & weight that make EVs have less ability to penetrate through society. The main part that can solve those limitations is the Energy storage which researchers try to improve the characteristics such as weight, cost, and specific energy. The energy storage is the most important part of EVs that ultimately determine the future of EVs.

3.1 Basic Terms of Battery Performance and Characterization

There are various terms are used for specifying performance of batteries. This section is going to explore those terms.

- **Ampere-hour Capacity:** "Ampere-hour (Ah) capacity is the total charge that can be discharged from a fully charged battery under specified condition. People also used Wh (or kWh) capacity to represent a battery capacity. The rated Wh capacity is defined as" [9]

  Rated Wh Capacity = [Rated Ah Capacity] x [Rated Battery Voltage]

- **C- and E- rate: "**In describing batteries, discharge current is often expressed as a C-rate in order to normalize against battery capacity, which is often very different between batteries. A C-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity. A 1C rate means that the discharge current will discharge the entire battery in 1 hour. For a battery with a capacity of 100 Amp-hrs, this equates to a discharge current of 100 Amps. A 5C rate for this battery would be 500 Amps, and a C/2 rate would be 50 Amps. Similarly, an E-rate describes the discharge power. A 1E rate is the discharge power to discharge the entire battery in 1 hour." [10]

- **Specific Energy:** "is used to define how much energy a battery can store per unit mass, also called gravimetric energy density which is expressed in Watt-hours per kilogram (Wh/kg) as

  Specific Energy = [Rated Wh Capacity] / [Battery Mass in kg.]

  Specific energy of a battery is the key parameter for determining the total of a battery weight for a given mile range of EV." [9]

- **Specific Power: "**Specific power, also called gravimetric power density of a battery, is the peak power per unit mass. It is expressed in W/kg as" [9]

  Specific Power = [Rated Peak Power] / [Battery Mass in kg.]

- **Energy Density: "**Energy density, also referred as the volumetric energy density, is the nominal battery energy per unit volume (Wh/vol.)." [9]

- **Power Density: "**Power density is the peak power per unit volume of a battery (W/vol.)." [9]

- **Internal Resistance: "**Internal resistance is the overall equivalent resistance within the battery. It is different for charging and discharging and may vary as the operating condition changes." [9]

- **Peak Power: "**According to the U.S. Advanced Battery Consortium (USABC)'s definition, the peak power is defined as [9]

$$P = \frac{2V_{oc}^2}{9R}$$

where V_{oc} is the open-circuit voltage and R is the internal resistance of battery. The peak power is actually defined at the condition when the terminal voltage is 2/3 of the open-circuit voltage.” [9]

- **Cut-off Voltage: “**Cut-off voltage is the minimum allowable voltage defined by the manufacturer. It can be interpreted as the “empty” state of the battery.” [9]

- **State Of Charge (SOC): “**SOC is defined as the remaining capacity of a battery and it is affected by its operating conditions such as load current and temperature. [9]

$$\text{SOC} = \frac{\text{Remaining Capacity}}{\text{Rated Capacity}}$$

If the Ah capacity is used, the change of SOC can be expressed as

$$\Delta\text{SOC} = \text{SOC}(t) - \text{SOC}(t_0) = \frac{1}{\text{Ah Capacity}} \int_{t_0}^{t} i(\tau) d\,\tau.$$

SOC is a critical condition parameter for battery management. Accurate gauging of SOC is very challenging, but the key to the healthy and safe operation of batteries.” [9]

- **Depth Of Discharge (DOD): “**DOD is used to indicate the percentage of the total battery capacity that has been discharged. For deep-cycle batteries, they can be discharged to 80% or higher of DOD.” [9]

DOD = 1-SOC.

- **State Of Health (SOH):** SOH can be defined as the ratio of the maximum charge capacity of an aged battery to the maximum charge capacity when the battery was new [7]. SOH is an important parameter for indicating the degree of performance degradation of a battery and for estimating the battery remaining lifetime. [9]

$$\text{SOH} = \frac{\text{Aged Energy Capacity}}{\text{Rated Energy Capacity}}$$

- **Cycle Life (Number of cycles):** “Cycle life is the number of discharge–charge cycles the battery can handle at a specific DOD (normally 80%) before it fails to meet specific performance criteria. The actual operating life of the battery is affected by the charging and discharging rates, DOD, and other conditions such as temperature. 2 Electric Vehicle Battery Technologies 21 The higher the DOD, the shorter the cycle life. To achieve a higher cycle life, a larger battery can be used for a lower DOD during normal operations.” [9]

- **Calendar Life: “**Calendar life is the expected life span of the battery under storage or periodic cycling conditions. It can be strongly related to the temperature and SOC during storage.” [9]

- **Battery Reversal: “**Battery reversal happens when the battery is forced to operate under the negative voltage (voltage of positive electrode is lower than that in the negative electrode). It can happen on a relatively weak cell in a serially connected battery string. As the usable capacity of that particular weak cell runs out, the rest of batteries in the same string will still continue to supply the current and force the weak cell to reverse its voltage. The consequence of battery reversal is either a shortening cycle life or a complete failure.” [9]

- **Battery Management System (BMS): "**BMS is a combination of sensors, controller, communication, and computation hardware with software algorithms designed to decide the maximum charge/discharge current and duration from the estimation of SOC and SOH of the battery pack." [9]

- **Thermal Management System (TMS): "**TMS is designed to protect the battery pack from overheating and to extend its calendar life. Simple forced-air cooling TMS is adopted for the NiMH battery, while more sophisticated and powerful liquid cooling is required by most of the Li-ion batteries in EV applications." [9]

3.2 Inside an EV Battery Pack

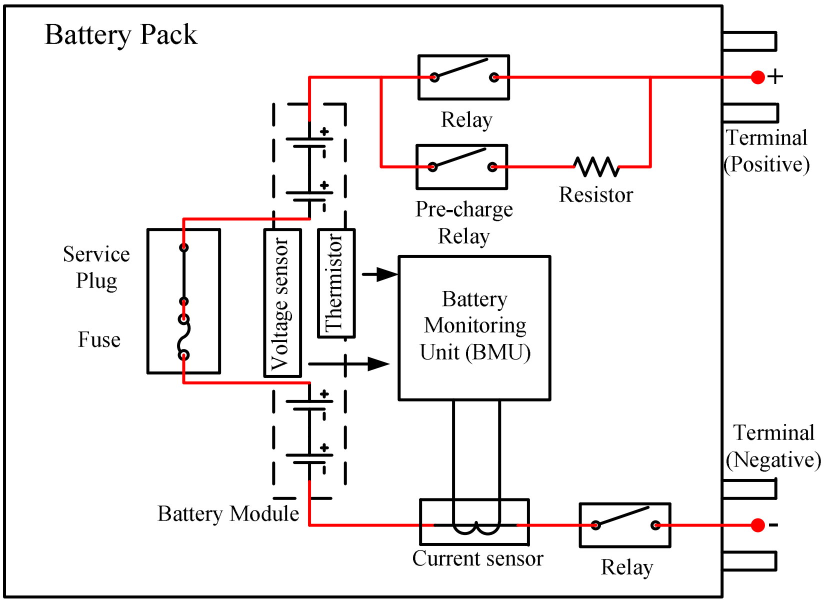


Figure 14. The basic diagram of internal battery pack [11]

EV Battery pack designs have complexity and vary shapes which depend on each manufacturer and specific application. However, inside the pack consists of several simple mechanical and electrical component systems which provide the basic require function of the pack.

Let start from battery cells, different material and shapes can be used in battery cells depend on various pack manufacturers. Series and parallel connection of discrete cells will be made to achieve voltage and current requirements of the pack. In one battery pack for all EVs can consist of several hundred individual cells. [11]

Module is small stacks of cells that come from the rearrangement of a large stack of cells. This module helps manufacturing and assembly. Several modules will be placed in a single battery pack and the complete electrical path will be made by welding each module together. The incorporate cooling mechanisms, temperature monitors and other device are able to be integrated with module. In the most case, the Battery Management System (BMS) can monitor the voltage produced by each battery cell from each stack in the module. [11]

A main fuse and a "service plug" or "service disconnect" are connected with in the electric path of the battery cell stack to limit the current of the pack under a short circuit condition and split the battery stack into two electrically isolated halves to present no high potential electrical danger to service technicians respectively. Moreover, the battery pack also contains relays or contactors and variety of sensors such temperature, voltage and current sensors. In most cases there are two main relays, one located at the positive output terminal and another one at the negative output terminal, which control the power of the pack to the terminal. The sensors will send inside data to Battery Monitoring Unit (BMU) or Battery Management System (BMS). Then BMS will communicate with the outside pack and performing other key functions.

3.3 Type of EVs batters

EVs batteries (Deep cycle) are designed to give power over a sustained period which is different from starting, lighting and ignition (SLI) batteries. The characteristics of traction batteries must be designed to have a relatively high ampere-hour capacity, power-to-weight ratio, energy to weight and energy density smaller, lighter batteries decrease the weight of the vehicle and enhance its performance. There are four common types of battery that have been used for EVs.

- **Lead-acid**

Lead-acid battery is a traction battery that is the most common and cheapest in the market. There are two types of lead-acid batteries which are automobile starter batteries and deep cycle batteries. Automobile starter batteries are used to provide start-up or backup power in gasoline and diesel powered vehicles. Deep cycle batteries are used electric vehicle such as fork-lift, low speed utility vehicles, golf carts. Recently, lead-acid is considered to be one of choices of EVs batteries in the future because it is cheap and has a fair lift cycle but the energy density is low. For this reason, researchers try to improve the energy density of lead-acid batteries. [32]

Table 4. Advantages and Disadvantage of lead-acid batteries

Advantage	**Disadvantage**
Cheap	Heavy
Well understood	Fire and explosion hazard
Recyclable	Low energy density (30–40 Wh/kg)
Fair life cycle	

- **Nickel metal hydride**

Nickel-metal hydride batteries have less efficiency than lead-acid batteries but they have higher energy density than lead-acid. In addition, life-cycle of nickel metal hydride batteries are very long. Hybrid cars such as NiMH RAV4EVs use these types of batteries and batteries work well after 100,000 miles and over the decade service. Nickel metal hydride is considered to be a relatively mature technology. [32]

Table 5. Advantages and Disadvantage of Nickel metal hydride batteries

Advantage	**Disadvantage**
Long life cycle	Low energy density (30-80 Wh/kg)
Nontoxic metal	High self-discharge
	Poor performance in cold weather
	Poor efficiency

- **Zebra (Zeolite Battery Research Africa)**

Zebra battery is a battery that uses molten salt as electrolyte. The operating temperature is 245 ˚C (473 ˚F). This temperature melts sodium aluminum chloride ($NaAlCl_4$) to be as an electrolyte. This type of batteries has higher energy density than lead-acid and nickel metal hydride. On the other hand, the big problem of this type is operating temperature. We have to waste some energy for keeping the operating temperature of this battery. [32]

Table 6. Advantages and Disadvantage of Zebra batteries

Advantage	Disadvantage
Long life cycle	High operating temperature
Nontoxic metal	Poor power density (<300 W/kg)
High energy density (120 Wh/kg)	Waste energy for heating the electrolyte

- **Lithium ion**

As we know that lithium-ion has been used for a decade in laptops and cell phones, the batteries deliver the high energy density which is around 200+ Wh/kg, good power density and 80 to 90% charge/discharge efficiency. For these advantages, lithium-ion batteries step into EVs world. Almost EVs that are recently produced use lithium-ion battery. However, we have noticed that the life of lithium-ion batteries in laptops and cell phones are last for a few years. This disadvantage can be eliminated by managing discharging and charging the battery between 50% and 80% respectively. To do this, we have to sacrifice the range of EVs because the battery cannot discharge all of its energy. To provide the full range of EVs, twice the size of the battery is equipped. This will increase the weight of electric vehicles but it is important for increasing the age of electric vehicles. [32]

Table 7. Advantages and Disadvantage of Lithium ion batteries

Advantage	Disadvantage
High energy density (100-150 Wh/kg)	Toxic
High power density	Fire and explosion hazard
No memory effect	Short life cycle
Low maintenance	High cost

3.4 The next generation of the traction battery

Technology of the battery has been developed unceasingly from early the 19th century. Varieties of batteries have been produced to supply different kind of electronic equipment. A different methods, different materials and different chemical solutions are used to create more than hundred types which have different characteristics, purposes, and advantages. Modern batteries can deliver more power, have high energy capacity, have a long life cycle, and have more safety. They play an important role in the electrical power grid which has been grown continuously during the 20 century. Recently, electric vehicles become an important technology that can solve several problems such as, the energy crisis, and pollution problems. Battery technology is one of the most important key that can make electric vehicle to succeed. The ideal battery for electric vehicle consists of different characteristics such as, high power and energy density, long life cycle, light weight, safety, easy to produce, fast charging and inexpensive. However, recent batteries cannot provide all the electric vehicle needs. The present types of batteries that are used in electric vehicle are lithium ion which has more accuracy than other types but it is still far from the ideal battery. Different types of batteries are experimented in laboratories and they will be ready for electric vehicle in the near future. The future batteries will be

- **Li Batteries**

Li-ion technology has been developed unceasingly from the last decade. Recently, lithium-ion plays an important role in the electric vehicle. The excellent of energy and power density make this type of battery to be considered in different car manufacturers. However, the lithium ion has several disadvantages such as life cycle, safety, high cost and difficult to recycle. For this reason, researchers try to develop this technology to eliminate its drawbacks by using different methods and materials. The next generation of the lithium ion batteries will improve their cathodes and anodes which improve their specific energy and improve their electrolytes which improve their safety. Moreover, some elements will be added to improve their characteristics. [12]

Lithium air (Li_2O or Li_2O_2)

Table 8. Advantages and Disadvantage of Lithium air (Li_2O or Li_2O_2) batteries

Advantage	Disadvantage
3351 mAh/g based on Li_2O (with Li_2O_2 the capacity become: 1675 mAh/g) [12].	Polarization more than 1.5V between the charge and the discharge [12]
	Electrolyte decomposition [12]
	Poor cycle ability and catalyst degradation [12]

Lithium sulfur (Li_2S)

Table 9. Advantages and Disadvantage of Lithium sulfur (Li_2S) batteries

Advantage	**Disadvantage**
1675 mAh/g based on Li_2S [12]	Low tap density of sulfur ~2.07g/cc "volumetric capacity 3467Ah/l" [12]
	Insulator character of sulfur (10-30) S/cm, need more carbon additive (low active loading, low capacity at the electrode level) [12]
	Can't be cycle over 3.6V due to the formation of soluble polysulfide "redox shuttle effect" [12]
	Low voltage output ~1.8V. Energy density: 6240 Wh/l [12]
	Low melting point ~ 115ºC safety? [12]

Lithium selenium (Li_2Se)

Table 10. Advantages and Disadvantage of Lithium selenium (Li_2Se) batteries

Advantage	Disadvantage
High tap density of selenium ~4.8g/cc "volumetric capacity 3240 Ah/l" [12]	675 mAh/g/ based on Li_2Se [12]
Good conductor character of selenium (10-6-10-7) S/cm, limited use of carbon additive (high active loading, high capacity at the electrode level) [12]	
Can be cycle till 4.6V without the formation of soluble polysulfide "redox shuttle effect" [12]	
High voltage output ~2.5V. Energy density: 8100 Wh/l (30% more than S) [12]	
High melting point 220ºC "safer" [12]	

The invention of Li-O and Li-S could result in developing our energy storage technology to store energy safely and inexpensive but we do not completely understand all of precipitation electrochemistry which might be higher risk [12]. These technologies will be available in the next 5-10 years.

- **Low temperature molten-salt battery**

This type of battery is the next generation of molten salt battery. This battery is developed to decrease the operating temperature from around 245 ˚C (473 ˚F) to be 57 ˚C (135 ˚F) far lower than sodium based batteries. This new type could provide around 290 Wh/L energy densities. Moreover, this battery use only nonflammable materials and will not ignite on contact with air nor is there thermal run away. For this reason, the batteries have more safety because waste-heat storage or fire-and explosion-proof equipment are eliminated and allow closer packing of cells. The size of the batteries might be smaller that lithium and molten-salt batteries. It might be half the volume of lithium ion batteries. The cost of low temperature molten-salt batteries will be cheaper than the lithium ion batteries [13]. This technology has been developed by Sumitomo Electric Industries Ltd., in partnership with Kyoto University and will be available in 2015 [14].

- **Ultracapacitors (Supercapacitors)**

Capacitors are a technology that has been developed for a while. In the past, the US military use them to start engines of tanks and submarines [15]. Ultracapacitors have some advantages that attract researchers to improve them such as very long of life cycle (more than hundred thousand cycles) very short charged time. However, they cannot store much energy like batteries. For the same size, Lithium ion can store energy more than 20 times over ultracapacitors. For the electric vehicle, the range of the vehicle is an important factor that is consider in the future. The next generation of ultracapacitors will be merged with batteries (Hybrid battery) [15]. Recently, nanotechnology is used to improve abilities of ultracapacitors [16]. "Graphene, carbon that is only one atom thick might help ultracapacitors to compete better on energy density. Some experiment showed that highly porous graphene can be stacked many layers deep while both sides of each layer remain accessible. In experiments, that has doubled or tripled the energy density of ultracapacitors made with graphene." [16] This might lead to the next generation of high energy density ultracapacitors which can replace all the old type of traction batteries in the near future.

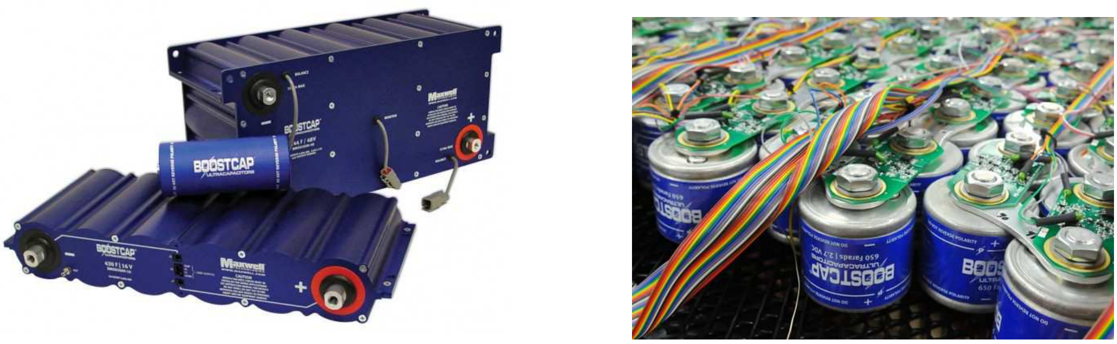


Figure 15. Ultracapacitors[15][16]

Table 11. Advantages and Disadvantage of Ultracapacitors (Supercapacitors)

Advantage	Disadvantage
"Virtually the unlimited life cycle - cycles millions of time -10 to 12 year life" [15]	"Linear discharge voltage prevents the use of the full energy spectrum" [15]
"Low impedance Super capacitors and ultra capacitors are relatively expensive in terms of cost per watt "[15]	"Low energy density - typically holds one-fifth to one-tenth the energy of an electrochemical battery" [15]
"Charges in seconds "[15]	"Cells have low voltages - serial connections are needed to obtain higher voltages. Voltage balancing is required if more than three capacitors are connected in the series" [15]
"No danger of overcharge" [15]	"High self-discharge - the rate is considerably higher than that of an electrochemical battery".
"Very high rates of charge and discharge" [15]	"Requires sophisticated electronic control and switching equipment" [15]
"High cycle efficiency (95% or more)" [15]	
"Low impedance" [15]	

3.5 Traction battery design

There are different sizes of traction batteries in markets. Each manufacturer has their own specification for their traction batteries depend on which characteristics they focus. If they focus on speed, they will produce high voltage batteries. The higher voltage of batteries, the faster a given can go. If they focus on distance, they will produce high energy density batteries. The higher energy density, the longer distance a given car can go.

To design batteries, manufacturers have to consider different factors such as pack requirement, cell chemistry, battery properties and key constraints to get the specification that they need. After that they can determine cell properties such as cell capacity, cell area electrode thickness, internal resistance and the design battery pack.

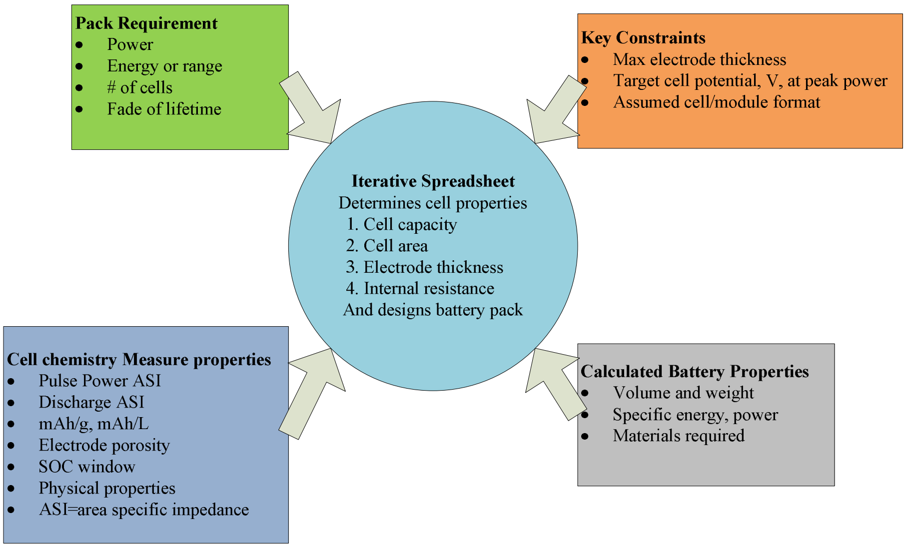


Figure 16. The battery design diagram [17]

3.6 Basic Electric Vehicle Conversions

This section is going to explore how to calculate parameters of electric vehicles such as, distance, speed and so on.

- **Speed**

Speed of electric vehicles depends on their voltage. The car that has higher voltage can run faster than the car that has lower voltage. (This similar to ICE's, the more fuel is used the faster you go-the more power is used the faster the EV goes. This will impact the total distance on a single charge.) [18]

- **Distance**

Several factors such as speed, pack KW rating, driving condition aerodynamics, vehicle weight, hills, temperature, driving styles and other have effect to the total distance of the electric vehicle [18]. The basic formula for determining distance is:

$$\frac{\text{KW of pack}}{\text{Wh/mi}} = \text{Distance}$$

We can calculate Watt-Hour per Mile (Wh/m) as

$$\text{Volts} \times \frac{\text{Amp Draw}}{\text{MPH}} = \text{Wh/mi}$$

The rule of thumb for EV is

Small Vehicle	250-300 Wh/mi
Small Pickup	350-400 Wh/mi

We can calculate Battery Pack Size (KW) as

$$\text{Pack Voltage} \times \text{Amp} - \text{Hour rating of battery} = \text{KW}$$

- **Usable Battery Pack Size**

We should not use all of battery energy because the life of a battery packs will be reduced very fast. To extend the life of battery pack, batteries should not be discharge over 80%. Moreover, the “Peukerts” effect can effect on some types of battery such as lead acid batteries which reduce the usable pack size of batteries because an EV discharge the batteries faster than the manufacturer tested and rated. However, if we use LiFePO4 Batteries we can ignore the Peukerts effect [18].

Usable pack size can be expressed as:

$$\text{KW} \times 0.80 \times \text{Peukerts} = \text{Usable KW}$$

Peukerts: Lead-Acid = 0.55

LiFePO4 = 1.0

We can see that Peukerts has highly effect to the Lead-Acid batteries. However, the cost of Lead-Acid batteries is cheaper than LiFePO4.

Example: Vehicle: Miata
Batteries: 12 - 12V Lead-Acid, rated at 100 ah

Pack Voltage = (12 batteries) x (12V each) = 144V

Pack Size = 144V x 100 Ah = 14,400 KW

Usable Pack = 14,400 x 0.8 x 0.55 = 6,336 KW usable

From experience, the Miata using a 144V system and it can draw around 90 amps at 50 MPH. Then we can find the Wh/mi usage:

Wh/mi usage = 144V x (90 Amps / 50 MPH) =259 Wh/mi

When we know the value of Wh/mi value, we can calculate the distance by:

Distance = 6,336 KW / 259 Wh/mi = 24 miles

For the Miata that use lead-acid batteries, it can run around 24 miles. If we replace the lead-acid batteries by the lithium (LifePO4) which its 144 Volt pack of lithium cells would consist of 45 of the lithium cells (they are nominal 3.2 volt each). We can calculate the distance by [18]:

Usable Pack = 14,400 x 0.8 x = 11,520 KW usable (No the Peukerts effect)

Distance = 11,520 / 259 Wh/mi = 44 miles

We can find the size of batteries by using the reverse calculated method.

Assume that you would like to go 44 miles per charge at 50 mph and want to know the size batteries you need (using lithium batteries). We can use the 259 Wh/mi average to calculate the size by [18]:

Ah/mi = (Wh/mi) / (pack voltage)

Ah/mi = 259 / 144 = 1.8 Ah/mi

You would like to go 44 miles and after 44 miles batteries should have 20% left in the batteries. You can calculate by:

Ah battery = Ah/mi x mi/charge x 1.2 (After drive have 20% left)

Ah battery = 1.8 x 44 x 1.2 = 95 Ah

We get the result that you need 95 Ah batteries at 144 volts for driving 44 miles

*** The component used must be rated for the voltage and amperage [18]***

We can calculate the performance of the batteries by calculating HorsePower (HP)

Watts = V x A

HP = watts / 746

Then we can find HP by using voltage and ampere by:

HP = V x A / 746

If we use a 144 volt pack of 200 batteries and 1000 amp controller (at a 5C draw). We can calculate HP by:

HP = 144 x 1,000 / 746 = 193

If we use a 288 volt pack of 100 batteries. We could have potentially 386 HP (without efficiency included). There is a problem. If we use high power levels, it risks for motor damage. The common "in the field" estimate of KW power a 9" motor can handle (for a short period) is 100 KW. Then we can calculate the limited Amps for the system [18]. From Watts = V x A, We can find the limited Amps for 144 volt and 288 volt system by:

Amps (144volt system) = 100 KW /144 = 700 amps

Amps (288 volt system) = 100 KW / 288 = 350 amps

These calculations based on theoretical value and averages and assumptions. There are a lot of factors that affect on the calculation such as:

- A 5% grade requires twice the power that is needed on level roads [18]
- Poor aerodynamics will use more energy [18]
- Poor wheel arraignment, low pressure, other mechanical drags will use more power [18]
- Weight is very important-the lighter the less energy needed to move the vehicle [18]
- Temperature-battery temperature below 50 degrees will diminish the range of the vehicle. Generally lead-acid and LifePO4 will loss 30% and 15-20% of their useful Ah at 30 ˚ F respectively [18].
- Heaters are needed to make the comfortable temperature in the car .To do this, the car needs around 2,500-3,000 watts for raising the temperature up and 1,500 watts for maintain the temperature which will lower its range about 15% [18].
- Driving habits can effect to the usage of power [18]
- Battery condition affects on the ability of storing energy of battery

CHAPTER 4

Impact of EVs on grid

Energy crisis especially gasoline and the air pollution problem are a big topic that are discussed in the United States. To solve these problems, Electric Vehicles (EVs) and distributed Generations (DGs) are the possible solution this era. For this reason, the growth of EVs and DGs increase rapidly. This means a large number of loads (EVs) and energy generations (DGs) will be added in to the system which makes tremendous change to systems.

4.1 The impact on the load balance of the distribution network

From last decade, electric vehicles have been increase continuously which means we add more load into the system. Figure 17 shows the U.S. projected electric vehicle, from 2010–2050. In 2050, 50% of the U.S. vehicle fleet will be electrified. If the average pack sizes of their batteries are 18.4 kWh, the mobile electric storage capacity would be around 2,900 GWh. This enormous amount could present problems to the grid management if electric vehicle charging is not handled effectively. [19]

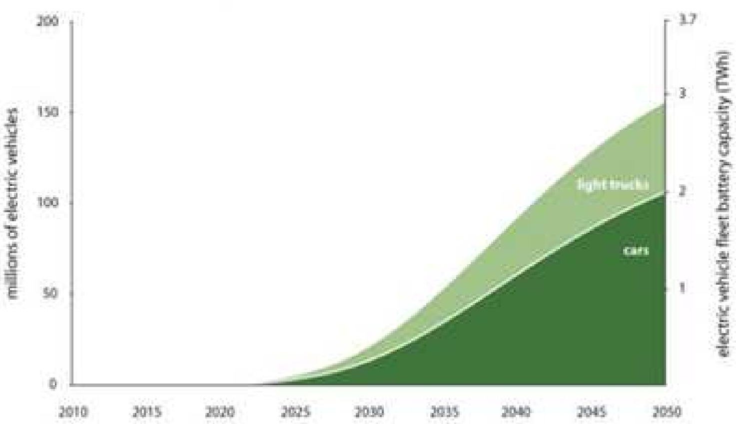


Figure 17. The U.S. projected electric vehicle, 2010–2050 [19]

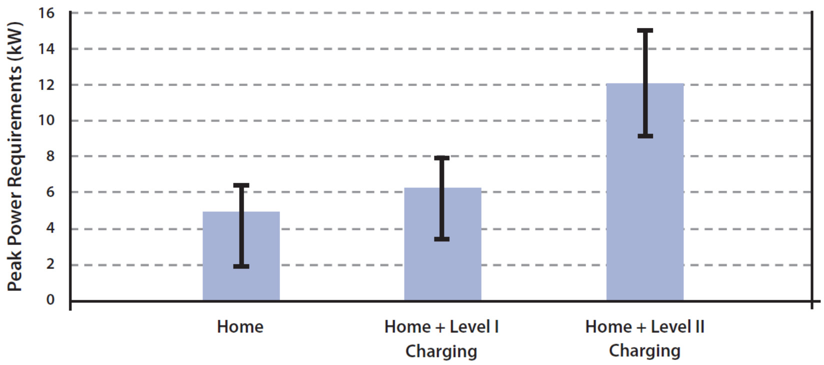


Figure 18. The power Requirement of a Single Home in the San Francisco Bay Area with and without Electric Vehicle Charging [20]

EVs are expected to charge at one of three power levels. Figure 19 is the Society of Automotive Engineers Charging standards (SAE J1772) which established by the Society of Automotive Engineers

“LEVEL I – up to 1.92 kW
LEVEL II – up to 19.2 kW
LEVEL III – not been standardized in the U.S. (Will enable full BEV charging in minutes)

Figure 18 illustrates Power Requirement of a Single Home in the San Francisco Bay Area with and without Electric Vehicle Charging**.** The narrow vertical bar represents the variance in average home peak loads for location throughout the San Francisco area. The broad bar shows the peak load requirement for the same home by itself and with EVs charging at the two standards levels: 1.4 kW (Level I) and 7.2 kW (Level II)” [20]

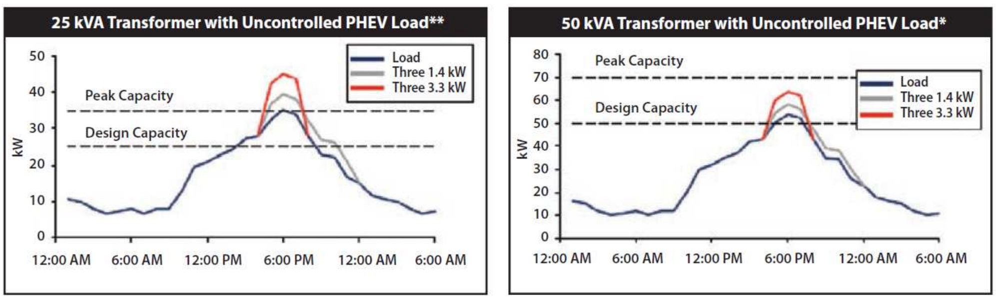
SAE International — SAE Charging Configurations and Ratings Terminology

AC level 1 (SAE J1772™)	PEV includes on-board charger	***DC Level 1**	EVSE includes an off-board charger
	120V, 1.4 kW @ 12 amp 120V, 1.9 kW @ 16 amp		200-450 V DC, up to 36 kW (80 A)
	Est. charge time:		Est. charge time (20 kW off-board charger):
	PHEV: 7hrs (SOC* - 0% to full)		PHEV: 22 min. (SOC* - 0% to 80%)
	BEV: 17hrs (SOC – 20% to full)		BEV: 1.2 hrs. (SOC – 20% to 100%)
AC level 2 (SAE J1772™)	PEV includes on-board charger (see below for different types)	***DC Level 2**	EVSE includes an off-board charger
	240 V, up to 19.2 kW (80 A)		200-450 V DC, up to 90 kW (200 A)
	Est. charge time for 3.3 kW on-board charger		Est. charge time (45 kW off-board charger):
	PEV: 3 hrs (SOC* - 0% to full)		PHEV: 10 min. (SOC* - 0% to 80%)
	BEV: 7 hrs (SOC – 20% to full)		BEV: 20 min. (SOC – 20% to 80%)
	Est. charge time for 7 kW on-board charger		
	PEV: 1.5 hrs (SOC* - 0% to full)	***DC Level 3 (TBD)**	EVSE includes an off-board charger
	BEV: 3.5 hrs (SOC – 20% to full)		200-600V DC (proposed) up to 240 kW (400 A)
	Est. charge time for 20 kW on-board charger		Est. charge time (45 kW off-board charger):
	PEV: 22 min. (SOC* - 0% to full)		BEV (only): <10 min. (SOC* - 0% to 80%)
	BEV: 1.2 hrs (SOC – 20% to full)		
***AC Level 3** (TBD)	> 20 kW, single phase and 3 phase		

*Not finalized
Voltages are nominal configuration voltages, not coupler ratings
Rated Power is at nominal configuration operating voltage and coupler rated current
Ideal charge times assume 90% efficient chargers, 150W to 12V loads and no balancing of Traction Battery Pack

Notes:
1) BEV (25 kWh usable pack size) charging always starts at 20% SOC, faster than a 1C rate (total capacity charged in one hour) will also stop at 80% SOC instead of 100%
2) PHEV can start from 0% SOC since the hybrid mode is available.
Developed by the SAE Hybrid Committee *ver. 031611*

Figure 19. The Society of Automotive Engineers (SAE1772) [22]



(a) 25 kVA Transformer (b) 50 kVA Transformer

Figure 20. The effect of uncoordinated charging on transformers [20]

Figure 20 illustrates the impact on both a 25 kVA transformer and a 50 kVA transformer of three PHEVs charging at two rates which are 1.4 kW and 3.3 kW on a warm summer day. The 25 kVA transformer is loaded over its design capacity and peak capacity. The 50 kVA transformer is loaded over its design capacity but below its peak capacity. These result could lead to voltage dips, service interruption and transformer failure. [20]

4.2 The impact on the reliable and the power quality

When electric vehicles highly increase in the nation, the increasing of energy generations are needed to provide enough energy. Renewable energy plays as a key to solve the energy crisis in U.S.

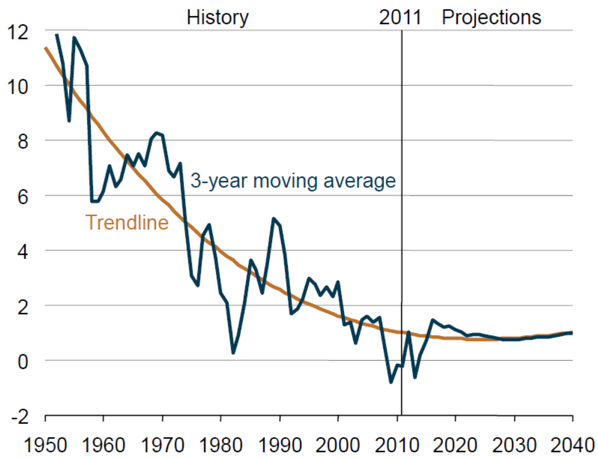


Figure 21. U.S. electricity demand growth, 1950-2040 (percent, 3-year moving average) [21]

"The figure 21 illustrates U.S. electricity demand growth. The electricity demand growth from 2011-2040 relatively slow but still increase 28% in projection (0.9% per year) from 3839 billion kilowatthours in 2011 to 4930 billion kilowathours in 2040. The electricity sales to the transportation sector from 2011-2040 is 6 billion kilowatthours to be 19 billion kilowatthours because of increasing sales of electric plug-in vehicle." [21]

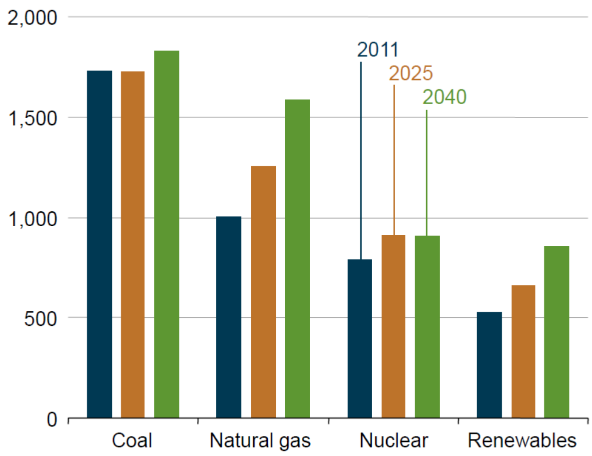


Figure 22. Electricity generation by fuel, 2011, 2025, and 2040 (billion kilowatthours) [21]

"Figure 22 shows Electricity generation by fuel, 2011, 2025, and 2040 (billion kilowatthours). Generation from renewable energy grows by 1.7% per year on average and share of total the generation rise s from 13% in 2011 to 16% in 2040." [21]

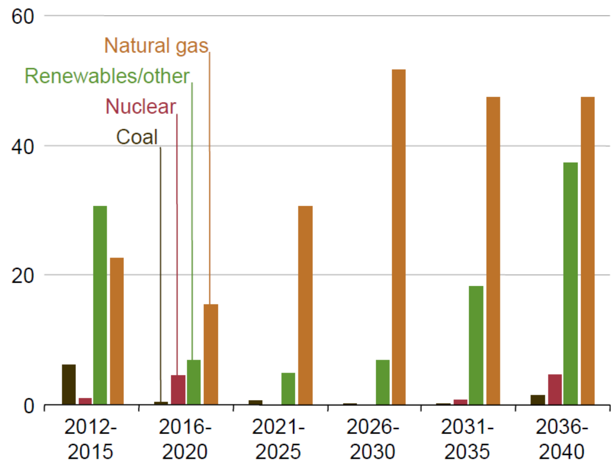


Figure 23. Electricity generation capacity additions by fuel type, including combined heat and power,2012-2040 (gigawatts) [21]

"Decision to add capacity and the choice of fuel for new capacity depend on several factors. 340 gigawatts of new generating capacity are added into systems from 2012 – 2040 due to the fact that the retirement of 103 gigawatts of existing capacity and growing electricity demand. Figure 23 illustrates Electricity generation capacity additions by fuel type, including combined heat and power, 2012-2040 (gigawatts). The natural gas-fired plant, renewable energy, coal and nuclear which account for 63%, 31%, 3% and 3% of capacity additions will be added into the systems from 2012-2040 respectively." [21]

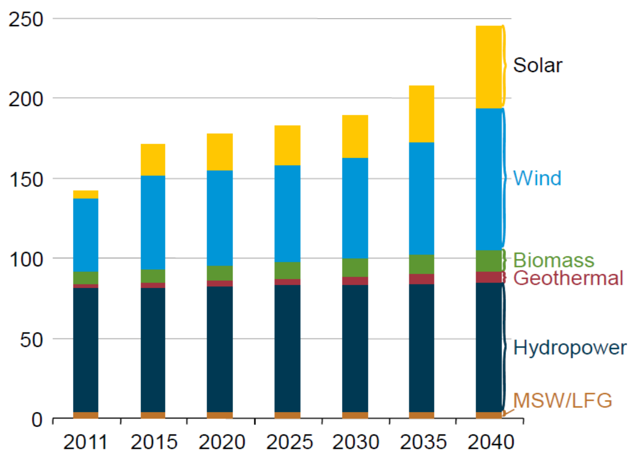


Figure 24. Renewable electricity generation capacity by energy source, including end-use capacity, 2011-2040 (gigawatts) [21]

"In 2040, renewable generating capacity accounts for nearly one-fifth of total generating capacity. Nearly all renewable capacity additions over the period consist of nonhydropower capacity, which grows by more than 150% from 2011-2040. Comparing between 2011 and 2040, solar generation capacity increase 1000% or 46 gigwatts and wind capacity increase around 42 gigawatts. Figure 24 Renewable electricity generation capacity by energy source, including end-use capacity, 2011-2040 (gigawatts)" [21]

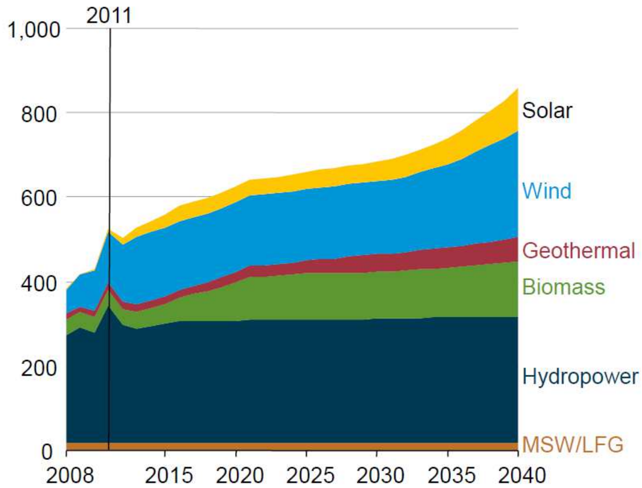


Figure 25. The renewable electricity generation by type, including end-use generation, 2008-2040 (billion kilowatthours) [21]

"Figure 25 Renewable electricity generation by type, including end-use generation, 2008-2040 (billion kilowatthours). From 2011-2040, renewable generation increases from 524 to 858 billion kilowatthours which growing by an average of 1.7% per year. The increase in wind-powered generation from 2011-2040, at 134 billion kilowatthours, or 2.6% per year, represents the largest absolute increase in renewable generation." [21]

From previous information, we can say that renewable generation especially wind generation (distributed generation) will highly increase in the near future. However, the input of wind generation depends on nature condition which we cannot predict the strength amount of wind. The highly variable nature of wind generation makes the power distribution system have low reliability and power quality. However, PHEVs and BEVs have the potential to meet this demand through both charging and discharging strategies which can improve the reliability and power quality of wind generations. [23] "Partially charged EV sitting unused at home or work could sense wind power's fluctuations in the grid, acting as a shock sorbent for the grid, advancing or slowing the charging process based on conditions of the grid." [23] "EVs can perform as storage, charging when there is an excess of renewable generation and provide energy from their storage if there is lack of generation. Moreover, EVs are able to be managed as an intelligent load that consumes energy when is required." [1] Figure 26 shows the simple diagram of energy flow.

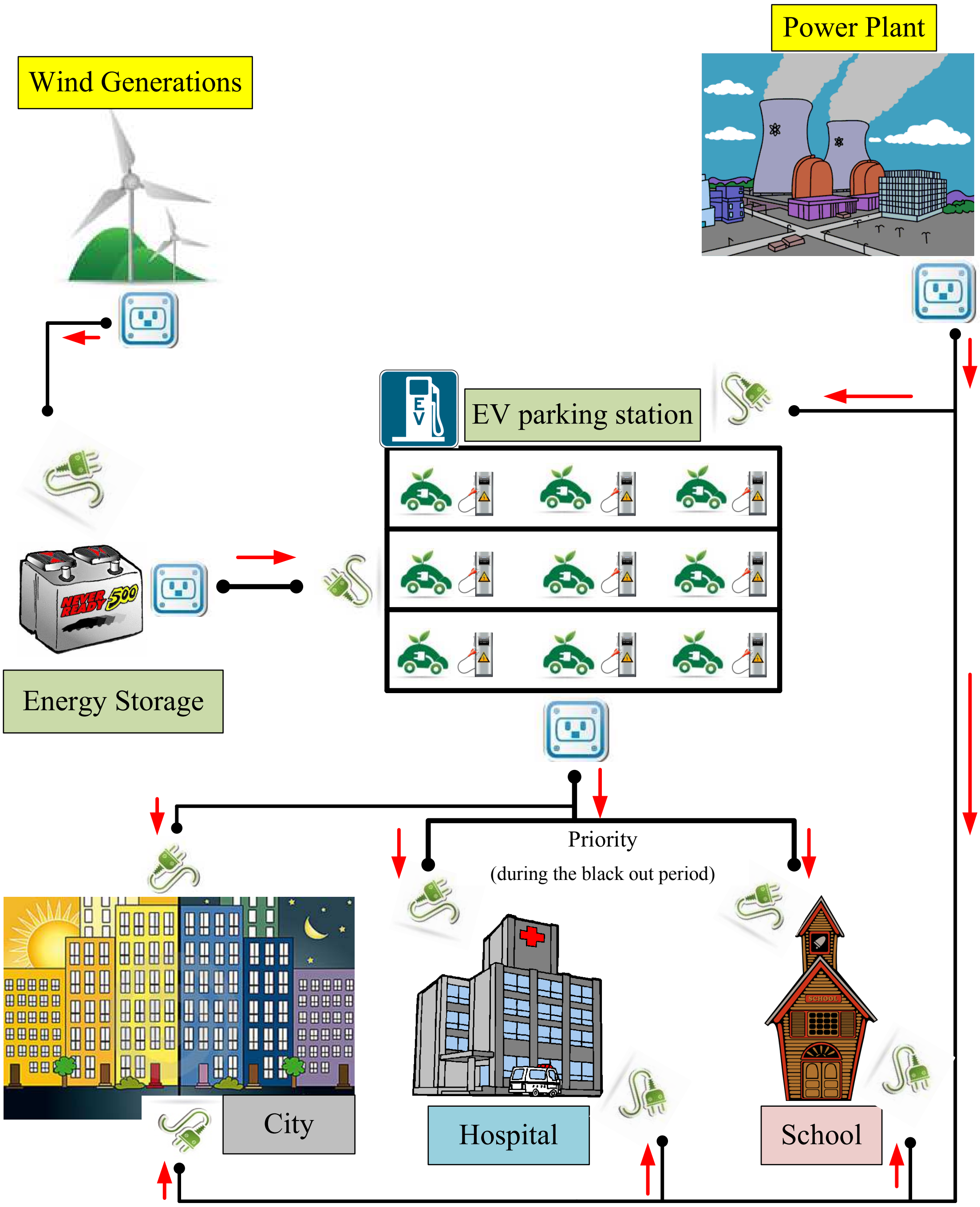


Figure 26. Energy flow diagram [33]

On the other hand, the EV charging devices could inject some harmonic into the system because of power electronic equipment in their structures. The operating principle of the EV charging device is to change the alternating current to be direct current to provide power to the battery which is quite simple but the structure of the EV charging device is complex. It consists of power electronic equipment, including AC/DC inverter, DC/DC converter, and the high frequency transformer and so on. There are three kinds of charging devices which are rectifier with a chopper and no control, rectifier with no control and DC/DC converter and rectifier with PWM and DC/DC converter. [31]

- **Rectifier with chopper and no control**

The basic parts of this type of the earliest charging device consist of 6 diodes and chopper. This type of charging device produces much harmonic and high THD because the nonlinear electronic devices with less control methods. For this reason, this type is not allowed to connect to grid. [31]

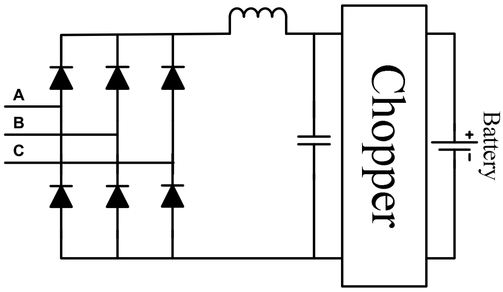


Figure 27. Topology of the first kind of charging device [31]

- **Rectifier with control and DC/DC converter**

This type of charging device is developed from the first type by changing the chopper to be high frequency converter. This type has less ripple wave of DC voltage and improves the quality of charging because the high frequency transformer that can isolate the high frequency effectively. However, it still consists of diodes which produce much harmonic and high THD. Then it cannot be allowed to connect to the grid. [31]

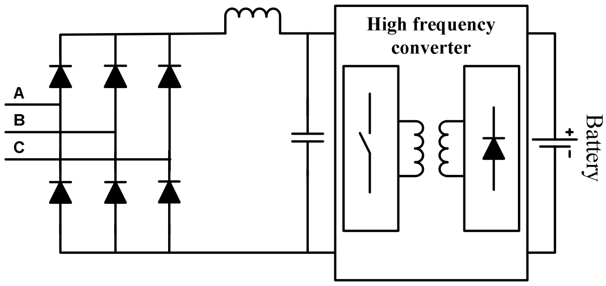


Figure 28. Topology of the second kind of charging device [31]

- **Rectifier with PWM and DC/DC converter**

This model is the present charging device that replaces the nonlinear devices by controllable switches. The improvement of microcomputer technology allows us to use PWM to control them. Using controllable switches have different advantages which are reducing harmonic to the grid and improve the power factor conversion efficiency. Moreover, this type consists of the high frequency converter part which can reduce the ripple wave of DC voltage. This type is considered to use in the grid. On the other hand, this type is expensive because the using of microcomputer control device. [31]

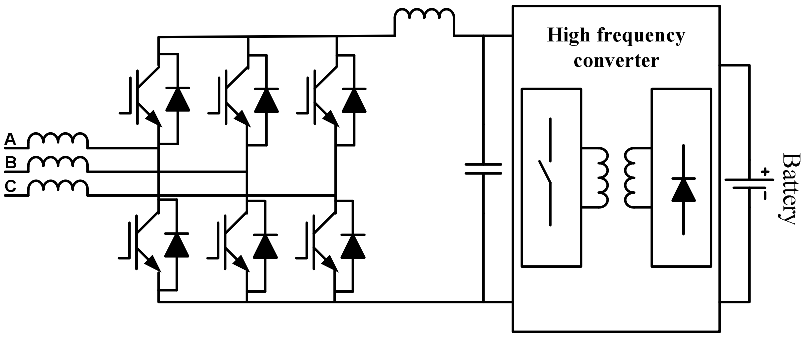


Figure 29. Topology of the third kind of charging device [31]

Charging devices which consist of power electronic equipment could provide some harmonics especially odd harmonic into the system. These harmonics will effect to the quality of power. The chapter 6 of this report is going to simulate the effect of connecting charging into the system which illustrates some harmonic spectral that occurs in the system.

CHAPTER 5

Controlling and Management

As we see in the previous section, there are two major impacts of EVs on the grid which are the impact on the load balance of the distribution network and the impact on the reliable and the power quality. The first is a disadvantage impact but the second is an advantage impact. To solve the first impact and achieve the second impact, we must have correct controls and management. The controlling and managing methods will be explored in this section.

5.1 Economic operation

Generally, electric vehicles will be plugged in and begin charging after their owners arrive home. The peak load will increase highly because the time of arriving home of each people will be similar. This will affect on expanded infrastructure. Early results from an ongoing Electric Power Research Institute (ERPI) project suggest that peak charging, higher charger power rating and increases in the number of EVs on a transformer could yield decreases in transformer lifetimes due to temperature-induced insulation aging from capacity overload. [20]

The peak load and the load factor could be reduced and improved respectively by adjusting the time of charging EV. There are two viable methods are introduced which are time-differentiated tariffs and centralized charging control structures. [20]

- **Time-differentiated tariffs**

"There are varieties of way in this method. They can static and based on time of use, or they can be signaled a day ahead, an hour ahead or in real time. The vehicle owners might response to time-of-use pricing by simply putting the vehicle charger on a timer set to avoid the most expensive time of day. However, there is a weak point in this method which is the utility companies offer little insight into neighborhood congestion levels. As the result, time-of-day, period-ahead, and even real-time pricing would improve system-wide load factor, but are unlikely to have a substantial impact on feeder overloading." [20]

- **Centralized charging control structures**

"In this method, utilities can remotely control charging to mitigate the impacts of EV charging on distribution circuits directly. The exact mechanisms for accomplishing this in ways acceptable to consumers have not yet been fully worked out, but advanced metering infrastructure would help enable such a scheme. In this method requires two-way communication link between the charging station and utility, knowledge of the system state, the number of vehicles requiring charging and state of charge of each of those vehicles. Controlling the charging of EVs may enable them to benefit utility operations by providing ancillary services such as frequency and/or voltage regulation." [20]

"Customer reactions to such a control scheme would be complicated and potentially negative. Implementing it might require a price break for participating customers and a mechanism for overriding the direct control at some cost. The difference demand between PHEVs and BEVs must be carefully consider. PHEVS offer their owners more flexibility of charging time because their fuel-power engine and be more willing to take advantage of lower rates. By comparison, BEV owner may want to keep their batteries fully charged, charging when they have a chance, and therefore may resist method that influence vehicle charging." [20]

5.2 Suitable time consideration

This section is going to explain how to consider the suitable period of time for charging EVs and how to approximate the number of EVs that can be plugged in into the system. To do these, we need to know the daily load profile of an area and power requirement of a single home in that area. The Peak load is the most important information that is use to consider and calculate the suitable time and capability of a system that how many EVs can be connected into the system.

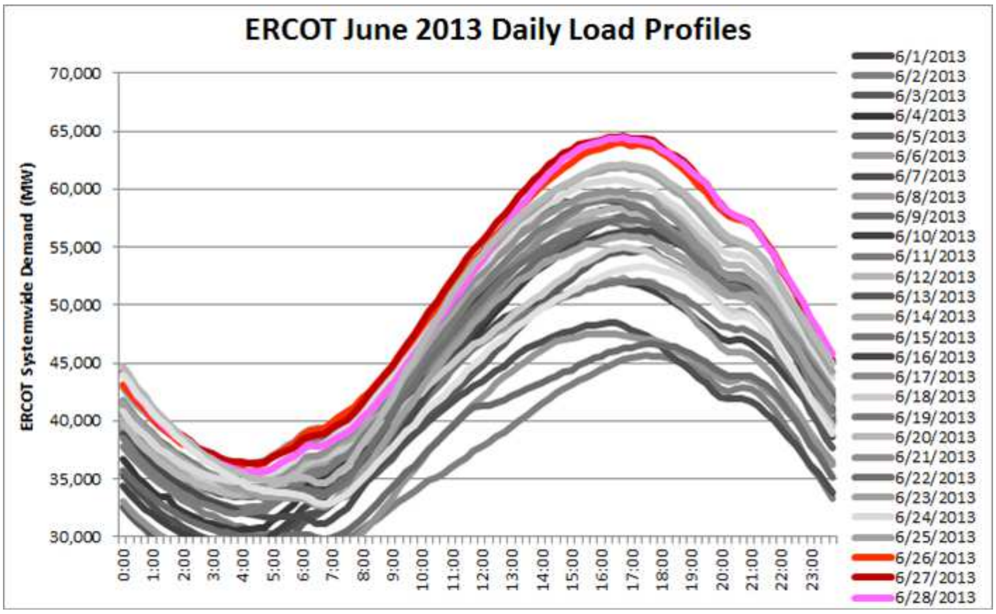


Figure 30. The daily load curve from 1st to 28th June 2013 [24]

According to the figure 30 shows the Electric Reliability Council of Texas (ERCOT). Daily peak loads in June are illustrated in this figure. The peak load of each day occurs at 16.40. This information is useful for utility companies to predict the future peak load and manage the cost for customers. As we know, the cost of energy depends on time of use. For this graph, at 22.00-10.00 will be the low cost rate and at 10.00-22.00 will be the high cost rate. According to the concept of time-different tariffs, EVs should be charge in the off-peak load period then the suitable time for charging is 22.00 to 10.00. The customers will pay the low cost rate if they plug in their EVs in this period.

5.3 The method of harmonic treatment

From the impact on the reliable and the power quality section, the quality of power is degraded because the effect of charging devices. The odd harmonic from the device is injected into the system which deteriorates the power device in the system because the increasing of voltage and current. There are three ways to mitigate this problem. [31]

1. Make the standard of EV charging devices and harmonic management of the nation. Do not allow the non standard EV charging device to the system. [31]

2. Increasing the number of converter to decrease the effect of harmonic in the RMS voltage and current with the high amplitude.[31]

3. Installing filter and dynamic reactive power compensation devices to eliminate harmonic and improve the quality of power in the system. [31]

These three solutions can mitigate the harmonic problem that is generated to the system by EV charging devices. This makes the system have better power quality. Moreover, these methods are able to help us to manage the increasing of EV in the near future. [31]

CHAPTER 6

The simulation of connecting the EV charging device to systems

This section is going to see the result from the simulation which uses Matlab to create the module for the structure and control methods of the charging device. The charging device is connected in a 0.38 kV distribution network system which base on the information in the paper. The charging device can change the alternate current to direct current to charge the EVs. The current harmonic of distribution network will be analyzed and we can get the research result.

6.1 Parameters configuration of the simulation module

The true parameter of charging device is used in this simulation module. I am going to compare the result of two cases which are the system without power electronic device and the system with EV charging device to see the clearly results. The first system, I am going to connect AC voltage 380, 50 Hz to general loads (resisters) to make the system without power electronic device. Figure 31 shows the system without EV charging device. Another system, I am going to connect three phase rectifier (EV charging device) into AC voltage 380, 50 Hz. In this simulation, the battery is replaced by the fixed value of resistor to study the grid harmonic. The final module is established shown in Figure 32.

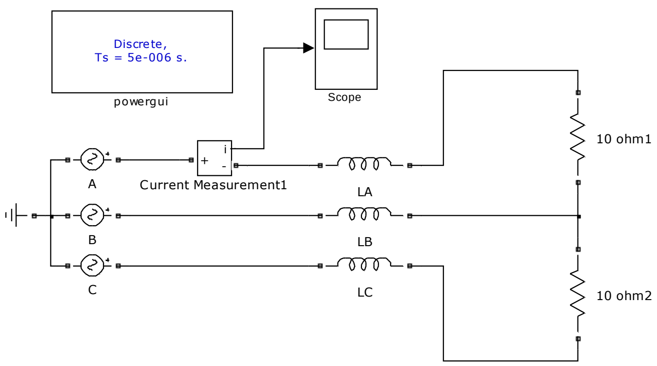


Figure 31. The system without EV charging device

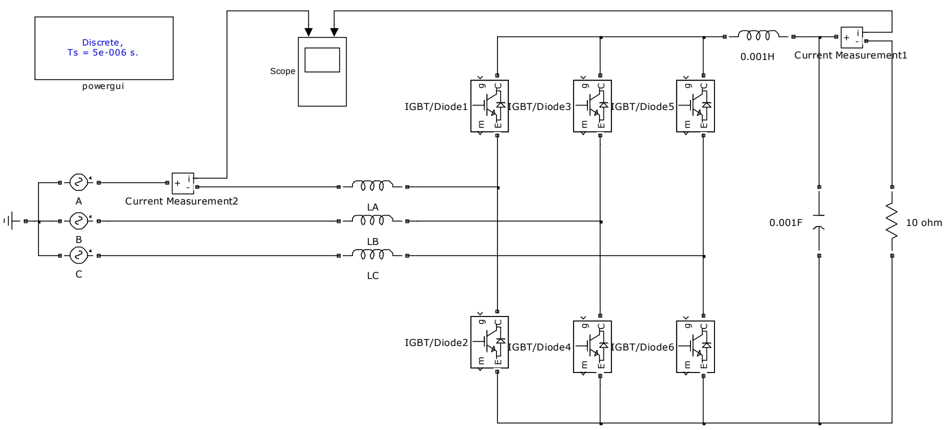


Figure 32. The system with EV charging device

6.2 Analysis of the simulation

The result from the first system is shown in the figure 33. We can see that the current wave from is similar to the sinusoudal waveform. This means there is no harminic in the system.

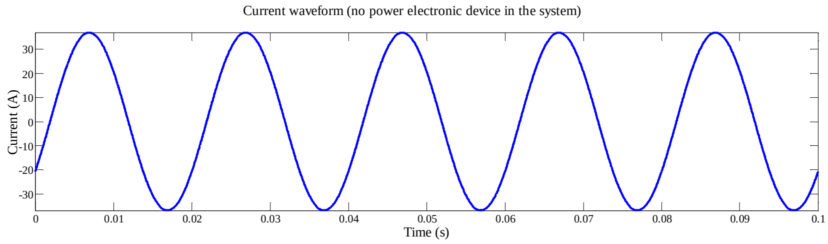


Figure 33. The current waveform of the system without EV charging device

The result from the system with EV charging device is shown in the figure 34. This waveform is different from the sinusoidal waveform. This means there are some harmonic in the system. Then I use FFT analysis from powergui tool in Matlab to see the harmonic spectral. Figure 35 illustrates the harmonic spectral of current waveform. The figure 36 illustrates the detail of harmonic spectral of the input current waveform. The current output in this system is shown in figure 37. At the steady state, the value of the current output is around 35 A.

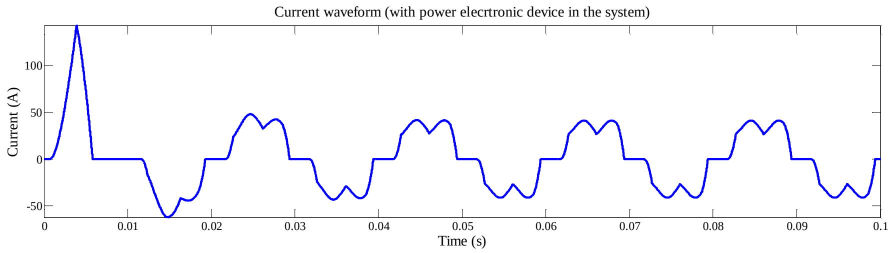


Figure 34. The input current waveform of the system with EV charging device

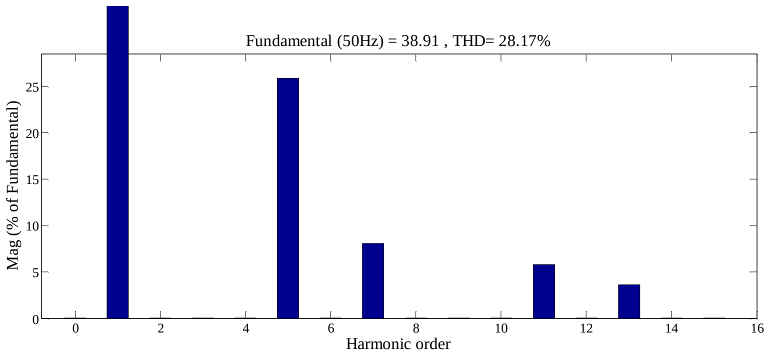


Figure 35. The harmonic spectral of the current waveform of the system with EV charging device

Sampling time = 5e-006 s
Samples per cycle = 4000
DC component = 0.0001035
Fundamental = 38.91 peak (27.51 rms)

Total Harmonic Distortion (THD) = 28.17%

Maximum harmonic frequency
used for THD calculation = 99900.00 Hz (1998th harmonic)

0 Hz (DC):	0.00%	90.0°
50 Hz (Fnd):	100.00%	-15.0°
100 Hz (h2):	0.00%	178.6°
150 Hz (h3):	0.00%	66.2°
200 Hz (h4):	0.00%	-14.2°
250 Hz (h5):	25.88%	95.4°
300 Hz (h6):	0.00%	256.1°
350 Hz (h7):	8.11%	127.9°
400 Hz (h8):	0.00%	176.3°
450 Hz (h9):	0.00%	120.5°
500 Hz (h10):	0.00%	42.1°
550 Hz (h11):	5.80%	203.4°
600 Hz (h12):	0.00%	-45.5°
650 Hz (h13):	3.66%	201.4°
700 Hz (h14):	0.00%	236.1°
750 Hz (h15):	0.00%	184.9°

Figure 36. The value of FFT analysis of input current with the EV charging device in the system

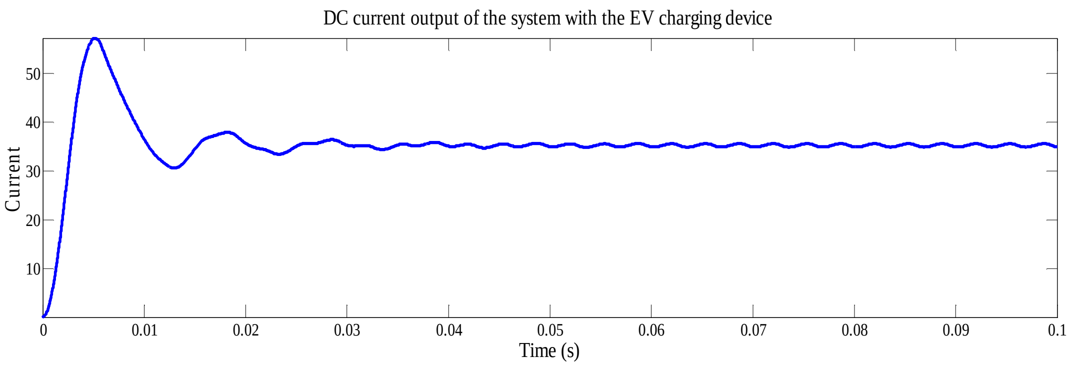


Figure 37. The output current waveform of the system with EV charging device

From the figure 34, the waveform of the current is not the sinusoidal waveform which means the power quality is low. The THD is 28.17%. Odd harmonic such as 5, 7, 11 and 13 which are 25.88%, 8.11%, 5.8% and 3.66% respectively will be added into the system which degrade the power quality of the distribution system and effect the normal operation.

Conclusion

Electric vehicles are one of the crucial solutions that can solve the energy crisis and the greenhouse gas problem because they use green energy (electricity) and produce zero emission. Moreover, the using of batteries to store energy for electric vehicles is able to help the nation to increase the penetration of renewable energy especially wind generations and solar generations in the future. EV can be considered as mobile batteries which are able to be used as shock absorbers to mitigate the fluctuation of those generations which increase reliability and stability in the power distribution system. However, the increasing of EVs could have some negative effects if they are managed and controlled incorrectly. The time of charging EV should be controlled carefully because the load will increase tremendously if they are plugged in at the peak load period. This can lead to voltage dips, service interruption and transformer failure. Moreover, some odd harmonic which is injected into the system degrades quality of power in the system because of the EV charging devices. According the result of the simulation, the odd harmonic that is produced by the charging device are 3^{rd}, 5^{th} and 11^{th} which affect on the current waveform. Then we need standard charging devices to mitigate that problem. In addition, we need to install dynamic reactive power compensation devices and filter devices to improve the ability to reducing harmonic that occur in the system.

Reference

[1] Villafafila-Robles, R. ; Lloret-Gallego, P. ; Heredero-Peris, D. ; Sumper, A. ; Cairo, I. ; Cruz-Zambrano, M. ; Vidal, N. “Electric Vehicles in Power Systems with Distributed Generation: Vehicle to Microgrid (V2M) Project” Electrical Power Quality and Utilisation (EPQU), 2011 11th International Conference on, pp. 1-6, 17-19 Oct. 2011

[2] Pillai, J.R.; Bak-Jensen, B.; , "Impacts of electric vehicle loads on power distribution systems," *Vehicle Power and Propulsion Conference (VPPC), 2010 IEEE* , vol., no., pp.1-6, 1-3 Sept. 2010

[3] Matthias D. Galus, Marek Zima, Goran Andersson, On integration of plug-in hybrid electric vehicles into existing power system structures, Energy Policy, Volume 38, Issue 11, Energy Efficiency Policies and Strategies with regular papers., November 2010, Pages 6736-6745.

[4] Electric vehicle
http://en.wikipedia.org/wiki/Electric_vehicle

[5] Induction Versus DC Brushless Motors
http://www.teslamotors.com/blog/induction-versus-dc-brushless-motors

[6] Hybrid Electric Vehicles, Plug-in Hybrid Electric Vehicles, All Electric Vehicles.
http://www.bls.gov/green/electric_vehicles/

[7] Hybrid Electric, Plug-in Hybrid, Battery Electric.
http://electricdrive.org/index.php?ht=d/Releases/cat_id/27079/pid/9676

[8] Example of PEVs, PHEVs, HEVs in the market.
http://www.hybridcars.com/best-selling-hybrids

[9] Kwo Young, Caisheng Wang, Le Yi Wang, and Kai Strunz: Chapter 2 Electric Vehicle Battery Technologies.
http://pdf.investingx.net/c/chapter-2-electric-vehicle-battery-technologies-w2638/

[10] A guide to Understand Battery Specifications, MIT Electric Vehicle Team, December 2008.
http://web.mit.edu/evt/summary_battery_specifications.pdf

[11] DMC Battery Testing Platform.
http://www.dmcinfo.com/latest-thinking/case-studies/view/projectid/121/hybrid-electric-vehicle-battery-test-system.aspx

[12] Next generation Lithium Ion and Beyond Lithium Ion;
http://bestar.lbl.gov/bli5/files/2012/06/Amine_session3.pdf

[13] Molten salt battery
http://en.wikipedia.org/wiki/Molten_salt_battery

[14] Low temperature molten-salt battery ten times cheaper than lithium ion by 2015
http://nextbigfuture.com/2011/03/low-temperature-molten-salt-battery-ten.html

[15] Supercapacitors Amp Up as an Alternative to Batteries
http://news.nationalgeographic.com/news/energy/2013/08/130821-supercapacitors/

[16] Supercapacitors and Ultracapacitors
http://supercapacitors.org/

[17] PHEV Battery Cost Assessment
http://energy.gov/eere/office-energy-efficiency-renewable-energy

[18] SOME BASIC EV CALCULATIONS
http://www.ev-propulsion.com/EV-calculations.html

[19] U.S. projected electric vehicle, 2010–2050
http://www.rmi.org/RFGraph-US_projected_electric_vehicle_stocks

[20] Chapter 5: The Impact of Distributed Generation and Electric Vehicles
http://mitei.mit.edu/system/files/Electric_Grid_5_Impact_Distributed_Generation_Electric_Vehicles.pdf

[21] Annual Energy Outlook 2013
http://www.eia.gov/forecasts/aeo/index.cfm

[22] Copyright SAE 2011 SAE Charging Configurations and Ratings Terminology
http://www.sae.org/smartgrid/chargingspeeds.pdf

[23] Using Electric Vehicles to Meet Balancing Requirements Associated with Wind Power
http://energyenvironment.pnnl.gov/pdf/PNNL-20501_Renewables_Integration_Report
_Final_7_8_2011.pdf

[24] ERCOT 4CP - June 2013 Review
http://energytariffexperts.com/blog/

[25] How Electric Cars Work
http://auto.howstuffworks.com/electric-car.htm

[26] High efficiency electric machines for EV
http://www.ip-zev.gr/files/teaching/T5-3_High_efficiency_electric_drives.pdf

[27] Motor Characteristics
http://www.micromotcontrols.com/htmls/Motor%20characteristics.html

[28] Brushless DC Motor Guide
http://www.anaheimautomation.com/manuals/

[29] DC motor
http://en.wikipedia.org/wiki/DC_motor

[30] Induction Motor Action
http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/indmot.html

[31] Pengxin, Zhang Zhebo, “ANALYSIS OF ELECTRIC VEHICLES' IMPACT TO THE ELECTRIC GRID” 2012 China International Conference on Electricity Distribution (CICED 2012) Shanghai, 5-6 Sep. 2

[32] Electric vehicle battery
http://en.wikipedia.org/wiki/Electric_vehicle_battery

[33] Clipart pictures https://www.google.com/