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Impact of plug-in electrical cars on energy demand, on power system and on environment

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IMPACT OF PLUG-IN ELECTRICAL CARS ON ENERGY DEMAND, ON POWER SYSTEM AND ON ENVIRONMENT

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
In partial fulfillment of the
Requirements for the degree of
Master of Science in Electrical Engineering

In
The Department of Electrical and Computer Engineering

By
Sital Tiwari
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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The use of an electric vehicle (EV) over a gasoline vehicle (GV) is often portrayed as environment friendly or green movement ignoring how the electricity is produced. EVs get credit for preserving green environment and preventing global warming by minimizing the dependency on oil. Most of the time, these assumptions that favor EV are not well justified. Therefore, proper studies on the impact of electric vehicles on energy demand, on environment and on power system are necessary before reaching to any conclusion. This thesis explores the possibility of energy consumption pattern shift within the different sectors of energy use due to the massive switching of EVs over traditional GVs. In an attempt to find out whether electric vehicles are really efficient over traditional vehicles in terms of energy use as well as emissions, a complete well-to-wheel analysis and estimations of emissions during their use are calculated and compared. Lastly, a survey on the effect due to high penetration of electric vehicle chargers on the residential power grid is presented.

INTRODUCTION

1.1 Background and Motivation

In last few decades, symptoms of climate warming are observed. Emission of carbon dioxide is blamed for that. Among other sources, burning fossils at power plants and gasoline driven cars contributes to this emission. Studies are conducted worldwide on this emission reduction. It appears to be such a serious concern now that it is being addressed by various academic sectors. Also US government formulates plans and policies in order to reduce this emission. There is also a concern that carbon rich fossils are exhaustible resources and these resources are wasted when used for personal transportation. Therefore, replacement of gasoline driven vehicles (GVs) by electrical ones (EVs) might be beneficial both for reducing carbon dioxide emission and for reducing demand for carbon rich fossils.

Assuming that all electric energy is obtained from carbon rich fossils, replacements of GVs by EVs are beneficial only if EVs are more efficient than GVs. To consider EVs to be energy efficient over GVs, energy produced by one gallon of gasoline in a power plant and delivered to EV, should give more miles than GV driven with the same one gallon of gasoline. Electric energy for driving EVs can also be obtained without burning fossils, from nuclear, hydro, wind or solar source. This is an additional advantage of EVs over gasoline driven cars. Assuming that all electric energy is obtained from other sources than carbon rich fossils, they reduce demand for fossils independently on their energy efficiency.

If indeed, the replacement of GVs by EVs would be beneficial for US energy security and economy, a question can be asked, is the US power system capable of supplying such cars?

According to Department of Energy's (DOE) Energy Outlook 2011 report [8], in U.S., around 38% of total energy including both electrical and mechanical is produced from oil, 28% from coal, 21% from natural gas, 6% from nuclear and the remaining 7% by renewable sources. The renewable includes hydro, solar and wind energy, geothermal and ocean wave energy. The major concern about the energy availability is the shortage of natural resources. We do not have an unlimited supply of coal, oil, uranium and natural gases on Earth. Experts from DOE claim that if the energy consumption pattern continues the same, it is assumed that coal consumption will be peaked by 2070 and is expected to last till 2270. Similarly, natural gas and oil are expected to last till 2220 and 2170, respectively [9]. As a possible replacement for these energy sources, majority of researchers [11-29] have given emphasis on renewable and environmental friendly fuels. Much more study and support is needed to meet the standards set by government and international agreements like Kyoto protocol, which is established to stabilize the greenhouse [10]. Being on the list of top ten emitters of greenhouse gases, the United States is not able to ratify the emission treaty of Kyoto protocol. However, in order to facilitate the environmental treaty ratifying process, the United States has promised for more research and scientific studies to support the green technology. The US has identified its dependency on foreign oil as a national security issue. Going for a green technology and developing alternative fuels is very logical for country where transportation is the largest customer of petroleum products [11]. As a result, "Going green" or using green technology by alternative sources of energy have been one of the hottest matter of discussion on energy resources over the last decade. Electrical engineers cannot stay away from the topic. The media and government lobbyists have pushed everybody in this matter so much that no one can stay away from thinking about global warming. Even though, coal and oil productions are heavily blamed for the major cause of global warming, it is very difficult to find a convincing approach that proposes economically practical alternatives for current energy consumption pattern. On one hand, some scientists are advocating for use of the alternative energy fuels whereas on the other hand some believe green technology isn't always "green". It is still debatable if water, wind and solar energy are economically and technically the most effective alternatives to the energy sources. There are still unanswered queries like: Can the renewable help us reduce our dependency on oil and coal? Are the processes involved in them clean and safe to the environment and finally the most important, are they economically practical?

The United States power grid is believed to be underutilized most of the time and is capable of generating and delivering the necessary energy as fuel for about 73% of the U.S light duty vehicles [11]. As an alternative to GV, if the U.S wants to reduce the dependency on petroleum and make a quick switch to biofuels and hydrogen then significant investment in the new fuel production and development of distribution infrastructure in needed. Most of the previous attempts to present the hydrogen fuels as an alternative option to the oil by providing government incentives and tax breaks have failed just because of the lack of economically viable infrastructure to dispense the hydrogen fuel [13]. Research done on fuel cell vehicle showed that it looked less promising that its promoters present it to be and the hybrid electric vehicles' overall efficiency is almost 1.5-2 times to that of fuel cell vehicles [12]. Several researches [11-29] predict that among all the alternatives to gasoline driven vehicles, electric vehicles will rise as a front-runner for competition with better efficiencies and lesser emission. The penetration forecast estimated in these researches [11-29] would make more sense if issues like cost and driving ranges are properly considered.

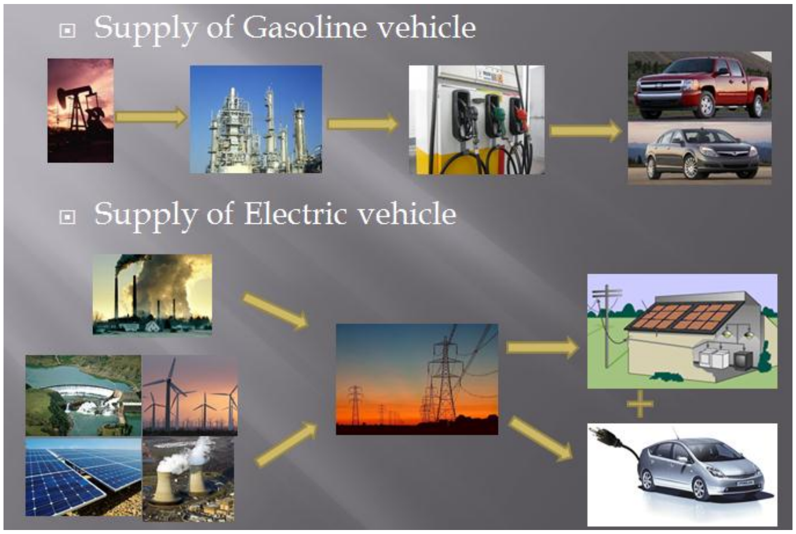

Fig 1.1 Diagram showing supply of GV and EV.

The above diagram shows the different energy flow routes for the case of the gasoline cars and electric cars. Energy comes to the wheel either through the gas refineries or the power plant generation. While comparing the efficiencies of the two vehicles, the whole process of energy flow from well to wheel has to be considered. A method is needed to compare the overall efficiencies before the massive switching from gasoline engines to electric cars occurs. Provided that there are alternative sources of energy, which have relatively less impact on the environment, electricity produced out of such sources would be the cleanest. Considering the fact that about 28% of the total energy produced is used by the transportation sector [8], if we switch the transportation sector to electrically powered state, we will be transferring the burden to the electric utilities without knowing the impact on the power distribution system. Further studies are required to see the effect on the distribution grid because of the increasing number of power electronics chargers of the EVs. If there will be significant voltage and current harmonics produced due to the electric vehicle chargers, they have to be handled appropriately. The possible adverse situations on the distribution grid and equipment have to be studied due to the potential new loads that will feed into the system. Therefore, the impact of electric vehicle charger on the power grid has to be studied along with the impacts on environment and energy demand.

1.2 Objectives

The primary objective of this thesis is evaluation of the effect of transition from GVs to EVs on energy and carbon-rich fossils demand in USA.

This shall be done by evaluating energy efficiency of all energy or fuel delivery components, such as for example, gasoline distribution, electrical transmission and distribution systems as well internal components of EV and energy conversion equipment, such as steam turbine, combustion engine, needed for energy supply for both sorts of cars.

The thesis will also collect data on the sources of energy available in the US. It analyzes the potential impact on energy demand, environment and power distribution due to replacement of GVs by EVs. Driving forces and obstacles for an EV in future market of personal cars are identified in this thesis as well.

CHAPTER 2

ENERGY DEMAND IN THE UNITED STATES

2.1 Total Energy Use

In 2007, the energy per capita per year in the Unites States and the world were 7759 kg and 1819 kg of oil equivalent [8], respectively before the transformation into end-use fuels. The energy use per capita has declined by about 4% for the US whereas; it has gone up by 10% for the world since 2000. Energy demand is expected to sky rocket for the countries that are not included in the Organization for Economic Cooperation and Development (OECD) since these countries will be seeking a rapid economic growth in the next decade. Energy price increase due to high demand in such countries is going to be a driving force for the U.S to find more alternative ways of producing energy and make the energy use process more efficient.

2.2 Energy Consumption by Source

Energy consumption is represented as equivalent energy generated annually by number of power plants of 1000MW capacity generating 8766GWh annually. The fuel sources are classified as nuclear, oil, liquid biofuels, natural gas, coal and renewables.

Table 2.1 Energy consumption by fuel source

Fuel source	Energy Consumed in 2009 [8]	Projection in 2035[8]
Coal	668 power plants equivalent	835 power plants equivalent
Fossil liquid and biofuel	1237 power plants equivalent	1404 power plants equivalent
Total	3143 power plants equivalent	3811 power plants equivalent

Due to the federal and state regulations for use of renewables in electricity generation, the energy generated due to them are projected to increase and contribute about 10% of energy consumed in 2035.

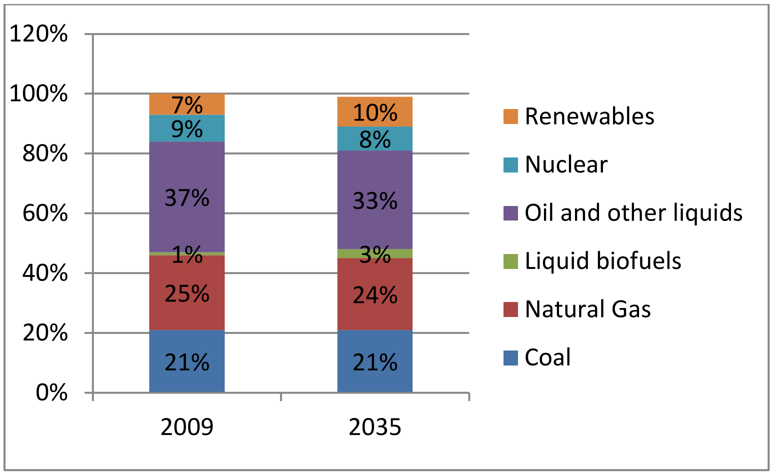

Fig 2.1 Energy consumption in the U.S [8].

The above figure with the history and projections of primary energy consumption is adopted from the Annual Energy Outlook 2011 from U.S Energy Information Administration [8]. The energy consumption based on type of fuel has been pretty stable in recent years and is projected to remain similar in near future. The current trend on energy use is not much different from how it is going to be in the future because petroleum products, coal and natural gas are still on the top as major energy producers.

2.3 Electricity Consumption by Source

In 2009, the total of 3745 billion kilowatt-hours of electricity was consumed in the U.S and current projection for 2035 is about 4880 billion kilowatt-hours with an increasing rate of 1% per year. In the U.S., Electricity generation sources in 2009 were as follows:

Table 2.2 Electricity generation sources in the U.S in 2009

Generation Sources	Percentage Generated
Coal	45%
Natural gas	23%
Nuclear	20%
Petroleum	1.0%
Renewable and Others	10%

Also the future projections for the generation sources are provided by the following graph.

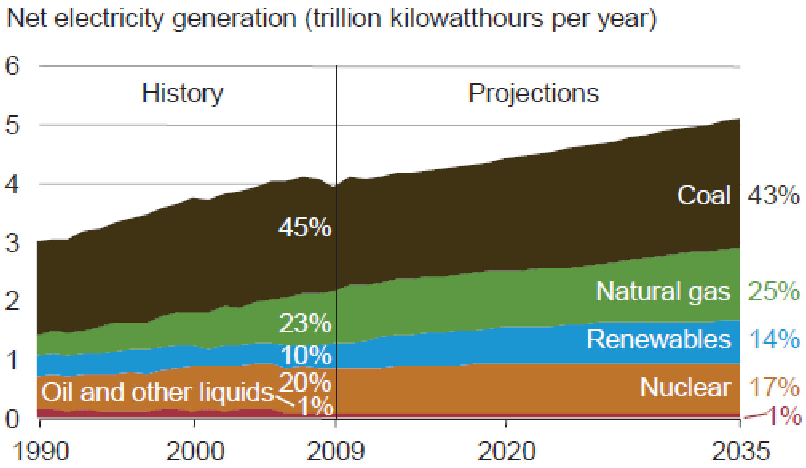

Fig. 2.2 Electricity generation in the U.S by source

The figure above is also adopted from Annual Energy Outlook 2011 Early Release Overview, U.S Energy Information Administration [8]. It seems like there would not be any significant change in terms of the energy source within 25 years from now. Coal being the cheapest and most abundant resource in nature still sits on the top, responsible for 43% of the total electric energy generation. Renewables including hydro are projected to be making 14% of the total generation. Nuclear power is considered one of the least carbon emission methods; however, it is surprising to see the projection declining for the nuclear plant. This risk of serious accident in nuclear plants causing tremendous damage to the human being and environment might be the reason why the projection for nuclear energy is declining.

The U.S electricity production capacity in 2010 is about 3992 billion kilowatt-hours which is the largest electric energy producer in the world. The electric infrastructures are designed to meet the full demand of power in the grid and the energy generated is normally very underutilized most of the time. The power system capability is used to the maximum only several hundred hours a year. It is estimated that on an average, the power system grid can power almost 73% of light duty vehicles like cars, sport utility vehicles, pickup trucks and vans assuming the driving distance per day to be 33 miles [11]. This is under the assumption that the power providers are running the generation at full capacity for 24 hours. The technical potential of powering the vehicles falls to an average of 43% of the light duty vehicles if they are only allowed to charge 12 hours a day at night [11].

2.4 Energy Consumption by Sector/Group

The DOE have classified the total energy consumption into four economic sectors: Transportation, industrial, residential and commercial.

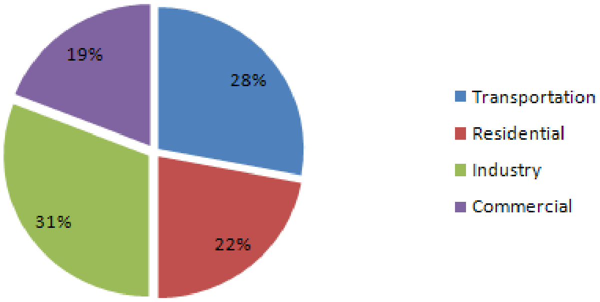

Fig 2.3 Total energy consumption by sector

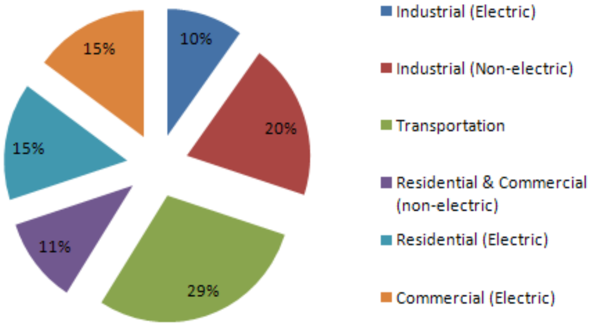

Fig 2.4 Total energy consumption by sector with electric and non-electric categories

The present situation of energy use is distributed as shown in the figure 2.3 and 2.4. The industrial and transportation sectors are two huge consumers for the net energy generated in the country. The transportation sector comprises all the vehicles and aircrafts which use gasoline, diesel, flex-fuel or electricity. The industrial sector consists of all the manufacturing industries. Residential consumption includes all the electric appliances used in house. Switching from traditional gasoline cars into EV is going to have an effect on this sector heavily. From this energy consumption data, we see that transportation sector is using almost one third of the total energy produced in the country. Replacing GV by EV is going to shift the energy consumption pattern from transportation sector to residential sector.

CHAPTER 3

COMPARISION OF ENERGY DEMAND BY GVs AND EVs

Electric vehicles (EVs), fuel cell vehicles (FCVs) and Hybrid Electric vehicles (HEVs) are often advertised to have higher overall efficiencies in compare to the traditional gasoline vehicles (GVs). This chapter compares the energy demand by GVs and EVs with the comparison of energy flow from the source to the vehicle. It calculates the actual amount of energy needed at the generation of electricity or gasoline in order to produce equal amount of Energy ($\boldsymbol{W_m}$) available for driving for EV and GV. It is also assumed that the same gasoline is used for driving a GV and operating steam turbine in a power plant for electricity used for EV.

3.1 Efficiency Comparison of Vehicles with Different Fuel Types

Well-to-wheel efficiency analysis will include the efficiencies for production of fuel or electricity and its use during the vehicle operation. It accounts for all the losses of energy during production and its transmission to the tank of the vehicle in the form of fuel or electricity. The efficiency analysis accounts for all the losses during the vehicle operation stage and the actual amount of energy that is useful at the wheels. The energy utilized by GVs or EVs after it gets to the shaft is similar. So the efficiency analysis from well to shaft of the motor is sufficient to compare the total efficiency of EV and GV. The efficiencies on each step of energy transfer points are gathered from various sources and the mean value as well as the worst case values on efficiencies are used to calculate the overall efficiency.

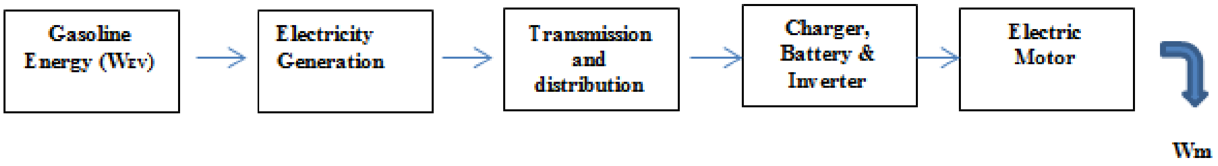

Fig 3.1. An EV well-to-wheel efficiency analysis stages

The above schematic 3.1 shows the path of energy flow in case of an EV. It is assumed that the shaft of the electric motor utilizes $\boldsymbol{W_m}$ energy and rest of the electric energy is lost during generation, transmission, distribution, charging process and in the electric motor operation process. Once, the efficiencies of all the elements on the path of the schematic are known, the input energy needed can be calculated. The calculation is shown in section 3.6. Similar analysis will be performed on GV and the two values will be compared.

3.2 Efficiency in Power Grid

This will involve the estimation of production of electric energy from the generation and the energy losses and distributed over the grid to the residential and industrial uses. When the energy used by gasoline cars and plug-in cars are to be compared, the power grid efficiency plays a major role. The availability and feasibility of the sources of power generation makes it even more critical. The grid efficiency has a direct impact on economy and environmental concerns. The power grid efficiency will be critical for the overall efficiency of an EV as the losses over the generation; transmission and distribution are going to carry along with the EV efficiency itself.

3.2.1 Efficiency of Electricity Generation

During generation the latent energy from sources like coal, gas, uranium or renewables are converted into mechanical energy and finally to electrical energy. The efficiency of the heat-to-mechanical energy conversion is dictated by Carnot cycle. The temperatures at the hot (T_H) and cold (T_C) reservoirs determine the efficiency of Carnot cycle (η_C). According to [42], (T_H)= 538 [°C] = 811 [°K] and (T_C)= 43[°C]= 326 [°K]. The efficiency of Carnot cycle is defined as

$$\eta_C = 1 - \frac{T_C}{T_H} = 0.61.$$

Hence, the theoretical upper limit of the steam turbine efficiency is about 60% obtained from the values provided by [42]. But according to other references [1] and [21] indicate that in a typical power plant, only about one-third of the original fuel is converted into electricity and the rest is wasted in heat. Fossil fueled power plants like coal plants, petroleum-fired plants and natural gas-fired plants have efficiencies about 30-35% [21] and the improved plant with integrated gasification combined cycle (IGCC) can have maximum up to 60% in which the wasted heat is captured to produce additional kWh of electricity [3]. The thermal efficiencies for nuclear plants are about the same as the petroleum or natural gas-fired plants but the energy density for nuclear fuels are much higher than crude oil or natural gas.

Energy density is defined as the kWh electricity produced from 1kg or liter of the raw material in a power plant. The renewable power generation like solar, wind and hydro, the efficiency would not make a bigger case since they are inexhaustible and free. The projection made by DOE till 2035 shows that coal is still going to be the dominant electric energy source and hence the entire generation efficiency is mostly affected by the efficiency of the coal fired power plants.

3.2.2 Efficiency of Transmission and Distribution (T&D)

This deals with the losses of energy between generation plants to the end users. Energy supplied from the generation can be lost in the T&D due to the resistances of wires or the equipment through which the electricity is passed. The figure below shows the actual T&D losses in the US from the year 2001 to 2005. According to report from DOE [3], about 6-7% of electric energy is lost in transmission and distribution. Another research [37] reports that the average efficiency of power transmission and distribution is about 93% due to ohmic losses.

The credibility of these values is not very high considering the fact that there are about three transmission transformer and one distribution transformer between the generation and the end users [4]. On an average efficiency of synchronous generator is about 98%, transmission transformer is about 99%, transmission line is about 98%, distribution transformer is about 98% and the feeder line is about 98%. The aggregate efficiency of all these values will be around $84\%(0.98 \times 0.99^3 \times 0.96^2 \times 0.98 \times 0.98)$.

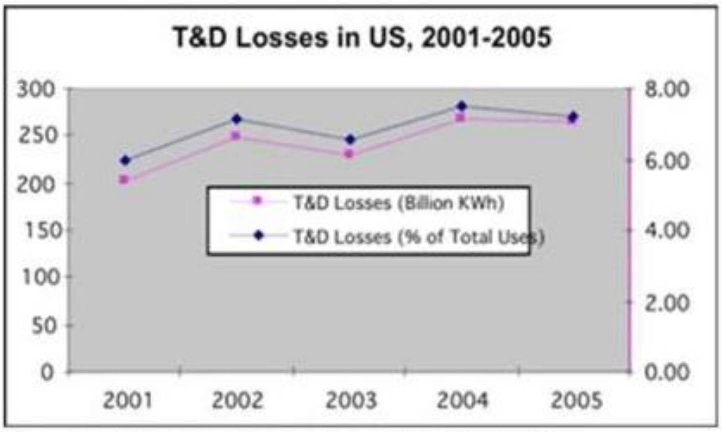

Fig. 3.2. T&D losses in power grid (% of generated energy) [3]

3.3. Efficiency of EV Charger

Most of the EV chargers are based on pulse width modulated (PWM) rectifiers. In PWM rectifier circuit, the power transistors are switched in much higher frequencies than the line frequency for the power factor correction [31]. The loss of energy in a transistor is very high when it crosses an active region twice during switching period. Therefore, some electric energy is expected to be lost in form of heat in the battery charge circuit components during the battery charging process. An experiment for measurements [36] of efficiency of EV battery charger indicated that the efficiency is about 94% with an EV battery of 144V charged on 220V AC supply. The 220VAC was rectified and then converted to the necessary voltage suitable for the battery in the experiment performed in [36]. The EV battery charger efficiencies according to other sources [13, 35] are about 92% and 94%. However, according to Rutherford in [17], the efficiency of PWM rectifier is limited to 85% because of the high frequency switching of the power transistors and it crosses the active region twice and therefore increasing the loss of energy in the transistor.

3.4 Efficiency of EV Battery

Energy is lost during both charging and discharging of the battery due to its internal resistance(R_i). The energy loss (I^2R_i) on the battery depends on the charging and discharging current. While a driving mode for an EV, this value changes with different driving conditions. Battery manufacturers typically publish the resistance data as AC impedance measured at 1 kHz for a new battery [42]. To obtain a reasonable value for actual internal resistance in order to get the effective efficiency of the battery is not an easy task. Several research paper reports that it is expected that the internal resistance increase with the declining SOC of the battery [38-42]. Due to the increase in battery internal resistance, the discharge time is shortened as well as the power loss increases [40]. Among various rechargeable batteries, Lithium-ion batteries are chosen for EVs because of their higher energy density and stable internal resistance [38-40]. The experiment conducted in [40] discovers that the Ohmic internal resistance of lithium-ion battery is close to constant with the range of SOC from 30% to 80%.

The EV batteries efficiency measurement results [41] indicated that the overall input-output energy efficiency over the SOC of 20%-100% is about 91-98% at different trials. This efficiency includes the battery efficiency during both charging and discharging. It also indicated that the input-output efficiencies of the lithium-ion cells are typically 94% over full 100% discharge for new cells. The calorimetric efficiency measurements of lithium-ion batteries in

[39] indicated that the efficiency is about 94-95% with the SOC kept constant at 70% and the charging current was altered. However, the experiment was conducted with test current of 120A and the result calculated was about 90%. Carrying the same experiment with lower current of 90A yielded a battery efficiency of 92% [39]. This efficiency for an EV battery will be higher because of the fact that the current levels are much lower compared to the experimental currents used in [39].

3.5 Efficiency of DC/AC Inverter

The DC/AC inverter is needed to convert the stored DC voltage from the battery to 3-phase variable frequency voltage for the electric motor to operate. These inverters are of PWM type, build of power transistors and switched at frequency of several kHz. Thus, the efficiency of the inverter is comparable to that of battery chargers of the value around 85%.

3.6 Efficiency of EV Motor

The electric motor used in EV can be brush DC motor, induction motor or synchronous motors like brushless DC motor. Brushless DC motors are preferred due to the size and weight reduction [38]. The efficiency on EV motor can vary according to the running speed and ranges from 90-93% and go up to 95% in case of high driving voltage due to less power losses [38]. So the efficiency of an EV motor will depend on the specified driving voltage and running speed. On an average, EV motor efficiency will be about 91%.

Table 3.1. Overall efficiency for an EV

Efficiency of	**Average values from various sources (%)**
Electricity Generation (η_G)	35
Transmission and Distribution (η_{TD})	84
EV Charger (η_C)	85
EV Battery (η_B)	94
DC/AC inverter (η_{IN})	85
EV motor (η_M)	91

The resultant efficiency of EV is the product of efficiencies of all the subsystems. Therefore, energy required at the generation when $\boldsymbol{W_m}$ is available for driving is:

$$\frac{W_m}{(0.35 \times 0.84 \times 0.94 \times 0.85 \times 0.85 \times 0.91)} = \frac{W_m}{0.18} = \mathbf{5.5} \times \boldsymbol{W_m} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{1})$$

Therefore, ~ $\mathbf{5.5} \times \boldsymbol{W_m}$ energy is required at the power plant in order to produce $\boldsymbol{W_m}$ energy available for driving for EV.

3.7 GV Efficiency:

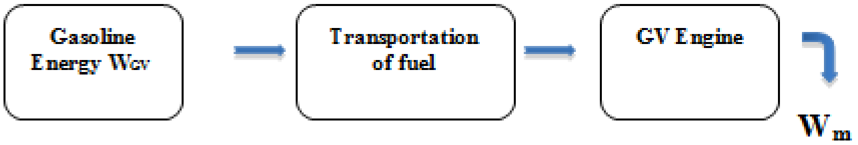

Fig 3.3. A GV well-to-wheel efficiency analysis stages

The above schematic 3.3 shows the path of energy flow in case of a GV. It is also assumed that GV also utilizes $\boldsymbol{W_m}$ amount of energy for driving. In GV's case, energy is lost during transportation of fuel and in engine during conversion of heat energy to mechanical energy. Gasoline produced at the refinery has to be transported to the fuel dispensers and it is assumed that only about 95% of the total produced gasoline is available for the GVs due to losses in transportation and distribution [13]. The efficiency of the engine is the ratio of the heat converted into mechanical work to the total heat that enters the engine. It depends on the initial and final temperature of the medium. The greater the range is the better the efficiency will be. Typically the actual amount if heat converted to mechanical energy in the internal combustion engine in GVs is about 23% and the rest of the heat lost to the circulating water, exhaust gases, radiation and conduction [32]. According to [33-34], the thermal efficiency of the engine varies with the horse power of the engine. However, the typical value of efficiency is close to 25% for the engine with capacity of 20HP and higher. The efficiency also depends on the engine speed as well the fuel to air ratio [32-34] but is about 20% for an internal combustion engine. Mitsubishi reports that the efficiency range for passenger cars with internal combustion engine is about 23-24% depending on the size of the engine. The total input energy required at the generation of gasoline for GVs is:

Table 3.2. Overall efficiency for a GV

Efficiency of	**Average values from various sources (%)**
Transportation and Distribution (η_{TD})	95
IC engine (η_{GV})	16

The resultant efficiency of GV is the product of efficiencies of all the subsystems. Therefore, energy required at the generation when $\boldsymbol{W_m}$ is available for driving is:

$$\frac{W_m}{(0.95 \times 0.16)} = \frac{W_m}{0.15} = \mathbf{6.6} \times \boldsymbol{W_m} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{2})$$

Therefore, ~ $\mathbf{6.6 \times W_m}$ energy is required at the power plant in order to produce $\mathbf{W_m}$ energy available for driving for GV.

From (1) & (2), the ratio of energy required at the generation in case of EV to that of GV is:

$$\frac{Energy\ needed\ in\ EV\ (EV_e)}{Energy\ needed\ in\ GV\ (GV_e)} = \frac{\mathbf{5.5 \times W_m}}{\mathbf{6.6 \times W_m}} = \mathbf{0.84}$$

$$\boldsymbol{EV_e = 0.84 \times GV_e} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{3})$$

From, (**3**) it is apparent that the carbon that will be burnt in case of use of a GV will be ~1.2times more than in case of EV. The results above show that in terms of energy use, a traditional GV utilizes more energy than an EV for equal amount of work done at the shaft. But majority of electricity in the US is produced from fossil fuels and hence having better efficiency of energy use in case of EV still is not going to help reduce the exhaustible fuel resources. In addition to that EV can only be environment friendly when majority of electricity generation is done by renewable sources like solar, wind and water. However, the cost of electricity generation from renewable sources would be more expensive than the tradition sources. The efficiency of converting the renewable to electricity is irrelevant to the calculation since they are free and inexhaustible.

3.8 Cost of 1kWh of Electricity from Various Sources

The costs of the original (wind, solar, water, oil, radioactive or coal) energy are substantially different. So it does not make sense to compare only the mechanical efficiency of different types of power plants. It will be clearer if we can find out the total cost in delivering the power with different sources of energy. For instance, the cost of 1kWh of electricity produced from coal plant and nuclear plant are calculated for comparison.

3.8.1 Cost of 1kWh of Electricity from Coal

Energy density of coal= 6.67 kWh/kg

Efficiency of coal-fired power plant = 30%

Actual energy from 1kg of coal after generation process = 2kWh.

Coal cost per ton or 1000kg = $145

Cost of 0.5kg of coal = $0.07

Hence, 7cents/1kWh is the cost of producing 1kWh of electricity from coal.

3.8.2 Cost of 1kWh of Electricity from Nuclear [23]

Energy density of natural uranium = 45,000 MW-day/tonne = 1,080,000 kWh/kg

Efficiency of nuclear plant = 35%

Actual energy from 1kg of natural uranium = 378,000kWh

Amount of natural uranium needed for 1kWh of electricity = 2.64×10^{-6} kg

Cost of natural uranium per kg = $2769

Cost of 1.1×10^{-7} kg = 0.7 cents/kWh.

Hence 0.7 cents/1kWh is the cost of producing 1kwh of electricity from nuclear plant.

3.9 Driving Force for EV Use

In 1978, DOE developed a method to calculate Corporate Average Fuel Economy (CAFE), which included the EVs [7]. CAFE is based on the harmonic mean, not the arithmetic average of the fuel economies of the vehicles in the corporate fleet (vehicles of same manufacturer) [7]. Harmonic mean is a type of average typically used when the mean of the rates is desired. Fuel economy is the distance travelled by a vehicle per unit of fuel used. CAFE is regulated by the government of the U.S and is set to certain target value every year. In a fleet of 3 different kinds of vehicles produced in numbers X, Y and Z with fuel economies FE_X, FE_Y and FE_Z respectively. Then, CAFE is defined as:

$$CAFE = \frac{X + Y + Z}{\frac{X}{FE_X} + \frac{Y}{FE_Y} + \frac{Z}{FE_Z}}$$

A manufacturer will see an overall boost in the CAFE just by one vehicle in a fleet with excellent fuel economy and hence allows the manufacturer to sell more vehicles in the same fleet with poor fuel economies.

Government controls the value for CAFÉ for the auto manufacturers. Government always tries to increase the CAFÉ mark because energy conservation is for the national interest. Auto-manufacturers can easily manipulate the CAFÉ value by producing some EVs in a fleet.

3.10 Obstacles for EV Use

It is important from a national perspective to reduce demand for energy and carbon-rich fossils as well as carbon dioxide emissions. However, from a user perspective, unless the price of EV is low, cost of energy (gasoline or electric) is low and there is convenience in using an EV, it might not be practical for a user to switch to EV from GV.

Presently, the driving range per charge for EV's are limited to 73 miles for Nissan leaf, 80 miles for Ford Electric and 100 miles for Mitsubishi MiEV. The effective mileage for these cars would really be half of values provided as the car needs to return back to home for another recharge. Charging infrastructures are not readily available everywhere like gasoline stations. Such an inconvenience can substantially reduce an interest for a user to buy an EV for daily transportation. The cost of EVs in present market is comparatively higher than other equally sized GVs and therefore is another obstacle for an EV to compete with GV.

CHAPTER 4

COMPARISION OF ENVIRONMENTAL EFFECT DUE TO VEHICLES OF DIFFERENT FUEL TYPE

Another aspect of comparison for the two types of vehicles is the environmental effect due to their use. This section of thesis compiles the data on emission caused in the process of fuel production and its' use. All the data is based on the report by Environmental Protective Agency (EPA) that summarizes the greenhouse gas emissions from 1990 to 2009. For GV, the emission during the fuel production mostly petroleum and natural gases have to be studied. Also, the emissions occurring during the vehicle operation has to be studied. In case of EV, different sources of electricity production and caused emissions have to be identified. EVs are considered clean with zero or very less emission during operation; however, there are issues with the battery disposal and effects to the environment. This section of thesis records the emissions reported in the year 2009 which is the latest report by EPA. More emphasis is given on the emission due to the transportation sector and electricity generation process in this thesis. Massive use of EVs in the future is going to shift the emission source from transportation sector to electricity generation sector because of the increased demand for electricity.

Emission is measured in units of teragrams (T_g) or million metric tons carbon dioxides equivalents. The total emissions of carbon dioxide from fossil fuels in 2009 due to electricity generation and transportation sectors were 2154 and 1724.1 T_g respectively. These figures are equivalent to 33% and 44% of co_2 emissions from fossil fuels for transportation sector and electricity generation respectively. This is really important to understand that electricity generation sector is already more responsible for more co_2 emissions. We can assume that this will go even worse when there is more demand for the electricity.

4.1 Green House Gases (GHG)

Earth's atmosphere naturally contains some chemical compounds that absorb the infrared radiation reflected from the earth's surface and help maintain the temperature of the earth's surface known as "greenhouse gases" (GHG). The naturally occurring GHG are water vapor, carbon dioxide (Co_2), methane (CH_4), nitrous oxide (N_2o) and halogens containing chlorine, bromine, fluorine, chlorofluorocarbons (CFC) and hydro chlorofluorocarbons (HCFC).There are also other indirect Greenhouse gases (IGHGs) like carbon monoxide (CO), oxides of nitrogen (No_x), non-methane volatile organic compounds (NMVOC) and sulfur dioxide (So_2). These gases have indirect effect on environment as they change the radiation absorption characteristics of the atmosphere.

After industrial revolution in the US, human beings also produce these gases during fossil fuel combustion and several other industrial processes and hence causing the natural GHG levels to rise. As discussed in chapter 2, majority of energy consumption in the US is produced from coal, petroleum and natural gases which are the primary cause of anthropogenic flux of emissions to the atmosphere. Emissions of GHG are proportional to the production of energy from these major sources.

4.2 Green House Effect

The solar energy that is absorbed by the surface of earth has to be reflected back to the space somehow as thermal radiation. This radiation is absorbed by atmosphere including GHG and reradiate back to earth. This process is defined as Green House effect which is also the reason for keeping the earth's surface warm. Some scientists believe with the increase in GHG emissions, the greenhouse effect is going to intensify and lead to "global warming" which simply means increase in the earth's surface temperature.

4.3 Sources of GHG

This chapter of thesis is more focused on the anthropogenic emissions of GHG rather than the naturally occurring ones as they are the difference maker for the impact in our environment. This section of thesis only presents the manmade GHG emissions when gasoline and electric vehicles are used. The electricity generation process and transportation sector are responsible for generation of GHGs like Co_2, CH_4, N_2o, SF6, No_x, CO and So_2. The table below shows the GHG emission produced during generation of electricity and petroleum products and their use.

Table 4.1 GHG emissions due to electricity generation and petroleum products and their use.

GHG	Source	Percentage of total emission
Co_2	Fossil fuel burn, natural gas system, coal mines	83%
CH_4	Natural gas systems, coal mines	10%
N_2o	Not significantly from fossil fuel burning	4.5%
Sf_6	Electrical transmission & Distribution	0.5%
CO	Fossil fuel burn, oil & gas activities	2%
No_x	Fossil fuel burn, oil & gas activities	0.3%
NMVOC	Fossil fuel burn, oil & gas activities	0.2%
So_2	Fossil fuel burn, oil & gas activities	0.3%

4.4 Environmental Impact of GVs

The total emissions due to the operation of GV will be recorded in this section. This will include reports on emissions during the fuel production and its use. The total emission due to transportation sector in the U. S is about 1812.4 T_g of Co_2 equivalent which about 27.3% of total emissions reported.

4.4.1 Emission During Duel Production for GVs

According to the U.S Energy Information Administration almost 96% of the vehicle on the road runs on petroleum fuels and about 3% on natural gas. The petroleum products and natural gas are basically responsible for only Co_2 and CH_4 emissions. In 2009, total emissions of Co_2 and CH_4 reported were 5505.2 and 686.3 T_g of Co_2 equivalent respectively. The total emissions including every sector were 6633.2 T_g of Co_2 eq.

Table 4.2 Emission during petroleum and natural gas production for GVs

GHG Emission	Fuel Production	Emission by GV (T_g of Co_2 eq.)	Total emissions (T_g of Co_2 eq)	% of Co_2 or CH_4 emission	% of total emission
Co_2	Petroleum	2.7	5505.2 of Co_2 emission	0.05%	0.04%
Co_2	Natural gas	32.2	5505.2 of Co_2 emission	0.6%	0.5%
CH_4	Petroleum	30.9	683.3 of CH_4 emission	4.5%	0.07%
CH_4	Natural gas	212.2	683.3 of CH_4 emission	31%	3.1%

4.4.2 Emission During Fuel Use of GVs

The following table records emissions of GHG during fuel use in case of GVs.

Table 4.3 Emission of GHG during fuel use of GVs

GHG Emission	Emission by GV (T_g of Co_2 eq.)	Total emissions (T_g of Co_2 eq.)	% of type of emission	% of total emission
Co_2	1719.7	5505.2 of Co_2 emission	31.2%	26%
CH_4	2.0	686.3 of CH_4 emission	0.3%	0.03%
N_2o	23.9	295.6 of N_2o emission	8%	0.36%

The following table records emission of IGHG during fuel use in case of GVs

Table 4.4 Emission of IGHG during fuel use of GVs

IGHG Emission	Emission by GV {G_g (Giga gram) of Co_2 eq.}	Total emissions (G_g of Co_2 eq.)	% of type of emission	% of total emission
No_x	6206	11468	54%	0.9%
CO	43355	51452	84%	0.65%
NMVOC	41.51	9313	0.4%	~0%
So_2	455	8599	5.3%	0.07%

4.5. Emissions During Generation of Electricity

The total emissions occurred during generation of electricity and use of an EV will be recorded in this section. The total emission due to transportation sector in the U. S is about 2193 T_g of Co_2 equivalent which about 39% of total emissions reported.

The following table records emissions of GHG during generation of electricity.

Table 4.5 Emission of GHG during generation of electricity

GHG Emission	Emission (T_g of Co_2 eq.)	Total emissions (T_g of Co_2 eq.)	% of type of emission	% of total emission
Co_2	2154.0	5505.2 of Co_2 emission	39.1%	32.4%
CH_4	292.2	686.3 of CH_4 emission	42.5%	4.4%
SF_6	12.8	14.9 of SF_6 emission	85%	0.19%

4.6 Environmental Impact due to EVs

It is reported in [22] that the impact of EV on transportation sector increases by 13.4% if the electricity is produced by coal and decreases by 40.2% if the electricity is produced by hydro power plants. The weight of the vehicle is a big issue for the efficiency of an EV as the higher rated batteries are heavier. Lithium is the lightest of all metals and possesses high energy density characteristics. Therefore, it is assumed that Lithium-Ion (Li-Ion) batteries would be the choice for majorities of EVs in future. According to [22], Li-ion battery does not contribute significantly to the environmental burden because the impact caused by the extraction of lithium for the battery manufacture is very minimal. However, research shows that other nickel and lead based batteries are toxic to human and disposal of these batteries might be a huge issue in the future.

4.7 Emission Comparison in GVs and EVs

The data of emissions discussed in this chapter indicated that the increase in EV use increases the GHF emission when coal is the primary source of electricity production. Even though GHG emission due to GV operation is higher than that of EV, the emission during the fuel production is much lower for GV. In other words, the electricity generation process being responsible for majority of the Co_2 production, it is not helping EV to become environmentally friendly. So replacing GVs by EVs in near future would not be a solution unless electricity is generated from other cleaner sources or non-fossil fuels. In addition to that we cannot ignore the fact that EV batteries also add more burden to the environment when disposed.

CHAPTER 5

IMPACT OF THE PLUG-IN EV BATTERY CHARGER ON THE POWER GRID

5.1 EV Trend

The first EV was reported in 1873 which was almost 12 years before the gasoline internal combustion engine vehicles actually came out when the scarcity of oil resources, the prices and the environmental impacts were not a concern [30]. Since gasoline-powered engines were more promising in terms of efficiency and performance; the development of EVs was almost forgotten from 1930’s to 50’s [30]. Nowadays, EVs are often advertised as an alternative to reduce dependency on fossil fuels and soaring oil prices. While analyzing the efficiency of energy use in chapter 3, it was concluded that the EVs have an advantage over GV in terms of energy use. However, EV would be considered the cleanest only when electric energy is not produced by burning fossils. Therefore, benefits of switching from GVs to EVs may depend on the progress in switching of electric energy production from those based on fossils burning to other sources.

A research [11] reports that the US current power plants can provide enough electricity to the EVs if 84% of total current vehicles were running on electricity. Also, only 8% increase in electricity generation is required for fulfilling the energy demand if half of the current gasoline vehicles are converted to electric powered vehicles [11]. But this research does not consider the fact that charging station development would be necessary for EV charging stations for fast charging and also the new loads (EV batteries) on the grid would impact on the grid capacity and design. Smart grid concept also reports that EV batteries can help in peak shifting and supply backup power to the grid when not in use defined as Vehicle to Grid (V2G) strategy [11]. This is highly impractical and questionable since the two-way energy flow requires bi-directional converters, which are very expensive to build. The EVs that are charged during the nighttime will not be available for providing energy to the grid during the daytime.

5.2 EV Penetration Forecast

In order to properly study the impact of the EVs on the grid, it is important to understand the driving forces for promotion of EVs in the market. Several studies [14, 15] have provided the EV penetration and usage forecast. An initial assumption of EV in the selected region was 3700 when the total number of EV coming out in 2011 from the major automobile industries was 100,000. These studies make their forecast prediction on the basis of government incentives provided for the EV development. If EVs can compete with the GVs without the government incentives and tax breaks, the penetration forecast will make more sense. The penetration of EV in future solely depends on the government energy policy. From a government perspective, in order to reduce dependency on oil and control GHG emissions, the energy policy is expected to favor on EV use over the GV. But from the general public or user perspective, EVs are not expected to be economically viable.

Government policy on EV promotion is expected to continuously rise because of its commitment to reduce dependency on oil and reduce GHG emissions. Another major force for increase in EV would be the compulsion of maintaining the Corporate Average Fuel Economy (CAFE) for all auto manufacturers. As a law, the auto manufacturers in the US are required to maintain a certain average fuel economy for the fleet of vehicles manufactured every year. This will be a major driving force for auto manufacturers to continuously produce more energy efficient vehicles.

5.3 EV Batteries

The most commonly used rechargeable batteries are lithium-ion. These batteries are advantageous over other batteries when they are used in EV because of their high energy densities. However, these batteries are expensive to build and require protection circuit in order to maintain current and voltage within safe limits. [26]. The following paragraph explains some battery technical specifications.

5.3.1 Nominal Energy

It is the total Watts-hours (Wh) available when the battery is discharged at a certain discharge rate from its' maximum voltage to the cut-off voltage. The discharge rate depends on the type of the battery. Cut-off voltage is the minimum allowable voltage for the battery and in general means the empty state of the battery. Currently available Battery capacities in the market are 54kWh, 24kWh for Tesla Roadster and Nissan Leaf respectively. Similarly, GM Chevrolet Volt and Mitsubishi i-MiEV have 16kWh batteries on it [16]. The price of the electric car is proportional to the cost of the battery and its performance.

5.3.2 Specific Energy

Specific Energy of a battery is the energy per unit mass. The unit for specific energy is Wh/kg. This helps to determine the total nominal energy that can be stored per unit kg. For example, Nissan leaf and Tesla Roadster's lithium-ion batteries are rated as 140Wh/kg and 120Wh/kg respectively.

5.3.3 Specific Power

Specific power of a battery is the maximum available power per unit mass. It provides the battery weight required to gain a provided power rating. It is measured in W/kg. Nissan leaf's battery has a specific power of 2500W/kg.

5.3.4 Energy Density

Energy density is defined as the nominal battery energy per unit volume. It provides the battery size or volume required to gain a provided range. It is measured in Wh/L. A lithium-ion.

5.3.5 State of Charge (SOC)

It is the expression of the present battery capacity as a percentage of the maximum capacity. So the charging time for an EV battery depends on the SOC of the battery.

5.3.6 Charging Time

It is the total time needed to charge the battery to the maximum capacity or nominal energy. The charging time for the typical batteries varies from 7-8 hours to 20-30 minutes for the fast charging batteries depending on the level of voltages and charger type.

5.3.7 Driving Range

Driving range is another crucial factor for an EV battery. Currently, Nissan claims that their fully charged battery gives close to 100 miles. However, the United States Environmental Protection Agency (EPA) rates Nissan Leaf battery for 73 miles per charge with various driving conditions. The charging time is rated to be 8 hours with the on board 3.4kW charger at 240 volts and 30 Amps supply. Tesla Roadster has a custom microprocessor controlled lithium-ion battery which can fully charge in 3.5 hours from Tesla high power wall connector at 240 volts and 70 Amps. The driving range specified by Tesla is about 245 miles.

5.3.8 Electricity Cost

DOE reports the average residential cost of electricity as 12 cents per kWh. For a 24kWh battery of Nissan leaf will cost $2.88 for a full charge without considering any losses in the charger. Nissan claims a driving range of 76 miles for the Leaf; however, it does not consider the situation of going only 38 miles and coming back home for another full charge. In this case the effective distance an EV can go per full charge is only 38 miles for $2.88.

5.3.9 Battery Internal Resistance and Power Loss

The internal resistance of a battery increases as the battery loses its stored energy. The EV battery is assumed to be rated @ 160 V when it is charged at 120 V AC single phase ($120 \times \sqrt{2} - 2 \times 0.7$). The current for the battery is going to be in the range of 150 Amps, which increases the power losses due to internal resistance. The power loss will continue to increase as the internal resistance increases with time.

5.4 EV Chargers

The vehicle battery charges are power electronic devices that convert the AC power system to DC and store the energy in the battery. If there is any threat to the distribution grid from harmonics and overloading, it will be because of these power electronics devices primarily due to presence of highly nonlinear ac-dc converters and having larger ratings. Chargers' circuits have diodes for full-wave rectification and thyristors are used instead of diodes to obtain bi-directional flow of energy. In this thesis, only single-phase EV charger is studied, as we are more concerned on the effect of EV charger on the residential distribution grid.

In [28-29], a commercially available EV charger was used to study the charger current waveform and the total harmonic distortion in single-phase supply. The charger operates at maximum rated current when the battery’s state of charge is low. [28] shows the relationship of battery state of charge and the total harmonic distortion.

5.4.1 Charger Configuration

Different possibilities of configurations in EV chargers have been discussed below depending on the circuitry of the charger. The input AC voltage can be stepped up using a transformer and then rectified to the battery needed voltage as shown in fig 5.3 [27] or the input AC voltage can be rectified and then converted to the battery required voltage as shown in gif 5.4 [30]. In both the cases, we can have either an inductive or capacitive filter for output voltage ripple reduction.

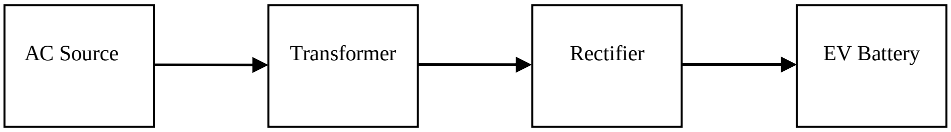

Fig 5.1 Possible configuration of an EV charger I

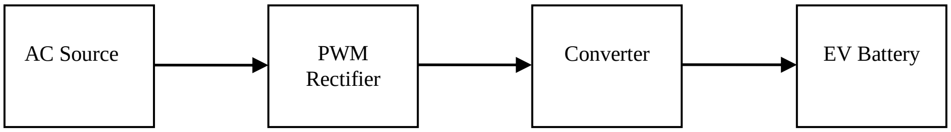

Fig 5.2 Possible configuration of an EV charger II

The configuration as shown in fig 5.4 has a PWM rectifier in the first stage which works as a power factor correction circuit to maintain the sinusoidal input current in phase with the input voltage. The second stage has a DC-DC converter, which is used to eliminate the voltage ripple.

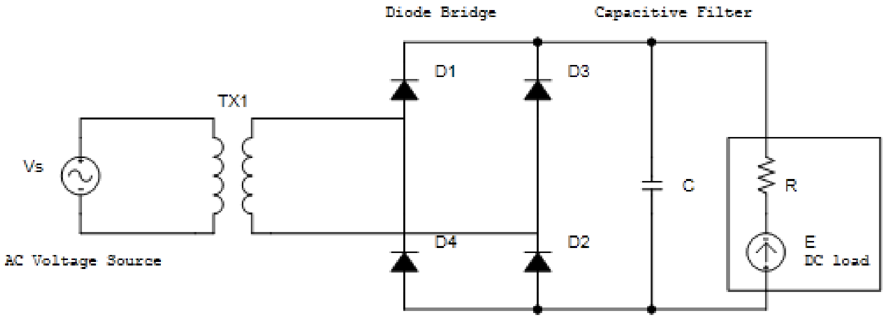

Fig 5.3Single-phase diode based rectifier with capacitive filter

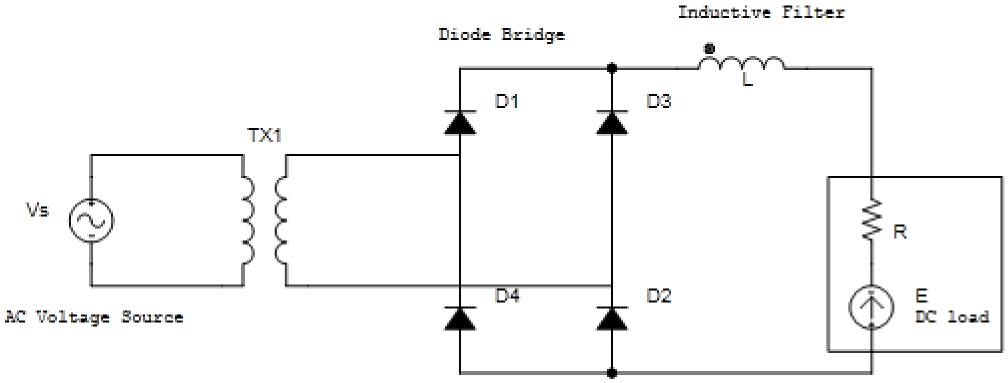

Fig 5.4 Single-phase diode based rectifier with inductive filter

In this configuration as shown in Fig 5.5 and 5.6, the single phase AC source is stepped up using a transformer and then rectified using the single-phase bridge rectifier. The rectifier has either a capacitive or inductive filter which helps minimize the output voltage ripple. The diode-based rectifier works on principle of higher voltage and lower voltage selector of two voltages. A transformer is used before the rectifier because it can help adjust the required input voltage needed for the DC load. For an active load like an EV battery, the diode D1 and D2 are in ON- State when the supply voltage is greater or in the positive half cycle than the internal voltage of the load. Diodes D3 and D4 are in ON-state during the negative half cycle of the supplied voltage. The output DC voltage (U_{d0}) and the output current I_{d0} mean value at the load are equal to [27]:

$$U_{d0} = E + 2\,\frac{1}{2\,\pi}\int_{-\alpha}^{\alpha}(\sqrt{2}\,U\;\cos\beta - E)\;d\beta$$

$$I_{d0} = \frac{U}{R}\,\frac{2}{\pi}\,(\sqrt{2}\sin\alpha - \frac{E}{U}\,\alpha)$$

Where, α = angle for which the input voltage and E are equal and the diodes D1 and D2 starts conducting. So, $\sqrt{2}\,U\;\cos\alpha = E$ & $\alpha = \cos^{-1}\frac{E}{\sqrt{2}U}$.

U= supplied voltage RMS

U_{d0}= output mean voltage

E= internal DC voltage of the load

5.4.1.1 Harmonic Distortion of the Rectifier Supply Current in Case of Capacitive Filter

During the process of reducing the ripple of the output voltage by the use of capacitive filter as shown in fig 5.4.3, it will distort the input current. The harmonic distortion of the rectifier supply current δ_i is defined as

$\delta_i = \sqrt{\frac{1}{\lambda^2} - 1}$ Where, λ is the power factor of the single-phase rectifier with a capacitive filter.

If we ignore the losses of power in rectifier diodes, λ = $\sqrt{2d}$ where d is defined as duty factor which is the ratio of conducting angle (4α) of the rectifier diodes to the period (2π). Therefore, $d = \frac{2\alpha}{\pi}$.

The following illustration shows the distortion of supply current due to presence of capacitor as filtering device.

Table 5.1 Distortion of Supply current with capacitive filter

	U_{d0}	(u_d)max	(u_d)min	α (radians)	d	λ	δ_i
Case I: maximum ripple not higher than 12% of output mean voltage	300V	$(U_{d0}+0.06\ U_{d0})$ =318V	$(U_{d0}-0.06\ U_{d0})$ =282V	0.48	0.30	0.78	0.79 or 79%
Case II: maximum ripple not higher than 10% of output mean voltage	300V	$(U_{d0}+0.05\ U_{d0})$ =315V	$(U_{d0}-0.05\ U_{d0})$ =285V	0.44	0.28	0.75	0.88 or 88%

The above illustration shows in table 5.1 shows that the more we try to make the output voltage smoother the more the input current becomes distorted.

5.4.1.2 Harmonic Distortion of the Rectifier Current in Case of Inductive Filter

Series of inductors as shown in figure 5.4.3 are used in place of a parallel capacitor in order to reduce ripples on the output voltage. As there is no DC voltage across the inductive filter, the mean output voltage at the load is equal to the supply voltage considering there are no losses across the rectifier diodes. In this case, output mean voltage (U_{d0}) = $\frac{2\sqrt{2}}{\pi}U$. So, apparent power (S) of the rectifier is: $S = U.\ I_{d0} = \frac{\pi}{2\sqrt{2}}\ P$. Hence, the power factor (λ) is always $\frac{2\sqrt{2}}{\pi}$ or 0.9 and harmonic distortion of the rectifier supply current (δ_i) is 0.48 or 48%.

5.5 EV Charging Levels

It is important to know the different charging scenarios for an EV battery since the impact on the grid will differ with the type of the charging station. There are three different levels of charging of an EV battery based on the level of voltage and current ratings and connectors [19]:

- *Level 1:* The battery is charged by the on-board charger which is already present on the car and does not need any external charging infrastructure. It is charged with single phase 120V AC from the household outlet. The current and power ratings are about 16 Amps and 1.9kW respectively. Depending on the size of the battery, it might take 3-8 hours to charge the battery completely with this level of charging.
- *Level 2:* The battery is charged by an on-board charger with AC voltage single or split phase with the range of 208-240V from the 3 wire distribution system. The current and power rating for this level of charging is greater than that of the basic level. The current ranges from 12 to 80 Amps and the power ranges from 2.5kW to 19kW.
- *Level 3:* It refers to the charging scenario where the EV battery are charged using DC off-board charger having high voltage and current ratings ranging from 300 to 600V DC and 400 to several amps of current. The power rating ranges from 15kW to 240kW.

5.6 Harmonic Distortion on Power Systems

Electric power system parameters change because of switching operations or change in loads and generator powers. The reasons for voltage at load to be distorted are because of voltage distortion and current distortion. The distortion that is caused in the generation side is known as primary distortion and the one in secondary or load side is known as secondary distortion. Primary distortion refers to the distortion caused by synchronous generator, high voltage DC lines, wind turbines and non-linearity of transformer on the distribution system. Secondary distortion is caused due to non-linear and time-variant loads. The sources of distortions in a three phase systems are single-phase system, high power rectifiers or AC to DC converters and arc furnaces.

Harmonics is defined as the component of a signal that is an integer multiple of the fundamental. In the U.S power system 60Hz is the fundamental frequency in which the power is transmitted. Harmonics do not exist as physical entities but they are expressed mathematically to analyze the distortion in current and voltage. They are expressed as a sum of harmonics [27]:

$$u(t) \triangleq \sum_{n \in N_0} u_n(t) \triangleq U_0 + \sqrt{2} \sum_{n \in N} U_n \sin(n\omega_1 t - \beta_n)$$

$u_1(t) = \sqrt{2}\, U_1 \sin(\omega_1 t - \beta_1)$, is the fundamental voltage and the remaining part

$$U_0 + \sqrt{2} \sum_{n \in N_d} U_n \sin(n\omega_1 t - \beta_n) \triangleq u_h(t)$$

$u_h(t)$ is the distorting voltage. Here, $N_d = \{0, 2, 3 \ldots\}$.

Similarly,

$$i(t) \triangleq \sum_{n \in N_0} i_n(t) \triangleq I_0 + \sqrt{2} \sum_{n \in N} I_n \sin(n\omega_1 t - \alpha_n)$$

$i_1(t) = \sqrt{2}\, I_1 \sin(\omega_1 t - \alpha_1)$, is the fundamental current and the remaining part

$$I_0 + \sqrt{2} \sum_{n \in N_d} I_n \sin(n\omega_1 t - \alpha_n) \triangleq i_h(t)$$

$i_h(t)$ is the distorting current. Here, $N_d = \{0, 2, 3 \ldots\}$.

The voltage total harmonic distortion (VTHD) is defined as the ratio of the RMS value of the distorting voltage, $||u_h||$, to the RMS value of the voltage fundamental harmonic, $||u_1|| = U_1$.The distorted voltage can be expressed as sum of the fundamental and distorting voltage components. $u(t) = u_1(t) + u_h(t)$

Here, $u_1(t)$is the fundamental harmonic and $u_h(t)$ is the distorting voltage.

$$\delta_u \triangleq \frac{||u_h||}{U_1} = \frac{\sqrt{\sum_{n \in N_d} U_n^2}}{U_1}$$

δ_u is defined as Voltage total harmonic distortion (VTHD). Here, $N_d = \{0, 2, 3 \ldots\}$.

The following table shows the voltage distortion limits in the U.S power systems.

Table 5.2 Voltage distortion limits in the U.S power systems.

Bus Voltage RMS range	Individual voltage distortion	THD
69 kV and below	3.0%	5%
69 kV-161 kV	1.5%	2.5%
Above 161 kV	1.0%	1.5%

Similar to the voltage, the current total harmonic distortion (CTHD) is defined as the ratio of the RMS value of the distorting component, $||i_h||$, to the RMS value of the current fundamental harmonic, $||i_1|| = I_1$. The distorted current can be expressed as sum of the fundamental and distorting current components. $i(t) = i_1(t) + i_h(t)$.

Here, $i_1(t)$ is the fundamental harmonic and $i_h(t)$ is the distorting voltage.

$$\delta_i \triangleq \frac{||i_h||}{I_1} = \frac{\sqrt{\sum_{n \in N_d} I_n^2}}{I_1}$$

δ_i is defined as current total harmonic distortion (CTHD). Here, $N_d = \{0, 2, 3 \ldots\}$.

5.7 Survey of Impact of EV Chargers on Power Grid

The studies of impact of plug-in EV on the distribution power grid are performed in several research papers [18-26, 28-40]. Most of the researches performed are on the impacts due to EV charging on voltage profile, transformer loading & aging, total harmonic distortions (THD), circuit breakers and fuses. There are mixed results on the studies conducted on the impact due to EV chargers on the distribution grid. Majority of reports speculate about an adverse impact whereas some shows very minor effect. The assumption made on this paper about the penetration level in future is overly conservative. Looking at the current EV development process and economic aspect of it, it is very unlikely that EV would exist in every household and serve as a primary means of transportation. These reports have performed harmonic load flow analysis on 3 different charging scenarios viz. time zone scheduling, charging rate and penetration level. The results showed that EV chargers would cause severe voltage/current harmonics, power losses and transformer overloading for high penetration level. The load demand is going to increase due to extended EV penetration that cause voltage drops for distant nodes, transformer solicitation, overlap residential evening load [16]. Another study [15] reports that the effect on the distribution grid would be different depending on the number of active chargers connected on the grid. When the load diversity is lower, the current imbalance increases. On the contrary, when the diversity of load is high, the current imbalance decreases. Voltage imbalances in both cases are within the limit. [15]. Due to the high prices for EVs, they are expected to be in affluent neighborhood where the houses are far apart from each other. This will reduce the load diversity in the distribution system and hence significant current imbalance is expected.

Transformer aging, over-heating, degradation and failure will be another issue due to the overtime work as the EV charging is most likely to be overnight. At a distribution level, 25kVA transformer usually serves 5-7 residential homes. Level 2 charging consumes power of about 6.6kW, which is equivalent to an additional home for the distribution transformer. Penetration of one EV charger on the power grid decreases the expected life span of a transformer by 2 years and addition of two EVs decrease the life span by 7 years [15]. Gomez & Morcos in [24] mention about the over-heating in distribution transformers, Ohmic losses on cables and over-current sensing in circuit breaker and fuses due to massive penetration of EV chargers on the distribution grid. The research done in [24] indicates that the current THD for EV batteries should be limited to 25-30% in order to have a good transformer life expectancy.

Another study [25] reports the data on the power losses and voltage deviation profiles because of impact on EV chargers. The total power loss reported was 25% in a worst case scenario of 100% EV penetration for 2 hours at night. The value was even higher about 30% when the worst case penetration occurred at peak hours of 6-8pm. Similarly the voltage deviation reported at night time with 50% penetration was about 17% and about 65% during peak hours in the evening.

Power system equipment should be designed effectively to accommodate the consequences that will be in the future due to EV battery charger. There are various opinions for mitigation of effect caused due to EV battery charging. Different regulated charging patterns can be implemented that help utilities to lower the power losses due to increasing EV penetration on the distribution grid, for instance changing the cost of charging in off peak hours. Rutherford in his paper [17] has discussed potential approaches for charge scheduling like staggered charging by the help of digital communication capabilities of smart grid in which the

EVs in a neighborhood are charged one at a time during off-peak hours. This helps the utility company to reduce the unnecessary loss-of-life of the distribution transformers.

In contrast to the reports mentioned earlier, [43] concludes that the commercial EV chargers do not give rise to excessive THD on the secondary of the transformer and the distribution grid. Field measurement confirmed that with 67% EV charger penetration on a neighborhood distribution grid, the rise in voltage THD was found to be less than 0.8%. Multiple field test sites confirmed that even with the massive EV penetration on the grid overnight should not be a cause for concern.

CHAPTER 6

CONCLUSION

In terms of total energy use or overall efficiency from well to wheel, EVs have an advantage over GVs as they require less energy to operate including the production of electricity. Consequently, use of EVs over gasoline ones reduce carbon dioxide emissions as well as demand for carbon-rich fossils. Due to various obstacles for EVs to compete against GVs in the present scenario, replacement of GVs by electrical ones can only be in national interest.

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VITA

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