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PHEV-EV Charger Technology Assessment with an Emphasis on V2G Operation

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Executive Summary

More battery powered electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) will be introduced to the market in 2011 and beyond. Since these vehicles have large batteries that need to be charged from an external power source or directly from the grid, their batteries, charging circuits, charging stations/infrastructures, and grid interconnection issues are garnering more attention. This report summarizes information regarding the batteries used in PHEVs, different types of chargers, charging standards and circuits, and compares different topologies. Furthermore, it includes a list of vehicles that are going to be in the market soon with information on their charging and energy storage equipment. A summary of different standards governing charging circuits and charging stations concludes the report.

There are several battery types that are available for PHEVs; however, the most popular ones have nickel metal hydride (NiMH) and lithium-ion (Li-ion) chemistries. The former one is being used in current hybrid electric vehicles (HEVs), but the latter will be used in most of the PHEVs and EVs due to higher energy densities and higher efficiencies. The chargers can be classified based on the circuit topologies (dedicated or integrated), location of the charger (either on or off the vehicle), connection (conductive, inductive/wireless, and mechanical), electrical waveform (direct current (dc) or alternating current (ac)), and the direction of power flow (unidirectional or bidirectional). The first PHEVs typically will have dedicated, on-board, unidirectional chargers that will have conductive connections to the charging stations or wall outlets and will be charged using either dc or ac. In the near future, bidirectional chargers might also be used in these vehicles once the benefits of practical vehicle to grid applications are realized.

The terms charger and charging station cause terminology confusion. To prevent misunderstandings, a more descriptive term of electric vehicle supply equipment (EVSE) is used instead of charging station. The charger is the power conversion equipment that connects the battery to the grid or another power source, while EVSE refers to external

equipment between the grid or other power source and the vehicle. EVSE might include conductors, connectors, attachment plugs, microprocessors, energy measurement devices, transformers, etc. Presently, there are more than 40 companies that are producing EVSEs.

There are several standards and codes regarding conductive and inductive chargers and EVSEs from the Society of Automotive Engineers (SAE), the Underwriter Laboratories (UL), the International Electrotechnical Commission (IEC), and the National Electric Code (NEC). The two main standards from SAE describe the requirements for conductive and inductive coupled chargers and the charging levels. For inductive coupled charging, three levels are specified: Level 1 (120 V and 12 A, single-phase), Level 2 (208 V-240 V and 32 A, single-phase), and Level 3 (208-600 V and 400 A, three-phase) . The standard for the conductive-coupled charger also has similar charging ratings for Levels 1 and 2, but it allows higher current ratings for Level 2 charging up to 80 A. Level 3 charging for this standard is still under development and considers dc charging instead of three-phase ac. More details in these areas and related references can be found in this Oak Ridge National Laboratory (ORNL) report on PHEV-EV charger technology assessment.

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Nomenclature

h	Individual harmonic number of the grid charging current
$I_{bt-ripple-total}$	Total rms sum of the battery charging ripple current at different frequencies (A)
$I_{bt-ripple}$	RMS value of the battery charging current ripple at one frequency(A)
i_{bt}	Battery current (A)
$I_{c,1,rated}$	RMS of the rated value of the fundamental component of the grid charging current (A)
$I_{c,1}$	RMS value of the fundamental component of the grid charging current (A)
$I_{c,h}$	Total rms sum value of the grid charging current harmonics (A)
P_{loss}	The total power dissipated in the battery during charging/discharging (W)
Q_0	Initial electric charge in the battery (C)
Q_n	Nominal electric charge capacity of the battery (C)
R_i	Equivalent internal resistance of the battery pack at a specified charging ripple frequency (Ω)
SOC	State of charge
SOD	State of discharge
TDD	Total demand distortion of the grid current

THD	Total harmonic distortion of the grid current
$V_{bt-ripple}$	RMS value of the battery charging voltage ripple at one frequency (V)

Acronyms

A ampere.

ac alternating current.

Ah amp-hour.

ANSI American National Standards Institute.

BEV battery electric vehicle.

BMS battery management system.

CC constant current.

CD charge-depleting.

CS charge-sustaining.

CV constant voltage.

cyl cylinder.

dc direct current.

DOD depth of discharge.

EMS energy management system.

EU European Union.

EV electric vehicle.

EV-ETS EV energy transfer system.

EVSE electric vehicle supply equipment.

FCV fuel cell vehicle.

gal gallon.

GM General Motors.

h hour.

HAN home area network.

HEV hybrid electric vehicle.

HF high frequency.

ICE internal combustion engine.

IEC International Electrotechnical Commission.

IGBT insulated gate bipolar transistor.

IR infrared.

kHz kilohertz.

kWh kilowatt-hour.

lb pound.

LCO lithium-cobalt-dioxide.

LFP lithium-iron-phosphate.

Li-ion lithium-ion.

LMS lithium-manganese oxide spinel.

MHZ megahertz.

mi mile.

MiEV Mitsubishi Innovative Electric Vehicle.

MOSFET metal-oxide-semiconductor field-effect transistor.

mpg miles per gallon.

MPGe miles per gallon equivalent.

mph miles per hour.

NCA nickel-cobalt-aluminum.

NEC National Electric Code.

NFPA National Fire Protection Association.

NiMH nickel metal hydride.

Nm newton-meter.

NMC nickel-manganese-cobalt.

NOx mono-nitrogen oxide.

OEM original equipment manufacturer.

ORNL Oak Ridge National Laboratory.

PFC power factor corrected.

PHEV plug-in hybrid electric vehicle.

PM particulate matter.

PV photovoltaic.

RES renewable energy sources.

RF radio frequency.

RTP real time pricing.

SAE Society of Automotive Engineers.

SOC state of charge.

SOD state of discharge.

SOH state of health.

TDD total demand distortion.

THD total harmonic distortion.

TOU time of use.

UL Underwriter Laboratories.

V volt.

V2G vehicle to grid.

V2H vehicle to home.

V2V vehicle to vehicle.

V2X vehicle to any load.

VRLA valve-regulated lead-acid.

W watt.

W/kg watt per kilogram.

W/l watt per liter.

Wh watt-hour.

Wh/kg watt-hour per kilogram.

Wh/l watt-hour per liter.

Chapter 1

Introduction

According to the international energy outlook report, the transportation sector is going to increase its share in the world's total oil consumption by up to 55% by 2030 [20]. Therefore, technologies related to reducing oil consumption have one of the upmost challenges in today's vehicle research.

Alternative vehicle technologies to replace conventional vehicles include HEVs, PHEVs, EVs (also known as battery electric vehicles (BEVs)), and fuel cell vehicles (FCVs). Compared to liquid carbon/hydrogen-based energy transportation, storing energy electrochemically in batteries is a reliable and cleaner way of storing transportation energy. This is due to the wide availability and cleaner generation/transmission of electricity as an energy source. This report will focus on vehicles that are charged by the grid using various kinds of chargers.

The dichotomy between HEVs and EVs/PHEVs is the presence of a charger in the latter group. The charger is a power conversion equipment that connects the vehicle battery to the grid. Chargers for these vehicles have the ability to foster the interaction of vehicle and the external power source, i.e. the utility grid. Chargers convert the ac voltage to a dc magnitude for the specific battery needs of PHEVs and EVs. In order for the utility to be spared by the impact of the large number of PHEV/EV connections, chargers play an important role in the grid integration of these new technology vehicles. Therefore, in this report, a broad range of background work is presented about PHEV, EV, and related system components such as charger and EVSE. This report not only discusses chargers with respect to their technical considerations but also gives the current market deployment information.

Design of the charger of a vehicle traction battery includes different options in terms of where to place the charger and how to design the charger. The circuit topology, location, connection type to the vehicle, electrical waveform of the charging coupler, and the direction of power flow can totally change the design of the charger (more on this classification is explained in chapter 3). Although the surveyed market vehicles employ different combinations of the above classification, most of the vehicles carry its charger on-board for increased charging availability. However, although carrying the charger on-board increases the availability of charging the vehicle, it also brings added cost and weight to the vehicle. Also, the power rating of the charger is inversely proportional to the charging time necessary to fully charge the vehicle battery. Therefore, it is desired to have a high power charging rate to make the EV charging experience comparable to the filling time of a gasoline tank. However, due to space and weight limitations on a vehicle, the on-board charger must be restricted in power rating. So, these two objectives contradict with each other and a compromise should be made. The power rating is also related to the type of the vehicle. For instance, EVs usually require a charger with a higher power rating compared to PHEVs due to having a larger battery. The battery size of an EV in the U.S. market range between 16 kWh - 53 kWh whereas a PHEV has its pack with 4.4 kWh - 20.1 kWh energy capacity (more details on surveyed vehicles are provided in chapter 5). Therefore, for comparable charging time, an EV usually requires its charger to have a higher power rating.

It is also possible to incorporate more than one operation mode in a charger by allowing the power to flow bidirectionally. Usually, the bidirectional power transfer stands for two-way transfer of active power between the charger and the grid. The general term of sending active power from the vehicle to the grid is called vehicle to grid (V2G). The economic benefits of this operation has been a research subject for more than a decade because of the large energy reserve of an electric vehicle battery and the potential of thousands of these connected to the grid. While PHEVs/EVs potentially have the capability to fulfill the energy storage needs of the electric grid, they can also supply energy storage system applications such as reactive power compensation and voltage regulation.

A charger is composed of two power conversion stages: a single/three-phase ac-dc conversion stage, and a dc-dc conversion stage. This report technically focuses on single-phase chargers that are mostly suited for on-board charging applications. The front-end ac-dc conversion stage can have power factor corrected (PFC) unidirectional, two-quadrant unidirectional, or four-quadrant bidirectional power transfer options. The design of the charger changes considerably between the different options and applications. Moreover, single-phase power conversion also adversely affects the energy storage requirements during reactive power operation due to increased ripple energy storage at the dc-link. Another concern is the limitation of the ac line current harmonics either during charging the traction battery or when the vehicle supplies power back to the grid. DC-DC conversion stage can either have isolated or non-isolated topology based on the mandated protection requirements by the auto manufacturers. Another concern is the limitation of battery charging current harmonics which adversely affect the lifetime of the battery. The standards that deal with electrical vehicle charging can be grouped into codes/standards dealing with power transfer, communications, protection, and manufacturing.

This report is organized into six chapters. The first chapter is the introduction. Chapter 2 elaborates on the vehicle types with grid chargeable batteries; namely, EVs and PHEVs. The advantages and disadvantages of EVs and PHEVs are summarized. Then it describes the battery technology that is used in current grid-connected vehicles. Chapter 3 is concerned with the important definitions and subjects related to vehicle battery charging. It is followed by the classification and comparison of all the different battery charging devices that have been used in the market. Chapter 4 highlights the power electronics topology structure of different chargers, and it studies the smart grid applications of the chargers. Chapter 5 describes the current market deployment of EVs/PHEVs in terms of their charging and energy storage components. Chapter 6 lists the related charging infrastructure and charging/charger standards imposed on the EV/PHEV battery chargers. Finally, chapter 7 concludes the report by summarizing the main points.

Chapter 2

Electric-Drive Vehicles and Battery Technologies

2.1 Definitions of HEV, PHEV, and EV

Today, there are three types of passenger vehicles available in the market operating with an electric drive-train powered by a battery: HEVs, PHEVs, and EVs or BEVs. HEVs have the smallest size battery pack, and therefore an electric motor is used to drive at very low cruise speeds or to assist the internal combustion engine (ICE) during higher power requirements. Therefore, HEVs offer customers a way to increase gasoline mileage by having batteries and electric drive systems work with the ICE. The most efficient hybrid vehicles reduce the gas consumption by around 40% compared to similar size conventional ICE vehicles. However, HEVs lack the availability to go for more than just short distances at low speeds with only electric power because the battery is not capable of storing enough energy to power the vehicle for a daily commute.

PHEVs, however, provide an all-electric range up to a pre-specified distance with a larger size battery pack, which is not inherent in HEVs. There are several definitions on how a PHEV is defined. According to [21], the battery pack capacity should be at least 4 kWh, and the PHEV must be rechargeable by an external source of electricity. Another definition adds the ability to drive the vehicle at least 10 miles in electric-only mode without consuming any gasoline as a requirement for a vehicle to be classified as a PHEV. By definition, an EV has only an electric motor in the traction drive which is powered by an on-board battery, and conventional vehicles have only combustion engines. The 2010 Toyota Prius HEV has only 1.3 kWh on-board traction battery capacity. As a comparison, the 2011 Chevrolet Volt PHEV has a 16 kWh battery capacity [22] and 2011 Nissan Leaf EV has a capacity of 24 kWh on-board battery energy storage [23].

PHEVs operate in charge-depleting (CD) mode when most/all of the energy comes from the battery during the all-electric mode; hence, the battery is in the deep cycle mode. If the battery reaches its minimum state of charge, the control system switches to the charge-sustaining (CS) mode where the battery experiences only shallow cycles. PHEVs are usually described as PHEV-X where X is the number of miles that a PHEV can go just with the electric energy. An explanation of the different operation modes in EV, HEV, and PHEV is shown in Fig. 2.1. The term full-cycle (deep-cycle) corresponds to a large charge-discharge window of the battery usually between 20-90% SOC. Meanwhile, a micro-cycle (shallow-cycle) stands for very low charge-discharge window for the battery SOC.

This report focuses on the investigation of chargers; hence, discussions mostly relate to PHEVs and EVs rather than HEVs. From this point on, PHEV term will be used mainly to account for both all-electric and plug-in hybrid electric vehicles since it greatly facilitates the readability of the report. If there is a need for further distinction between the two, each of the abbreviations will be used separately.

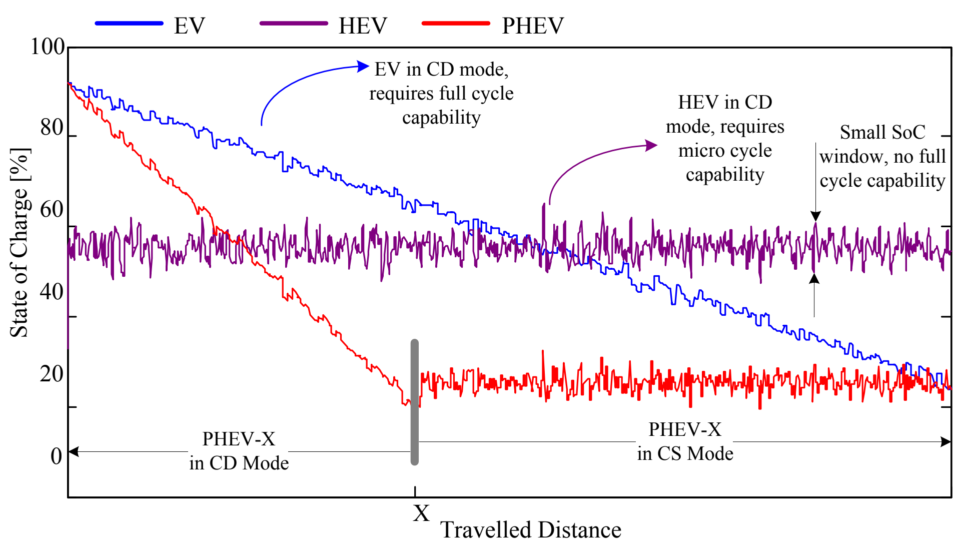


Figure 2.1: Charge depleting and charge sustaining modes for the EV, HEV, and PHEV [8].

2.2 Advantages of PHEVs and EVs

There are several advantages of using battery powered vehicles such as EVs/PHEVs as opposed to using ICE vehicles. Here, not only the technical superiorities of electric drive systems but also the social impacts of the technology are underlined.

2.2.1 Energy Efficient Operation and Fuel Cost Savings

The energy efficient operation of PHEVs compared to ICE vehicles stems from the mechanical difference in the design of two vehicle groups. Since PHEVs have an electric motor, they do not idle and save braking energy as opposed to ICE's inefficient operation and energy consumption at the same conditions. Moreover, having grid electricity as the main fuel as opposed to gasoline and with more efficient operation, EVs can save more than $900 per year for an average drive in USA. The explanation is as follows.

%50 of all drivers in the U.S. drive less than 25 mi (40 km) per day, and %70 of all drivers drive less than 40 mi (64 km) per day. For an average drive of 30 mi (48 km) per day, annual driving distance equals to $30 \times 365 = 10,950$ mi (17,618 km). For a 25 mpg (10.6 km/lt) gas pump to wheel driving efficiency of a gasoline car, it burns $10,950/25 = 438$ gal (1,655 lt) of gasoline per year. Using a gasoline cost of $3/gal, this makes a total of $1,314 of annual fuel cost. For a 34 kWh/100 mi (21 kWh/100 km) driving plug to wheel driving efficiency of an EV, it consumes $10,950 \times 34/100 = 3.72$ MWh of electrical energy per year. Using 11 ¢/kWh of electrical energy cost, the annual cost of electrical energy for recharging an EV on average is $3,720 \times 11/100 = \$409$. Therefore, the annual cost saving is $1,314 - 409 = \$905$ per year on average. For an average driving of 25 mi (40 km) per day, annual cost saving becomes $754 per year.

2.2.2 Reliability of Fuel Supply and Reduced Maintenance

Using domestically produced electric power for vehicle propulsion reduces the risk of the effects from the increased fuel prices brought by financial crises, political conflicts, and natural disasters. In addition, using the electricity generated by domestic sources reduces foreign oil dependency, improves the transportation sector's reliability, and enhances the national energy security. Imported oil may also cause potential hazards to the environment during failures or leakages [24].

EVs replace many mechanical components of the ICE which require frequent maintenance. To name a few, EVs need much less lubricating oils and they do not have fuel filters, clutches, spark plugs, oxygen sensors, timing belts, catalytic converters, or mufflers. Hence, there is no need for periodic tune-ups for EVs. This brings maintenance cost savings to the user of the EV.

2.2.3 Public Health Benefits

The most important benefits of the PHEVs lie in increased health conditions for the society. PHEVs will introduce significant impacts to society that will directly alleviate public health. PHEV charging removes tailpipe emissions to miles away from urban centers where people are exposed to particulate matter (PM) pollution, ozone and smog formation, and greenhouse gases. Air pollution from PM caused 65,638 premature deaths in US in 2008 [25]. Moreover, researchers conclude a direct and transparent relation between life expectancy and PM pollution. Compared to a conventional vehicle, a PHEV can reduce mono-nitrogen oxide (NOx) emissions up to 90% for each km driven reducing ozone and smog formation, and associated respiratory-related diseases [25].

In contrast, generating the same amount of energy at a central power plant will spread PM emissions in reduced concentrations to a much larger atmosphere providing a cleaner air for the public. Moreover, controlling and curtailing emissions are more easily achieved in a large power plant than in millions of vehicles. Also, PHEVs introduce very low noise pollution to the environment compared to ICE vehicles [26].

Moreover, renewable energy sources (RES) do not operate with negative feedback control, meaning that if the load does not meet the source, the source cannot adjust its output power accordingly. Therefore, unless there is an energy buffer between the RES and the load, it will waste the harnessable energy, since energy source cannot be stopped. Deployment of PHEVs will help the RES to utilize its energy output by accepting its excess energy for charging when it is not needed by the load. For instance, during the night when there is not much load demand, wind turbines may produce substantial amount of energy. Therefore, a PHEV can utilize this excess wind energy to charge its battery. This reduces the extra need for fossil fueled infrastructure to charge the PHEV batteries which further decreases consequent pollution. With this scheme, the return on investment on the RES equipment will be increased [27].

2.2.4 Energy Storage Services Provided by PHEVs

Another potential benefit of PHEVs is the ability to maintain the reliable operation of the grid by coordination between the vehicle and the utility. There are various services that PHEVs can supply to the grid which are add-on values to the above mentioned benefits of this technology. Since every PHEV has a charger that can convert ac to dc, this charger can be developed so that it can also send power back to grid for V2G operation. Based on the specific service provided, the utility can benefit by using a considerable amount of energy storage at the distribution system level.

2.3 Drawbacks of PHEV and EV Technology

Convinced that the deployment of electric drive vehicles are the technology of the next decade, an analysis should also include the barriers and shortcomings of this technology. These drawbacks will demonstrate both technical and social impediments to the adoption of this technology.

2.3.1 Initial Cost of the Components and Insufficient Component Supply Industry

One of the most mentioned hindrances to the deployment of PHEVs is the initial cost of the battery pack. In addition, there are only a few number of Li-ion suppliers that can produce cells in large volumes. Moreover, there are other difficulties associated with manufacturing power system components. PHEV power electronics and related control systems are the system components that will make this new technology feasible and are just as important as the current battery technology challenges. However, the supply industry for power electronics for PHEV market are not ready yet to support large volumes of PHEV production [28]. Furthermore, one should also consider the cost of EVSE that should be installed at home garages for vehicle charging, usually with an extra cost to the vehicle. One can agree that to expedite the adoption of EVs, fast charging stations are required. This is another challenge due to the large investment costs and high power requirements.

2.3.2 Concerns Regarding PHEV Technology by Society and Industry

Considering decades of studies devoted to EVs, and several market vehicle models, it is fair to say that there is a hesitation towards the transition from ICE to EV technology in society and in industry. This might be due to the lack of a proven successful demonstration of any type of EV/PHEV in the market. Also, low gasoline prices always keep the ICE vehicles preferable over EVs despite the aforementioned benefits because of the maturity of the ICE technology. In addition, if EV technology is adopted in the market, it will displace a considerable amount of mechanical components from the vehicle. Therefore, the associated service, parts, and supplies industry will have a paradigm shift. Consequently, the transition to the new technology depends on both social acceptance and the technical advancements required for PHEVs [29]. A successful demonstration will only be achieved when society and industry are ready to invest in this new technology.

2.3.3 Effects of Electricity Blackouts on EV Charging

Another adverse effect of having an EV is the necessity to depend on grid electricity all the time. PHEVs, on the other hand, carry a back-up gasoline tank and ICE that will help with emergency needs such as a black-out or depleted battery pack. Therefore, PHEVs can operate even during an extended black-out. On the other hand, chargers can also be designed so that an EV can be charged by another PHEV/EV to reach a nearby charging station during emergency situations.

2.3.4 Required Updates in the Distribution System

As the new PHEV loads enter at the residential distribution system level, there may be a need to install larger substation transformers in the service area and residential transformers depending on their rating. Losses and power quality are the other issues that the utilities are concerned about. With an increased number of PHEV chargings, voltage drops may get worse beyond the tolerance values. This may also lead to voltage stability problems. Therefore, of utmost importance is the need to regulate PHEV - grid interaction. The design of the battery charger will be crucial in this effort to effectively control the power flow and, as a result, maintain continuous service of electrical energy.

2.4 Battery Technologies for PHEVs and EVs

For years, the biggest hindrance of deployment of EVs has been the lack of a portable high-energy storage device. With recent developments in battery technology, it has been easier to overcome this obstacle. During this advancement of vehicle grade batteries, the main categories that the vehicle battery research has focused on are: energy, power, life span, safety, and cost [30].

The energy stored in a battery determines the electric drive range and is measured in amp-hour (Ah) or watt-hour (Wh). The electric drive range of a PHEV is proportional to the amount of stored energy, as more energy is required to drive the vehicle in electric-only mode. Since the available space is limited in vehicles, researchers usually focus on the energy density (watt-hour per liter (Wh/l)) or specific energy (watt-hour per kilogram (Wh/kg)) of a battery. The amount of stored energy is more of a concern for EVs compared to PHEVs, since EVs do not have a gasoline tank to extend the driving range on a single charge.

The battery power is measured in watt (W); however, as in the energy and energy density, battery researchers focus on power density (watt per liter (W/l)) or specific power (watt per kilogram (W/kg)) in battery terminology. Higher battery power translates into higher motor torque or vehicle acceleration. The power rating is also important to determine how fast a battery can be charged which is usually much slower compared to discharging.

The battery life span includes two different cycle measurements; the first of which is the minimum calendar life. A vehicle battery is expected to operate above a specified capacity for the calendar life period of 15 years with limited degradation [30]. The next important item for the battery lifetime is the cycle life which relates to the total number of charging-discharging cycles that the battery is exposed to during its lifetime. A battery experiences both deep and shallow charge-discharge cycles depending on its operation mode. A deep cycle means one complete charging and discharging of the battery usually between 20% and 90% of the state of charge (SOC)*. A shallow cycle usually occupies a very narrow SOC window, i.e. 40% - 60%. A shallow cycle is more battery friendly compared to a deep cycle since a smaller SOC window is used. In other words, a deep cycle affects the battery lifetime more than a shallow cycle.

Safety should always be kept as the number one priority for all of the operating conditions. Batteries require strict safety precautions, which are detailed in section 3.1.4.

*The definition of SOC is given in section 3.1.1

Batteries should meet the above requirements with an affordable cost goal. For years, high battery costs have prevented the technology from being widespread. However, with recent research and development advances, PHEVs and EVs have been in the market recently with the cost and performance characteristics comparable to conventional vehicles in the market [22, 23].

There are three main battery technologies that stand out from the rest. These are lead-acid, NiMH, and Li-ion technologies. In this section, these batteries are investigated and compared with respect to their weight, volume, energy, charge and discharge power, operating temperature range, life span (cycle and calendar), cost, safety-electrical abuse tolerance, and availability.

2.4.1 Lead-acid Battery

The lead-acid battery was the most preferred option to power early EVs; therefore, it is readily available at a reasonable cost owing to the maturity of the technology, manufacturing, and high volumes of recycling. Its good discharge power capacity makes it easier to respond fast to load changes. In contrast, it has a low energy density and is heavy. Also, lead-acid batteries have short life spans as a consequence of the deterioration from deep discharges. The first EV released to the market General Motors (GM) EV1 used a lead-acid battery to provide power to an electric drive motor.

2.4.2 NiMH Battery

A NiMH battery has simple charge and discharge reactions, and it does not have soluble intermediates or complex phase changes as opposed to lead acid batteries [31]. Therefore, NiMH batteries have higher power and energy densities and a longer intrinsic cycle life. Also, a NiMH battery can tolerate moderate overcharges and deep discharges. Due to the high energy density of NiMH batteries, the range of a vehicle with a NiMH battery is doubled compared to a vehicle with the same size and weight lead-acid battery [31]. Finally, due to low internal resistance, a NiMH battery has a higher charge acceptance capability compared to lead-acid battery which results in higher charging efficiency.

One drawback of the NiMH batteries is the high self-discharge rate compared to lead acid batteries, which causes batteries to lose charge when not used. The self-discharge is 5-10% on the first day and averages around 0.51% per day at room temperature [32].They also have higher cost compared to lead-acid. The charge acceptance capability drops at high temperatures that result in low cell charging efficiency at these temperatures. Most of the HEVs currently in the market employ a NiMH battery including Toyota Prius and Honda Insight.

2.4.3 Li-ion Battery

Lithium-ion battery cells are expected to become viable energy storage devices for coming generations of PHEVs according to experts [33]. The superiority of Li-ion batteries have been demonstrated over other types of batteries in supplying greater discharge power for faster acceleration and higher energy density for increased all-electric range. Furthermore, higher efficiency operation and lower weight make them preferable for vehicular applications. However, some issues including cell life (calendar and number of charge-discharge cycles), cost, and safety still need improvement and are the main impediments to widely employ Li-ion batteries in PHEVs [33, 34]. One important issue with Li-ion batteries is the need to equalize each cell charge to balance out the total charge among the cells in a more precise way compared to lead-acid and NiMH chemistries. In addition, since lithium is more chemically reactive, it is more intolerant to abusive conditions which require the battery management system to protect it from overcharging and overheating. Poor cold temperature operation is another drawback of Li-ion battery.

The term Li-ion does not specifically correspond to particular battery chemistry as NiMH does. Rather, it includes several chemistries that can be classified with respect to different cathode contenders. Some of the major cathode compositions are lithium-cobalt-dioxide (LCO), nickel-manganese-cobalt (NMC), nickel-cobalt-aluminum (NCA), lithium-manganese oxide spinel (LMS), and lithium-iron-phosphate (LFP). Although each type of Li-ion cell has some advantages, lithium-iron-phosphate cathode is a new and promising cathode for PHEV applications with increased safety and stability features [33, 35]. Its failure due to overcharging does not emit too much heat. However, it has lower cell voltages compared to other cathodes and hence many of these have to be connected in series requiring more balancing control. To solve the low cell voltage problem, nanostructures are being used. This new nanotechnology offers better power and longer life than earlier generations [33].

A Li-ion cell with lithium titanate spinel anode rather than graphite is also advantageous for a vehicle to charge/discharge faster. In addition, it has improved cycle and calendar lifetime. In this case, energy density is compromised at the expense of getting a much broader operation temperature range as well as a safer voltage range [36].

Consequently, researchers agree that among batteries Li-ion batteries stand out for their advantages of higher energy density and lighter weight [1–5, 33–37]. Life cycle, abuse tolerance, and cost are the next barriers to overcome for this technology. Most of the vehicle manufacturers that made publicly available EV/PHEV models in the market use Li-ion batteries. Each of these commercially available vehicles technology and market information are explained in Section 5.1.

2.4.4 Comparison of Battery Technologies

As a summary, battery technologies are compared with different performance and cost characteristics in Table 2.1. This table is a result of a literature survey based on both battery cell manufacturers data sheets and individual cell tests [1–5] . As it is shown in Table 2.1, each different lithium-ion cathode composition cell has pros and cons, and they are still under development.

Table 2.1: Different battery cell comparison [1–5].

Battery type	Specific power (W/kg)	Specific energy (Wh/kg)	Cost	Safety	Life		Manufacturer
					Calendar	Cycle (deep)	
Lead-acid	Low	Low	Very low	Proven	Low	Low	Many
NiMH	Moderate	Moderate	Moderate	Proven	Good	Good	Many
Li-ion LCO	Good	Good-excellent	High	Low	Low	Poor	Many, mostly consumer electr.
Li-ion LFP	Good-excellent	Good	Low	Excellent	Good	Good	A123, Valence, and Gaia.
Li-ion NCA	Good-excellent	Good-excellent	Moderate	Low	Good	Good	Toyota, Johnson Controls-Saft
Li-ion NMC	Good	Good-excellent	Moderate	Moderate	Moderate	Poor	Hitachi, Panasonic, Sanyo
Li-ion LMS	Moderate	Good	Moderate	Moderate	Moderate	Poor	GS Yuasa, LG Chem, Samsung

Chapter 3

Definition and Classification of EV/PHEV Chargers

The first two chapters of this report showed that the lithium-ion battery cells are expected to be the technology of energy storage for coming generations of PHEVs. As described, battery chargers play an important role by maintaining the condition and health of the battery while utilizing it for the best performance. Before presenting the literature study related to the battery chargers in detail, definitions regarding charging and chargers are required.

3.1 Introduction and Definitions

This section describes the important charger terminologies and standards that are needed to understand battery chargers and battery charging.

3.1.1 Battery and Charging Definitions

State of Charge

In order to predict how many driving miles left for the electric mode in a PHEV/EV, one needs to interpret the fuel gauge of the battery. SOC is the gauge that is used to understand the amount of charge which is proportional to the amount of energy that can propel the vehicle with only electric power. It is analogous to the fuel gauge that is used to show how much gas is left in the tank of an ICE vehicle.

There are different methods used to determine the electrical energy that exists in the chemical bonds of the battery. One simple and efficient method is to measure the current, thereby charge, entering and leaving the battery which is called coulomb counting. Based on this method, SOC can be found using Eq. 3.1:

$$SOC = \frac{Q_0 \pm \int i_{bt} dt}{Q_n} \times 100 \tag{3.1}$$

where Q_o is the initial electric charge present before charging/discharging the battery [C], Q_n is the nominal electric charge capacity of the battery [C], and i_{bt} is the battery current [A]. i_{bt} can be either negative or positive depending on the current direction. If the current is entering the battery, SOC will increase and vice versa. As shown in Eq. 3.1, SOC is a normalized value that is written in percentage for easier readability of the battery gauge.

State of Discharge

Another definition is also used to measure the discharge state of the battery, state of discharge (SOD). It stands for the complement to SOC, meaning that it describes how much electricity has been taken out of the battery. Therefore SOC and SOD always sum to one. Mathematically, it follows as:

$$SOD = 1 - SOC \tag{3.2}$$

SOD is also termed as depth of discharge (DOD) which corresponds to the same definition.

State of Health

A method of assessment to determine the condition of the battery cell is called state of health (SOH). It measures the condition of the battery to determine if battery operates above its factory guaranteed operating conditions. It is a relative measurement to the brand new battery cell. However, there is no direct method of assessing SOH like SOC. Rather, the history on the usage of battery is recorded in battery management system (BMS) to derive representation of SOH. The function of the BMS will be explained later.

Charging Rate

Every individual battery cell has a charging current rate as a default manufacturer value. This is often termed as C-rate. C stands for the rated charge current of the battery cell that will fully charge the battery in one hour. All the charging currents are often referred to the rated current using the C rate such that n×C is a charge rate equal to the n times the rated charging current where n is a real number. For instance, 0.1C charging rate means the charging current is 10% of the rated charging current of the battery cell. As n increases, the charging time required to fully charge the battery cell decreases and vice versa.

3.1.2 Charging Profiles

The common charging profiles used in the industry for Li-ion batteries are constant current (CC) and constant voltage (CV) charging. During CC charging, the current is regulated at a constant value until the battery cell voltage reaches a certain voltage level. Then, the charging is switched to CV charging, and the battery is charged with a trickle current applied by a constant voltage. Lithium-ion batteries with a cathode composition being lithium-cobalt-oxide, which is mostly used in consumer applications, (cell phone, camera, mp3 players, etc) have the following charging profile shown in Fig. 3.1. These batteries have a maximum charging voltage of 4.2 V. One observation from the charging profile is that the battery cell requires around 50 min to finish CC charging phase starting from 0% SOC with 1C charging current. At the instant when the battery reaches 75% SOC, the charger switches from CC to CV charging. The CV charging takes around 2 h 40 min resulting in a total charge time of 3.5 h [9]. Therefore the charge time required to charge the battery cell up to 75% SOC is around 25% of the total charge time. In comparison, to cover only 25% SOC, the charger needs to charge for 75% of total charge time during CV charging. In comparison, Li-ion LFP batteries present a different charging profile compared to Li-ion LCO batteries because of the difference in the chemical structure. For LFP batteries, CC charging stage takes 75% of the total charging time whereas CV charging occupies 25% of the total charging time as shown in Fig. 3.2.

3.1.3 Charging Levels in the U.S.

There are three charging levels based on the voltage and current ratings used to charge a vehicle battery: Level 1, Level 2, and dc fast charging. However, only Level 1 and Level 2

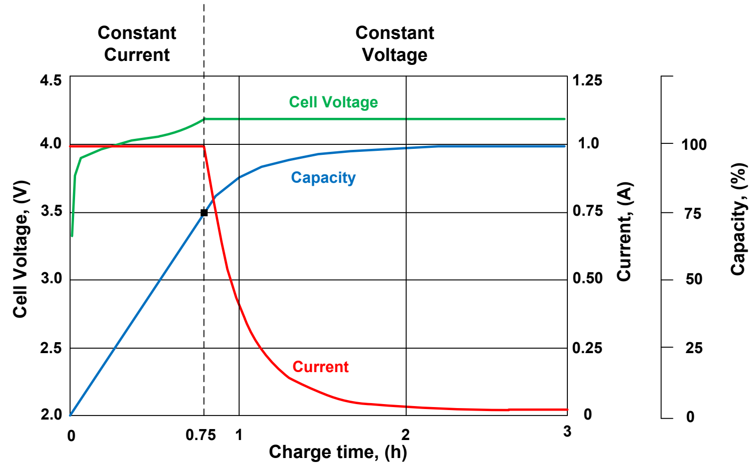


Figure 3.1: Li-ion LCO battery CC-CVcharging profile [9].

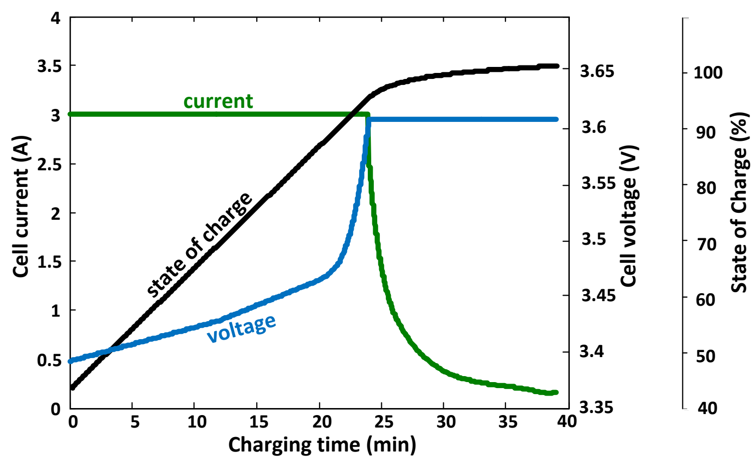


Figure 3.2: Li-ion LFP battery CC-CV charging profile.

have been standardized yet [38]. DC charging, or previously known as Level 3 charging, is still under development [38]. Fig. 3.3 shows the map of the U.S. standard outlet receptacle ratings. There are different chargers; most of them are introduced in the next chapter, rated at Level 1, Level 2, or dc charging schemes.

Level 2 charging is much more preferred because of reduced charging time compared to Level 1 charging. This method employs standard 208-240 V ac single phase power outlet that has a continuous current rating less than 80 A [38]. For example, Nissan Leaf EV has a total of 8 h charging time using its 3.3 kW on-board charger to fully charge its 24 kWh depleted battery pack [23]. Also, it takes around 4 h to fully charge the depleted 16 kWh Chevrolet Volt PHEV battery [22].

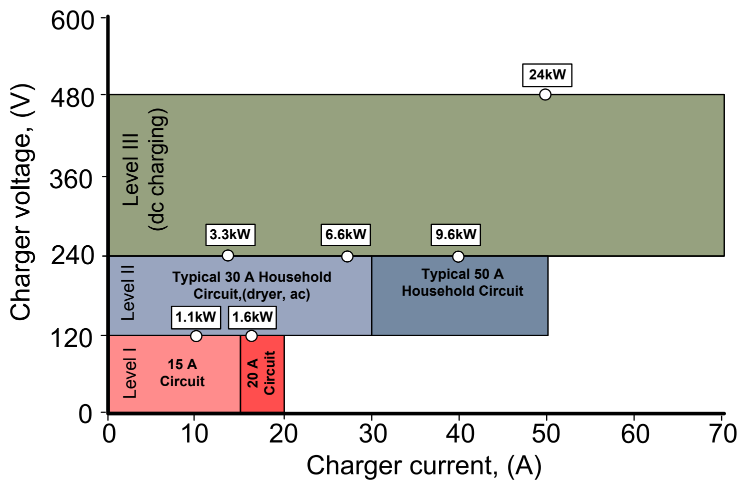


Figure 3.3: Charging outlet circuit breaker map with respect to receptacle voltage and current ratings [10].

Another charging method is fast charging or dc charging. At these charging stations, ac voltage is converted to dc off the vehicle and the vehicle is dc coupled to the charging station. Charging power can go up to higher values compared to the on board charging*.Therefore, it will help vehicles to be charged in a shorter time. However, decreased battery lifetime is an issue because of the increased heat generation of the batteries at higher rates of current charging. As an example to decreased charging time for this type of station, Nissan Leaf EV will be charged with an off-board quick charge station in 30 min from a depleted SOC to 80% SOC [23].

3.1.4 Battery Charging Security and Charging Power Quality

For lithium-ion batteries, the precautions in handling a secure battery operation are more important than other type of batteries. Since they are prone to failure in harsh working conditions, it is mandatory to have the utmost protection in vehicle applications both for customer and expensive battery safety point of views. Therefore, battery manufacturers also sell battery management systems, BMS for short, with added price to the battery cost. BMS is responsible for overseeing safety in charging and discharging operation. The key protection goals for Li-ion batteries include over-voltage, deep discharge, shutting-off in case of over temperature, shutting-off in case of over-current, and individual cell charge

*More details on the definitions of the on-board and off-board charging are explained in section 3.2.2.

balancing [33, 39]. Especially for inrush current conditions, the BMS needs tight regulation not to allow any overcharging current entering the battery cells. BMS should also perform SOC and SOH determination, history (log book) function, and communication with other system components such as charger, grid, and the motor drive.

Since the battery manufacturer is responsible for the BMS, the charger only sends power to the battery pack where the BMS is also included. Also, the chargers' dc output voltage waveform must be well regulated. In other words, the low/high frequency components present at the output voltage must be less than the maximum allowed voltage ripple harmonics to protect the health, and thereby the lifetime of the battery.

Currently, there is not much information about the effects of ripples on lifetime of the Li-ion batteries in the literature. It is difficult to find direct impacts of the ripple on the battery especially considering that each different Li-ion technology has different structures. However, there is a mature experience about lead-acid batteries in the literature and in the market [6, 40–48]. Hence, this experience can give the designer of the charger an idea about the limits on voltage and also current ripples.

Battery manufacturers give ripple limits to which a battery can be exposed. Table 3.1 summarizes the ripple limits taken from different manufacturers for lead-acid valve-regulated lead-acid (VRLA) batteries. The design of the charger should be optimized by selecting correct inductance, capacitance, switching frequency, and feedback compensator values to meet these requirements.

In order to understand the adverse effects of ripple on batteries in general, one needs to know how the ripple current converts to extra heat. A typical single-phase charger output voltage has two main ripple frequencies: one is at the second harmonic with respect to grid frequency, and the other is at the converter switching frequency. The two current harmonic components dominate the charging current harmonics and should be regulated in magnitude.

Table 3.1: Different battery manufacturer limits for charging current and voltage ripple [6].

Manufacturer	Battery type	Voltage ripple	Current ripple
Yuasa	Lead-acid	N/A	C/10
Dynasty, Johnson Controls	Lead-acid	1.5% rms and 4% peak-peak	N/A
C&D Tech	Lead-acid	N/A	C/20

Assuming a simple battery model shown in Fig. 3.4, the extra ripple current will convert into extra heat due to the internal resistance of the battery pack, R_i in Fig. 3.4.

Temperature increase should be limited by controlling this extra current. To show the effect of temperature increase on batteries, some of the derived assumptions about lead-acid batteries in the literature are: 1) a temperature increase of about 7-10 °C causes half of the lifetime of the battery to vanish [40, 42], 2) each degree C rise in battery temperature can decrease calendar life by around 10% [6], 3) maximum allowable temperature increase should be around 3-5 °C, and 4) corruption and wear in the battery can also cause capacity loss [41].

In conclusion, the charger design procedure should include the battery ripple restrictions into account to reduce the extra heat dissipation in the battery cell. Therefore, the output voltage of the battery charger must be limited in its ripple voltage magnitude both in second harmonic ripple and in converter switching frequency ripple. Due to the electro-chemical process in the battery, the lower frequency ripple current will cause more heat dissipation compared to a higher frequency ripple current that has the same rms value.

3.1.5 Grid Connection Power Quality

The most important specification of a charger is the amount of current distortion that a charger draws from the grid. It is reported that high amounts of total harmonic distortion (THD) in line current (around 10%) can cause up to 6% decrease in the substation transformer lifetime [49]. Therefore, if this distortion is not limited, it can pose a threat

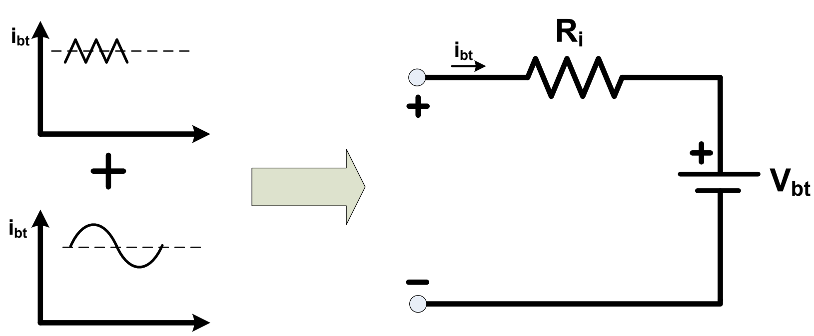


Figure 3.4: A simple equivalent circuit of the battery pack.

on the utility grid. THD is defined as follows:

$$THD = \frac{I_{c,h}}{I_{c,1}} \tag{3.3}$$

where $I_{c,h}$ is the root mean square (rms) sum of all of the harmonics of the charger current [A], and $I_{c,1}$ is the rms fundamental (60 Hz) component of the charger current [A]. However, this definition is not enough to account for all charging currents of a charger. Moreover, a charger can also be charged with small amounts of charger current, i.e. 10% of the rated charger input current, if there is real time adjustment of charger current. In this case, a much smaller charger current is drawn from the utility. Therefore, a higher THD might not be a big issue for the grid. Also, if the charger has to achieve the same THD at the rated charging current case, it would be beyond the capability of the circuit. This is a consequence of the increased switching requirement of the charger when the current magnitude is too low compared to the rated current. Therefore, there is another definition of distortion called total demand distortion (TDD), which is defined as follows:

$$TDD = \frac{I_{c,h}}{I_{c,1,rated}} \tag{3.4}$$

where $I_{c,1,rated}$ is the rated fundamental current of the charger [A]. According to [7], TDD values for an appliance connected to the distribution system is shown in Table 3.2. THD is equal to TDD when charging occurs at the rated current.

Table 3.2: Maximum harmonic current distortion in percent of current [7].

Individual harmonic order (odd harmonics)	Percent (%)
h<11	4.0
11≤h<17	2.0
17≤h<23	1.5
23≤h<35	0.6
35≤h	0.3
Total demand distortion	5.0

3.2 General Classification of EV/PHEV Chargers

Since the inception of the first EVs, there have been many different charging systems proposed. It will be helpful to review the employed charging technologies and compare them, before going into explanation of the different chargers in the literature. This will help understand the advantages and disadvantages of each method. The chargers that can be used to charge these vehicles can be classified based on the circuit topologies (dedicated or integrated), location of the charger (either on or off the vehicle), connection (conductive, inductive/wireless, and mechanical), electrical waveform (dc or ac), and the direction of power flow (unidirectional or bidirectional) as listed in Table 3.3. The first PHEVs typically will have dedicated, on-board, unidirectional chargers that will have conductive connections to the charging stations or wall outlets. In the near future, bi-directional chargers might also be used in these vehicles once the benefits of practical vehicle to grid applications are realized.

3.2.1 Dedicated Chargers vs. Integrated Chargers

A charger can be designed in two ways. First, it can be a dedicated circuit that solely operates to charge the battery. Second, the traction inverter drive can serve as the charger at the same time when the vehicle is not working and plugged into the grid for charging. This option is commonly known as integral/integrated chargers. Both of the designs have advantages and drawbacks.

A dedicated circuit compared to an integral design requires additional circuits; namely a rectifier/inverter and a dc-dc converter. On the other hand, the integral design reduces the extra circuit(s) used for charging. The common circuit used in traction and charging may be the drive inverter [13], the dc-dc converter [8], or both [50]. Therefore, the integrated

Table 3.3: Charger classification chart.

Classification type	Options
Topology	Dedicated or Integrated
Location	On-board or Off-board
Connection type	Conductive, Inductive, or Mechanical
Electrical waveform	AC or DC
Direction of power flow	Unidirectional or Bidirectional

design saves the cost of an extra power conditioning circuit as well as the space and weight required for that circuit.

The charging time of an EV/PHEV is limited by one of the following restrictions: the power rating of the charger, the rating of the circuit breaker that vehicle is plugged in, or the maximum power that the battery can accept.

Integrated chargers have the advantage of charging the battery at higher power levels, compared to a dedicated charger because of the high power rating of the drive inverter and dc-dc converter. On the other hand, integrated chargers also exhibit some disadvantages. Most integrated chargers proposed in the literature use the motor winding reactance as the input filter of the rectifier circuit which causes increased line current THD due to non-optimum values. Also, they show decreased efficiency compared to dedicated chargers. Moreover, the dc-dc converter used in motor drives should be controlled such that battery voltage and current ripple limits are fulfilled. Section 4.1.5 presents more technical discussion on integrated chargers.

Both of these chargers can employ near unity power factor via power factor correction. In other words, ac side current waveform follows the voltage waveform such that the battery and charger appears as a resistive load.

3.2.2 On-board Chargers vs. Off-board Chargers

In PHEVs, the battery charger can be either located on- or off-board the vehicle. The on-board charger provides PHEV driver additional options to charge the vehicles battery. Since the charger is on-board, it can be used to accept different charging levels as well as to match different vehicle battery requirements. On-board chargers can support Level 1 and/or Level 2 charging. Therefore, with an on-board charger, a vehicle can be charged at any outlet that is available at home garages or work places with ground protection. Availability of such charging places will increase the adoption of the PHEV technology.

An off-board charger is located in an external dedicated infrastructure. Therefore, it offloads weight and volume onto the EVSE which delivers power from the grid to the PHEV. The vehicles that only rely on off-board chargers do not have the availability of getting charge wherever there is a Level 1 or Level 2 outlet. Since the necessary circuitry stays off the vehicle, the driver needs to charge the vehicle from the specific dedicated infrastructure.

This decreases the availability of charging places. However, off-board chargers make use of faster charging and can charge a vehicle in a considerably shorter amount of time.

Considering the requirements demanded from a PHEV, the discussion of on-board and off-board chargers is crucial. PHEVs have to match the same or near availability and ease of use of the corner gas pumps to show a successful and wide spread market demonstration. For example, a 6.6 kW Level 2 charger can charge a vehicle with 30 kWh battery pack in approximately 5 h which is good for 100 miles driving range. However, a gas pump can charge a vehicle approximately in 3 min that can provide 300 mi of driving which is equivalent to 90 kWh of battery charge. This corresponds to a charging rate of 1.8 MW. The PHEV charging cannot come close to that much fast charging. However, there are off-board charging solutions to expedite the charging process.

Having an off-board, fast charging option on a PHEV greatly decreases the charging time. Therefore, a charger that can combine all on and off-board charging will be the best in terms of charging availability and speed. To achieve this, it can be possible to connect a PHEV with an on-board charger to a dc off-board charger by directly connecting the off-board charger to the battery with a special configuration. In this case, however, the off-board charger has to be able to recognize the type and size of the battery that is being charged. Coupled with this, it is important to note that fast charging may have some adverse impacts on the battery which is manifested as decreased capacity over years due to increased rate in chemical conversion process [51].

Although an on-board charger puts extra volume and weight on a vehicle, the total charging system costs are lower than that of the off-board chargers'. A 1 kW, Level 1, on-board charging system costs around $300, and a 6 kW, Level 2 charging system is priced at $1,300 [52]. On the contrary, the off-board Level 3 chargers have a significant cost disadvantage. Most of the EV/PHEVs currently in the market employ on-board chargers.

3.2.3 Inductive, Conductive, and Mechanical Chargers

There are three different methods of charging an EV battery: inductive, conductive, and mechanical charging. Conductive charging contains metal to metal contact between the charging plug and the vehicle inlet, and it is the most widespread method used in todays PHEVs.

On the other hand, inductive charging connects ac grid to the vehicle indirectly via a take-apart high frequency (HF) transformer with air gap. The term inductive is used because of this design. The most common option today that automatically charges an EV is called wireless charging. The charging takes place by driving the EV over a charging coil [53–55]. Another option is the manual charging concept. The user charges the PHEV using a paddle as if using a gas pump. The primary and secondary windings of the transformer are placed in the charging paddle and the vehicle inlet, respectively.

The last method is used to charge a vehicles battery is to replace the depleted battery pack with a full one in battery swap stations [56]. Since the battery is replaced, it can be called mechanical charging of battery. The three charging options are compared below in terms of charging accessibility, cost, and efficiency.

Charging accessibility

The charging accessibility increases greatly with currently available Level 1/ Level 2 conductive charging places at homes. This is a significant advantage for conductive charging since it includes the home charging (Level 1 and Level 2). However, inductive charging does not have this asset. The cost of installing inductive chargers is also an impediment to make it more accessible than conductive chargers.

While charging the PHEV at home is the most convenient way, an outside charging station should be available to support EVs and PHEVs on the road when they are out of charge or during a long trip. These chargers will directly extend the time/miles the vehicle is used with battery power and help customers overcome the range anxiety for EVs. Fast charging of the PHEVs outside home increases the chance of widespread deployment of PHEVs. It can be done via inductive or conductive methods. However, fast charging has two major obstacles; difficulty of injecting high current to the battery and the infrastructure costs [57].

Another method to charge a PHEV battery, mechanical charging, is proposed to decrease the time required to fully charge a battery. The major advantage of mechanical charging lies in charging speed. Since the battery to be placed in the vehicle is already charged prior to the switching, it takes less than five minutes to change it in the station. Therefore, it is comparable to fill up a tank with gas. On the other hand, battery switching warrants each manufacturer to use the same size batteries and place it in a similar location in their vehicles. Also, an automated infrastructure should be built where the battery swapping will be achieved in minutes [56].

Cost

The on-board conductive charging has more advantages when compared to inductive charging in terms of infrastructure costs. Off-board conductive charging is more expensive than either inductive or on-board conductive systems [57]. However, off-board charging systems will work like gas stations where more than one vehicle can be charged at the same time. This will decrease the costs per kW charging power. In addition, the infrastructure costs of these charging stations will not be reflected to the customers as in the case with the gas stations.

Efficiency

Charging a vehicles battery should be as efficient as possible to minimize the total charging losses. Energy losses occur at power processing circuits and charging interface. An inductive charger has three conversion stages; the first one is from 60 Hz ac to HF ac, and the second one from HF ac to dc, and the third stage is high voltage dc to battery dc voltage for better dc voltage and current regulation. In comparison, the conductive charger rectifies ac grid power to dc and adjusts the dc voltage level by dc-dc conversion process. This conversion can either be done by isolated or non-isolated converter topologies. In addition, the inductive coupling is less efficient because of the air gap between the coils. Metal to metal contact provides a more efficient way of transferring energy.

Other issues

Since conductive charging can be used at homes widely due to inherent conductive way of plugging the receptacle to the outlet, it has the definite advantage of charging batteries during the night. Therefore, it helps utilizing the electricity grid better during the night when the power demand is low.

3.2.4 AC vs. DC Chargers

Currently all the chargers require the input power to be provided from the ac electrical grid. This requires rectifying ac to dc and converting dc to dc in a suitable manner that is acceptable for the battery. Alternatively, since the battery is a dc power source, it is more efficient in terms of the charging power losses to cut through the power conversion stages and charge the battery with dc power sources such as solar panels or fuel cells. However, the

(a) (b)

Figure 3.5: (a) AAA emergency charging service [11] and (b) Nissan mobile EV charging vehicle [12].

output voltage of the dc sources may still need voltage adjustment to appropriately charge the battery. Usually, the output voltage of fuel cells and photovoltaic panels are very low compared to the battery voltage. Therefore their output voltage should first be boosted to the dc link voltage level. After, the charging control requires using another buck stage, which is commonly available in an on-board charger.

Another dc charging operation occurs during an emergency situation. When an EV is left out of charge because of either not charging in time or due to an electricity outage, a second vehicle can transfer emergency charge that will take the EV to a nearby charging station. This situation is actually very common with todays ICE vehicles showing the necessity of this operation. However, the driver of the ICE vehicle has the option of carrying a gallon of gasoline whereas for EVs, it is a must to have another electrical power source or storage device. Besides, the charge transfer is also common today. When the on-board 12 V battery of an ICE vehicle is out of charge, another vehicle can quickly transfer power to it via a jumper cable. This is called vehicle to vehicle (V2V) operation. As an example to this operation, AAA has started a service that charges depleted electric vehicles for emergency situations to help the customers get to a nearby charging station as shown in Fig 3.5a. In the U.S. and Japan, Leaf owners also get emergency service if they run out of electrical charge as shown in Fig. 3.5b.

3.2.5 Unidirectional vs. Bidirectional Chargers

Most first generation EVs and PHEVs that will be in the market use unidirectional chargers from utility to vehicle. Introduction of PHEVs to the market will alleviate the penetration of the alternative energy sources such as photovoltaic (PV) solar panels and wind turbines. Furthermore, if power can be transferred not only from grid to vehicle but also from vehicle to grid, each car will operate as a distributed power source.

In order to deliver and receive power, a charger should be able to operate in both directions. Theoretically, all chargers can supply power to the grid with small modifications to the charger. However, more advanced analyses reveal that depending on the function of V2G, the design of the charger may change [58–61]. Chapter 4 explains more on what is required to fulfill bidirectional operation using chargers.

3.2.6 Conclusion

In this section, chargers are classified in terms of their design differences. However, there is not a single charging method that will fulfill all the customer expectations. It will most likely be a combination of different methods that will maximize the charging availability of an EV.

As explained in the introduction part of this study, charger design is crucial to satisfy the customer expectations in a way that the utilization of different methods will help customers to use them when they need a charge on the way. Among the noteworthy chargers of the industry and literature which initially attracted the attention of several number of vehicle manufacturers, are dedicated, on-board, conductive, ac, and unidirectional chargers. However, there is a great potential to further develop the topologies and make the charger design more advanced with functions for future smart grid applications, more efficient to reduce heat sink size, cheaper to decrease the vehicle cost to customer, and with a greater power density for faster charging speeds for the same charger weight. In the next sections, the developments of industry and in the literature will be presented in this framework.

Chapter 4

PHEV Charger Power Electronics and Grid Integration

A battery charger is a device that is composed of several power electronics circuits used to convert ac electrical energy into dc with an appropriate voltage level to charge the battery. It has the potential to increase charging availability of the PHEVs since it can operate as a universal converter accepting different voltage, power, and frequency levels.

The focus of this chapter is to analyze and survey the available topologies applicable for on-board conductive bidirectional power transfer operation. Bidirectional power transfer means that the active power can either be transferred from the utility to the vehicle (charging) or from the vehicle battery to the grid (discharging). The charger topology investigated in this section is a single-phase Level 1 and Level 2 compatible bidirectional charger. Some other charger topologies including unidirectional topologies are also highlighted to compare with the surveyed bidirectional topologies. The three-phase fast chargers and inductive/wireless chargers are not in the scope of this chapter.

4.1 Topology Configurations for the PHEV Charger

There are basically two power conversion stages required to charge the battery using grid electricity: one is the ac-dc rectification and the other is the dc-dc conversion as shown in Fig. 4.1. Each of these stages can be formed with many different passive and active component combinations (inductors, capacitors, and semiconductor switches). Any combination of the two aforementioned stages will result in a different complete topology.

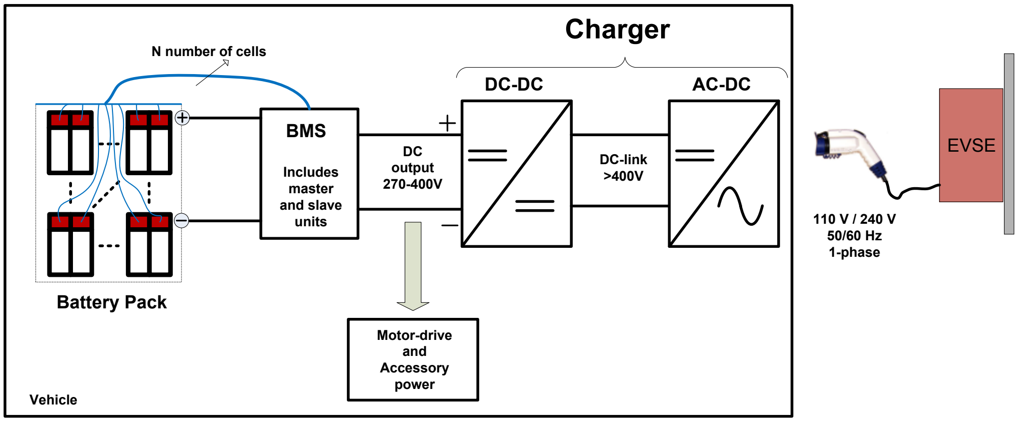


Figure 4.1: Schematic of an on-board charger with other charging components.

Rather than giving different available ac-dc power conversion circuits, only the ones that are found promising in the literature to be used with on-board Level 1 and Level 2 charging are listed here.

The discussion includes single-phase Level 1 and Level 2 chargers. Off-board dc fast charging topologies can be analogous to the ones discussed here. However, this charging level employs a three-phase system. Therefore, it will require increased number of component and higher ratings for the devices.

As shown in chapter 5, the common nominal battery voltage levels in PHEVs and EVs that are in the market, are in between 300 V- 400 V. The terminal voltage levels of PHEVs/EVs are higher than HEVs mainly because of increased power requirement from the battery. Higher terminal voltages will allow for smaller cabling size and considerably decrease the current ratings of active and passive devices for a given power level. Due to high battery voltage and a 120 V/240 V grid connection, a boost rectification stage is preferred over a buck rectification stage to prevent an unnecessary high conversion ratio between the dc link and the battery terminals.

A charger can be configured in three different ways in terms of its active and reactive power transfer capability with the utility grid. These are shown in Table 4.1. The first option is the PFC unidirectional charger that is in use in todays PHEVs and EVs. Its operation boundary is shown in Fig. 4.2a as the red line on the positive power axis of the P-Q power plane. This charger operates close to unity power factor and only allows controlling the active power used to charge the battery. Therefore, it operates only on the positive x-axis of the P-Q power plane. The second option, two-quadrant unidirectional charger allows only

Table 4.1: Different types of chargers based on power transfer operation.

Charger type	Active power direction	Reactive power direction
Power factor-corrected unidirectional	Grid-to-vehicle charging	Zero
Two-quadrant unidirectional	Grid-to-vehicle charging	Inductive or capacitive
Four-quadrant bidirectional	Grid-to-vehicle charging or Vehicle-to-grid discharging	Inductive or capacitive

charging of the battery but not discharging it. It can also support capacitive or inductive reactive power to the grid. The area inside the half-circle shown in Fig. 4.2b marks the operation area of the charger. Last, the four-quadrant bidirectional charger operates in the full circle shown in Fig. 4.2c. All of the charger types have a maximum power limitation marked as P_{max} and Q_{max}, which are defined by the charger apparent power rating and the outlet power rating that the charger gets power from.

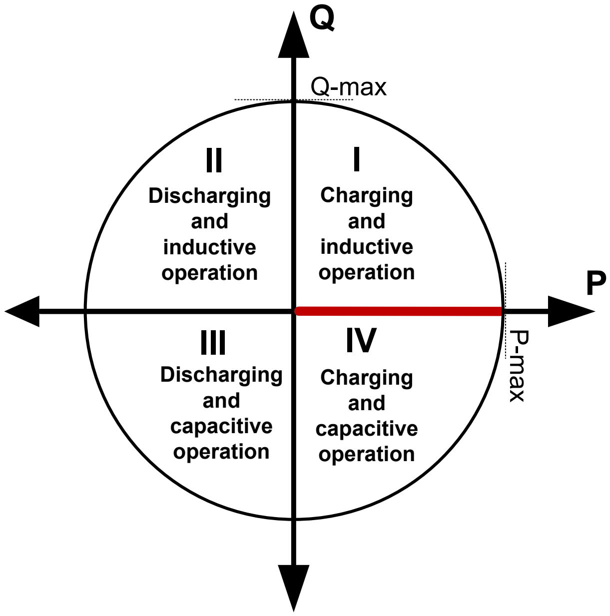
The following section will present an overview of the power electronics topology of the charger types listed in Table 4.1. The topologies listed here in the next section only include ac-dc rectification. The dc-dc conversion circuits are separately explained later in this chapter in section 4.1.4

4.1.1 Power Factor-Corrected Unidirectional Chargers

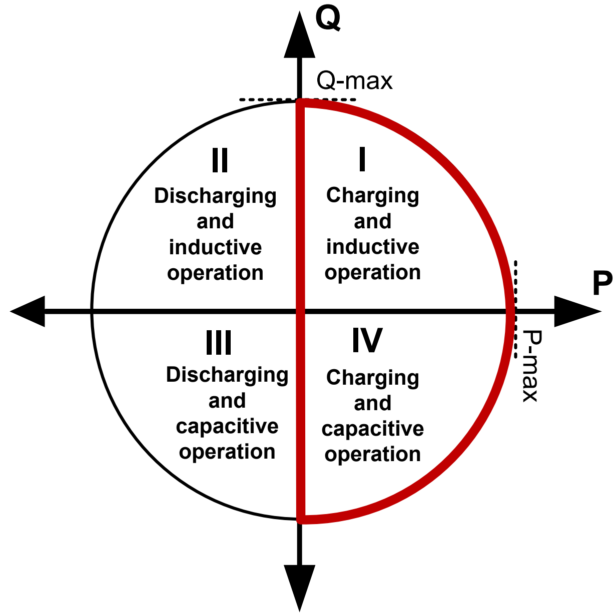
PFC unidirectional chargers only transmit power from the utility to the vehicle battery and operate with almost unity input power factor. In other words, they are not designed to exchange reactive power with the grid. Today, all of the PHEV and EV manufacturers that are in the market use this type of charger. Some of the ac-dc rectification stages are highlighted in the next sections.

Conventional AC-DC Boost Converter

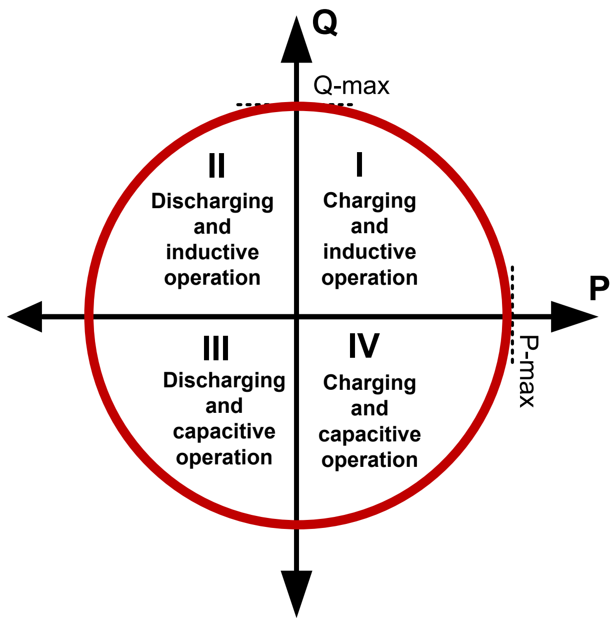
In this topology, a front-end diode bridge is used to rectify the input voltage as shown in Fig. 4.3. A boost section follows it. This topology is widespread for low power applications. Due to conduction losses of the diode-bridge, it is not well suited for power levels higher than 1 kW [62, 63]. Another problem is the design of the dc inductor at high power levels. As a solution to this problem, interleaving techniques are proposed as shown in the next section.



(a) Power factor-corrected unidirectional charger operation



(b) Two-quadrant unidirectional charger operation



(c) Four-quadrant bidirectional charger operation

Figure 4.2: Operation regions of different chargers shown in red in P-Q power plane.

Interleaved AC-DC Boost Converter

Interleaving the boost section of the conventional PFC is first introduced in [64] and shown in Fig. 4.4. The main advantages of this topology are decreased rectifier ac input and dc

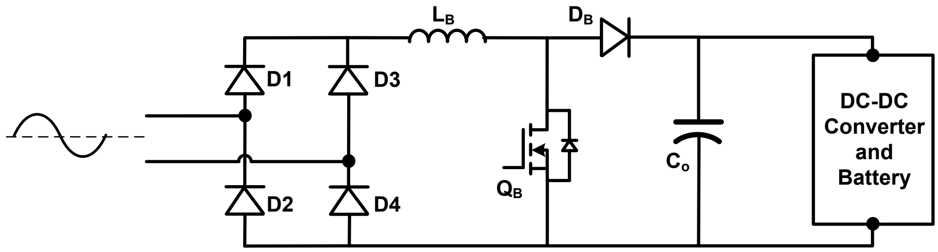


Figure 4.3: Conventional ac-dc boost converter.

output current ripple for the same switching frequency compared to a conventional ac-dc boost converter. Reduced input current ripple decreases the required switching frequency to meet a current THD level required by the utility. Reduced output ripple also results in decreased high frequency dc-link capacitor ripple requirement. Another advantage comes with the reduced current rating of the active switches as the interleaving converter halves the input current. One disadvantage of the topology is the conduction losses of the input bridge rectifier as well as increased number of semiconductor devices and associated gate control circuitry. This topology is preferred by the industry for on-board charging applications and is used for a 3.3 kW Level 2 charger [65]. Moreover, in a personal communication with Dr. Fariborz Musavi of Delta-q technologies, he suggested that the 2011 Chevrolet Volt is also employed with this ac-dc converter stage in its charger which is also rated at 3.3 kW output power level [66].

Discussion

Although power factor-corrected unidirectional chargers are mostly suited for high power factor applications, they can still be used for reactive power compensation with certain limits. However, there are two main disadvantages of this operation. First, reactive power

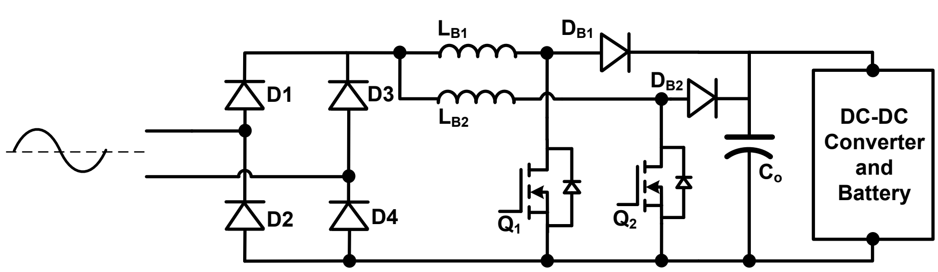


Figure 4.4: Interleaved ac-dc boost converter.

operation can only be achieved by natural commutation of current through the diodes. This poses a strict limit on the amount of phase difference that can be introduced between the grid voltage and grid current depending on the inductance value of the boost inductor. Otherwise, the current THD exceeds the allowed limit by the utility. For instance, the application given in [67] has only a maximum of 14% reactive power operation range compared to full power rating of the charger. A second disadvantage is that the charger must always be charging the battery in order to supply reactive power to the grid. In other words, if the battery has full SOC, reactive power operation is not possible. Considering these two limitations, power factor-corrected unidirectional chargers are not promising compared to other type of topologies for reactive power operation. The following sections describe the suitable topologies for this type of applications.

4.1.2 Two-quadrant Unidirectional Chargers

Two-quadrant unidirectional chargers can be used for reactive power compensation in addition to charging the battery. They have the full reactive power compensation ability as opposed to limited operation of the PFC unidirectional chargers. Some of the possible configurations of this class are listed below.

Bridgeless AC-DC Boost Converters

This converter type eliminates the input diode-bridge to attain higher efficiencies at increased power levels at the expense of using a higher number of active switches, and increased control and sensing circuit complexity. The topology proposed in [68] is called symmetrical bridgeless boost rectifier and is shown in Fig. 4.5. Another topology called asymmetrical bridgeless boost rectifier is proposed in [69] and is shown in Fig. 4.6.

4.1.3 Four-quadrant Bidirectional Chargers

Dual-buck AC-DC Half Bridge Converter

A dual-buck ac-dc half bridge converter shown in Fig. 4.7 was first introduced in [70] and also employed for a battery storage system to demonstrate four-quadrant operation capability with increased efficiency [71]. By placing the two active semiconductor switches in a diagonal structure rather than symmetrical/asymmetrical structure, four-quadrant operation

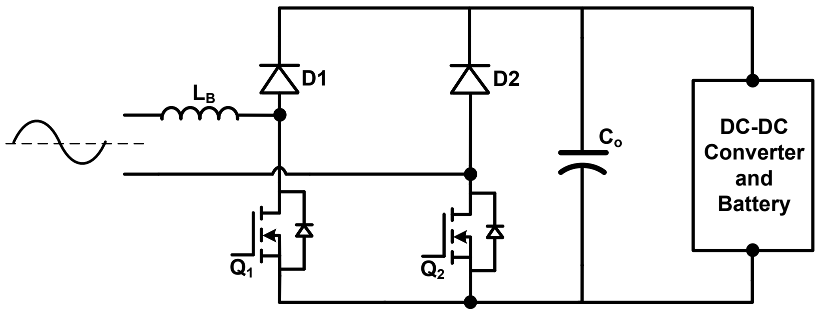


Figure 4.5: Symmetrical bridgeless boost rectifier.

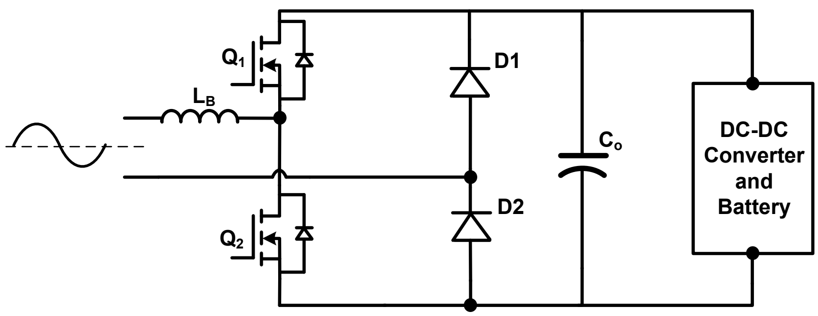


Figure 4.6: Asymmetrical bridgeless boost rectifier.

is achieved. The circuit does not need shoot through protection as there are no active switches connected in series. The circuit requires two split dc-link capacitors and two input inductors.

Conventional AC-DC Half Bridge Converter

This type of converter diagram is illustrated in Fig. 4.8. It includes two dc link capacitors, two switches, two diodes, and a coupling inductor for grid interconnection. Two sufficiently large capacitors share the dc link voltage equally. The switches S1 and S2 cannot be on at the same time to prevent any short circuit or shoot through. This requires a time delay when the switches are operated sequentially. When the switch S1 is on, either S1 or D1 conducts depending on the direction of the charger current. Similarly, when the switch S2 is on, either S2 or D2 conducts depending on the current direction. The switches may be either insulated gate bipolar transistors (IGBTs) or metal-oxide-semiconductor field-effect transistors (MOSFETs) based on the power rating of the charger. The topology is suitable

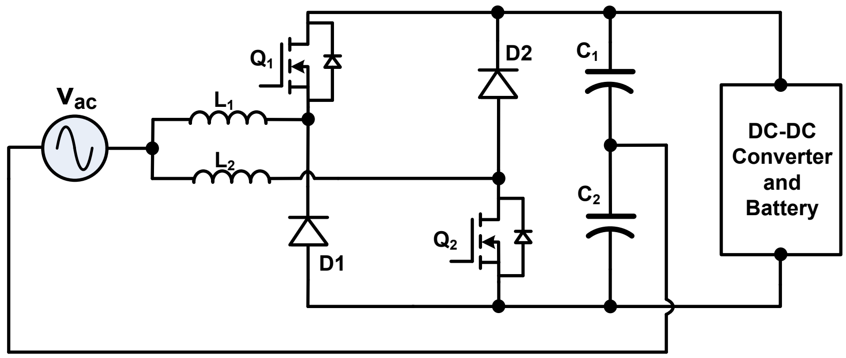


Figure 4.7: Dual-buck ac-dc half-bridge converter.

to transfer power in four quadrants. Ideally, the peak voltage and current ratings for the transistors and diodes are as follows:

$$V_T = V_D = V_{dc} \tag{4.1}$$

$$I_T = I_D = i_{c-peak} \tag{4.2}$$

where V_T and V_D are transistor and diode voltage ratings, respectively [V]; I_T and I_D are transistor and diode current ratings, respectively [A]; V_{dc} is the dc link voltage [V]; and $i_{c,peak}$ is the peak charger current [A]. A half bridge converter requires bipolar switching because there are only two possible output voltage levels, $+V_{dc}/2$ and $-V_{dc}/2$, as shown in Fig. 4.9.

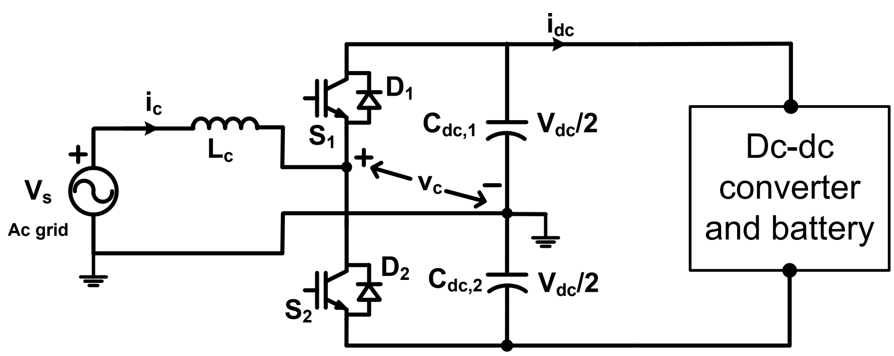


Figure 4.8: Half bridge ac-dc converter diagram.

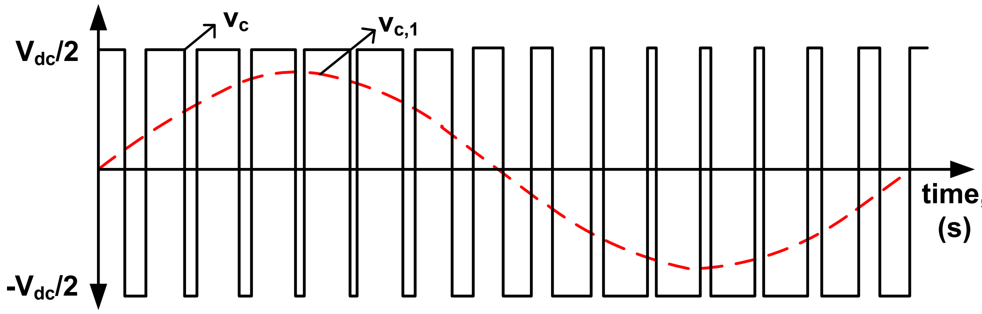


Figure 4.9: PWM output voltage waveform of the half-bridge inverter.

AC-DC Full Bridge Converter

The full bridge converter is shown in Fig. 4.10. It is comprised of a dc link capacitor, four transistors (either MOSFETs or IGBTs), four diodes, and a coupling inductor. Voltage of the capacitor is doubled in this configuration. Since the charger current depends on the level of the charging, the output current stays at the same peak. The topology is suitable for four quadrant operation and the peak voltage and current ratings for the switches are as follows:

$$V_T = V_D = V_{dc} \tag{4.3}$$

$$I_T = I_D = i_{c-peak} \tag{4.4}$$

The full-bridge converter can operate in unipolar modulation and has three output voltage levels; $+V_{dc}$, V_{dc}, and zero as shown in Fig. 4.11. Since there are three output voltage levels for the full bridge inverter, the number of switchings required for the same current THD level is effectively reduced with the full-bridge inverter compared to half-bridge inverter.

4.1.4 DC-DC Converter Stage

The fundamental bidirectional dc-dc converters are explained in this section. The two dc-dc converters under discussion are half bridge bidirectional dc-dc converter and dual active bridge bidirectional dc-dc converter.

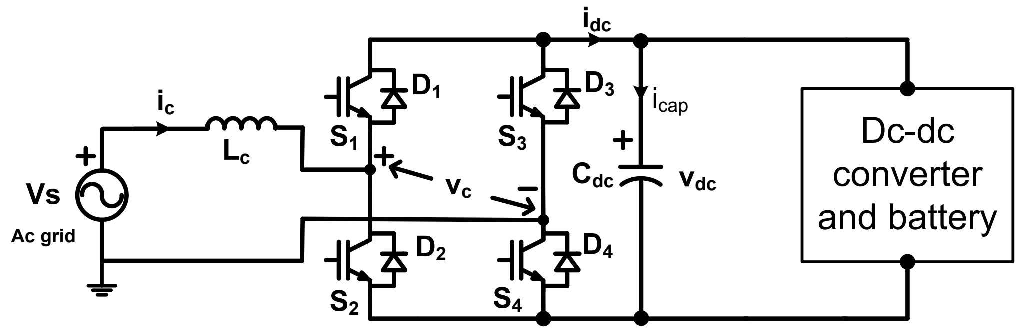


Figure 4.10: Full bridge ac-dc converter diagram.

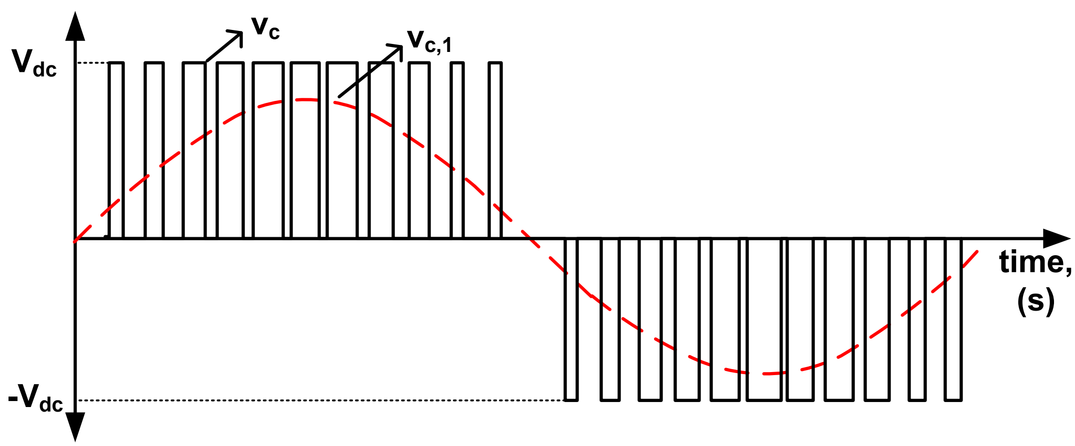


Figure 4.11: PWM output voltage of the full bridge inverter with unipolar switching.

Half Bridge Bidirectional DC-DC Converter

This converter has two transistors (IGBT or MOSFET), two diodes, a filtering capacitor and an inductor as shown in Fig. 4.12. It can transfer power in both directions. However, it can only operate as a buck converter in one direction and as boost converter in the opposite direction as illustrated in Fig. 4.13.

The bidirectional operation of the charger requires a higher dc link voltage value than the peak value of the line voltage to keep the modulation index of the inverter less than one. This is also required for sinusoidal charger current. Therefore, the dc link voltage is usually required to be higher than 350 V for 240 V grid connection. For increased control stability, the minimum dc link voltage should be selected to be at least 400 V. This value

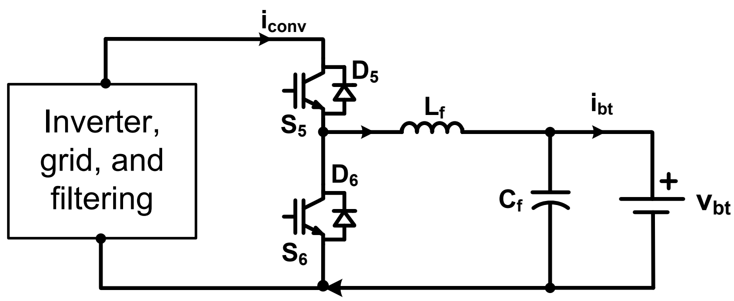
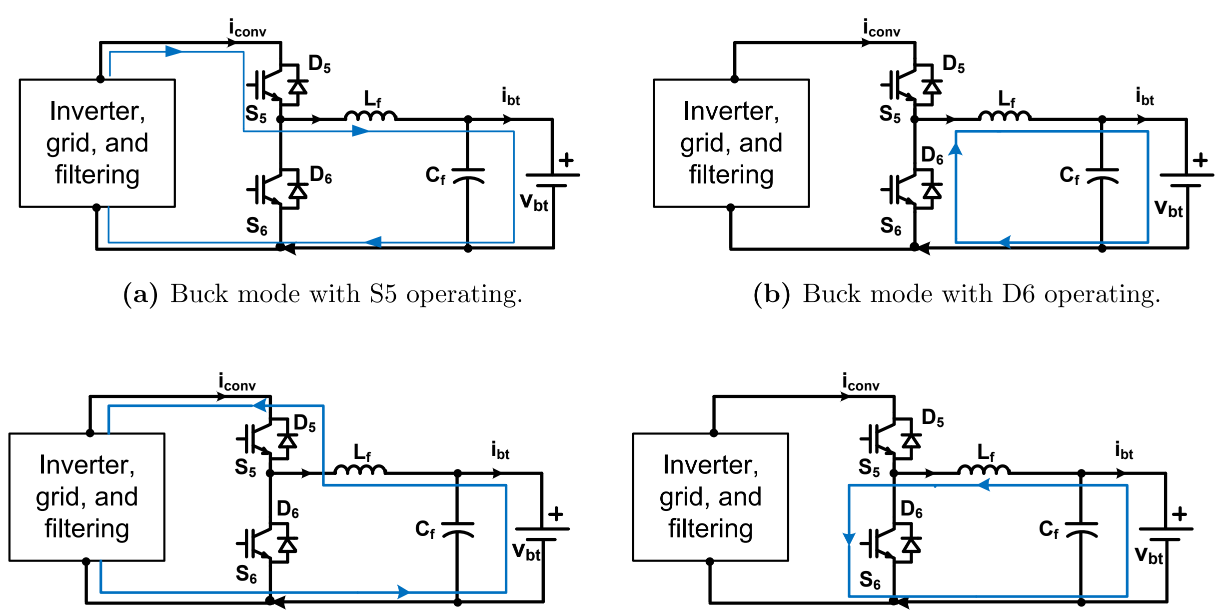


Figure 4.12: Half bridge bidirectional dc-dc converter diagram.

is higher than the regular battery pack voltage which is at 200 V - 390 V level. Therefore, the operation of the dc-dc converter is one way buck (from dc link to battery) and one way boost (from battery to the dc link).

Switches S5 and D6 operate during buck operation when the energy is transferred from the dc bus to the battery, i.e. charging operation. During this operation, S6 is turned off. In contrast, when the battery is being discharged, switch S6 and D5 operate and S5 is turned off. One disadvantage of this converter is the lack of electrical isolation of the battery from the dc link and the grid.



(a) Buck mode with S5 operating.

(b) Buck mode with D6 operating.

(c) Boost mode with D5 operating.

(d) Boost mode with S6 operating.

Figure 4.13: Buck and boost mode of operation for the bidirectional dc-dc converter.

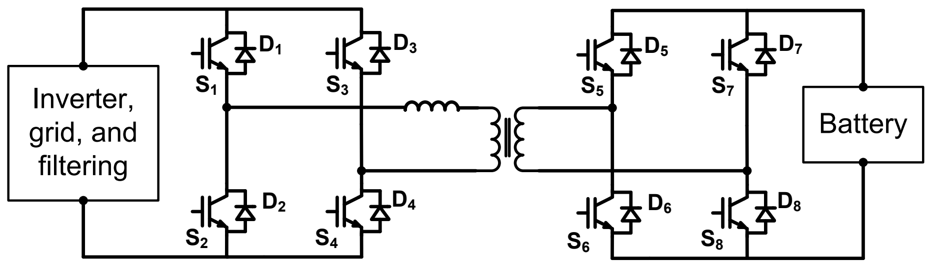


Figure 4.14: Dual active-bridge bidirectional dc-dc converter diagram.

Dual Active Bridge Bidirectional DC-DC Converter

A dual active bridge dc-dc converter has the merits of providing isolation and a higher buck/boost ratio between the dc link voltage and the battery since it has a HF transformer. The configuration of the converter is demonstrated in Fig. 4.14. This converter requires much more increased number of components than the non-isolated topology: eight transistors (IGBT or MOSFET), eight diodes, an inductor, and a HF transformer. Therefore, it has a more complex control circuitry.

The first stage of the converter inverts the dc link voltage into ac voltage during battery charging. Then, the ac voltage is electrically isolated through an HF transformer. Last, the ac voltage again is rectified to appropriately charge the battery. The process is reversed when the battery has to discharge back to the grid.

This topology is only used if a very high voltage ratio or isolation is required between the dc link and the battery pack. Usually the conversion ratio between the dc link and the battery is not selected to be very high for charger applications. Auto manufacturers, for increased safety of the users, mandate the electrical isolation requirement between the high voltage battery and charging outlets that are connected to the grid.

4.1.5 Integrated Charger Topologies

The literature studies mostly focus on designing chargers with low volume, weight, and cost. Therefore, researchers have looked at partly/completely integrating the charger into the traction drive so that the size, cost, and volume of the charger can be reduced [13,50,72–76]. What is more, utilizing the already available high power traction drive, the charging time can theoretically be reduced. While there are different topologies proposed, only the ones

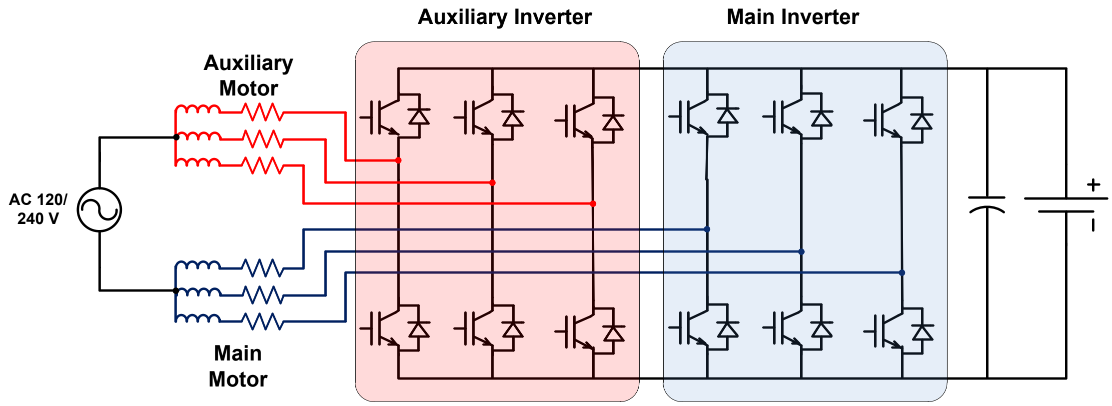


Figure 4.15: An integrated charger employing two inverters [13].

used in electric vehicle applications and published with enough technical details are discussed here.

ORNL Integrated Charger

One of the recent topologies developed at ORNL shows the performance of an integrated charger described in [13] and shown in Fig. 4.15. Here, authors utilize two inverters that are already present in a Toyota Prius HEV. The first inverter is an auxiliary inverter that is usually used for the air compressor drive motor, the water pump motor, or the generator in the vehicle. The main inverter is used to drive the motor. The auxiliary inverter is usually 1/3 of the main inverter in power rating size. Hence, only the main inverter is rated at high power level. By selecting a leg from the auxiliary inverter and another leg from the main inverter, and using the electrical machine inductance, the topology is converted to a single-phase charging circuit as shown in Fig. 4.15. This topology can only be realized using a Y-connected electrical machine.

Level 1 charging with 1.3 kW output charging power shows that the topology is 92.1% efficient, the line current THD is close to 12%, and input power factor is 0.98 [13]. Level 2 charging with 14.5 kW output charging power recorded an efficiency of 93.6%, and the current THD at that level is 6.60%.

Although this topology saves the extra charging circuit, it has several drawbacks. Because of the fixed inductance of the system, the selected switching frequency (15 kHz) is not enough to decrease the line current THD to acceptable levels (less than 5%). To further decrease the current THD, higher switching frequency will be required which will further increase the

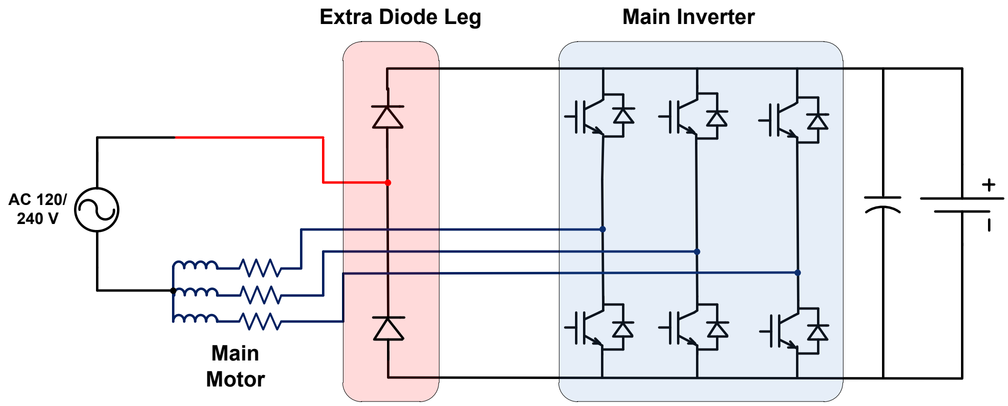


Figure 4.16: Solution to bypass the auxiliary inverter [13].

losses. Another disadvantage mentioned in the paper is the rating of the auxiliary inverter is much lower than the rating of the main inverter that would decrease the proposed fast charging time considerably. To avoid this, an extra diode leg is needed so that the auxiliary inverter will be bypassed as shown in Fig. 4.16. However, this solution will further decrease the equivalent inductance of the system that will counteract the THD of the line current. Therefore, an external filter inductance is required for this topology to achieve acceptable line current THD values.

Although not mentioned in the study, the dc-dc converter is necessary to meet charging requirements of the battery. Without a dc-dc converter, due to the conventional power equation of the single-phase inverter, the battery will see a large voltage and current ripple. Therefore, to improve the safety and lifetime of the battery pack, a dc-dc converter is needed. Generally, traction drives such as the one used in the Toyota Prius HEV employ a dc-dc converter between the inverter and the battery. That dc-dc converter can also be employed for battery charging voltage and current regulation.

AC Propulsion Integrated Charger

Another topology that is used in the market is the integrated drive and charging system manufactured by AC Propulsion and shown in Fig. 4.17 [76]. This charger is rated from 200 W to 20 kW and can operate with either 120 V or 240 V outlets. Efficiency of the system for 1.44 kW with Level 1 charging is around 85% and it is around 95% for 14 kW input power with Level 2 charging [76]. The relays K1, K2, and K2′ are used to switch from motoring to charging mode and vice versa. In traction mode, relay K1 is closed and K2 and

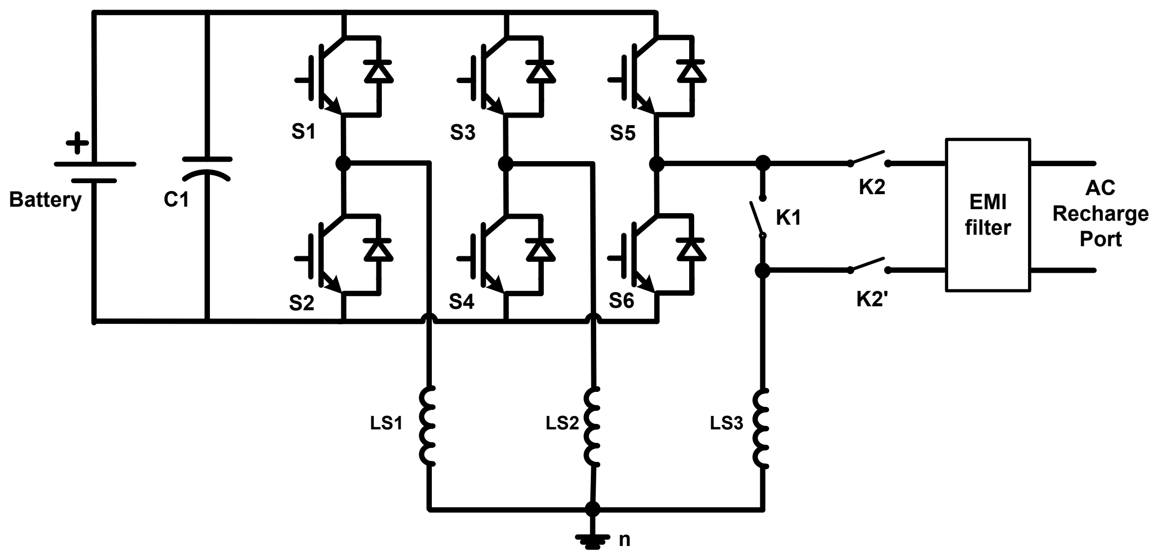


Figure 4.17: AC propulsion integrated charger [66].

K2′ are open. In charging mode, relays K2 and K2′ are closed and relay K1 is open. When charging, switches S1 and S2 are kept off, and switches S3-S6 operate to form a single phase full-bridge ac-dc converter. This system design does not employ a dc-dc converter, but it can be added if desired.

Partly Integrated Chargers

In addition to the above approaches, a charger can also partly share the circuitry with the drive-train. Rather than fully embedding the charger into the motor drive, it can only utilize the dc-dc converter already available in the drive-train. This approach is shown in Fig. 4.18. The advantage of this usage is the elimination of one extra dc-dc converter from the charger circuit. For example, Toyota Prius HEV uses a half bridge bidirectional dc-dc converter. Since this boost dc-dc converter is already rated at high power, it can also be used to charge the vehicle battery during charging operation. Moreover, already available large electrolytic capacitor can also be used to filter out second harmonic ripple due to the single-phase charging. The disadvantage of this approach is that the traction dc-dc converter is designed to be non-isolated due to the efficiency and cost concerns. Using the same converter as a charger will only provide a non-isolated charging option.

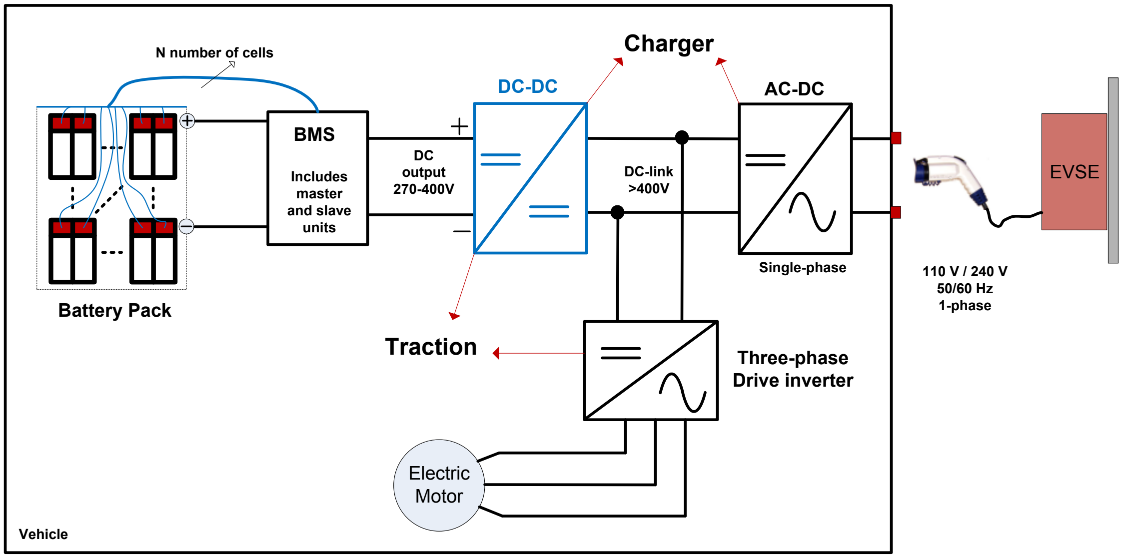


Figure 4.18: Partly integrated charger into the traction-drive.

4.2 PHEV Charger Applications in Smart Grid

4.2.1 PHEV Integration into the Smart Grid

The increase of public concern for renewable and secure energy issues forces utilities to provide more dependable, cleaner and lower-cost electrical supply. "Smart Grid" is a relatively new concept, and being used to refer next generation grid that is more information-based. Since computer-based applications provide intelligent and prompt control for complex systems, smart grid applications can be used to address main concerns on the grid such as distribution reliability, grid reliability, power quality, utilization, sustainability, market efficiency, and grid safety.

A recent DOE report predicts that the annual sales of EVs and PHEVs combined can reach up to 300 thousand vehicles by the year 2035 [77]. Another study claims that the annual sales of EVs and PHEVs combined would reach up to 500 thousand by the year 2020 with more than a cumulative of 2.5 million of them on the road [78]. The PHEV/EV charging is one of the primary concerns of smart grid applications due to its effect on power generation, transmission, and distribution when the large scale of PHEV load is considered. While the requirement for more power generation will be a concern with an increased number of PHEVs/EVs, the distribution system level issues raise more questions. Several studies look at the effect of PHEV charging at distribution system level. Studies show that depending on the number of PHEVs connected, the rating of the chargers in those PHEVs, size of the energy storage, rating of the distribution transformer (25-100 kVA), harmonic content of the charging current, geographical location, and if any charging management control is employed, the lifetime of the distribution transformer may reduce down to its 30% of regular life expectancy [79, 80]. To prevent such problems on the distribution system, the utilities must build infrastructure to enable smart grid incentives like variable rates, smart meters, grid communications, and distributed energy management.

The main question is when do costumers like to charge their PHEVs. The utility and customer preferences will be definitely different. Utilities are trying to fully use the existing capacity, save on infrastructure expansion, and put less stress on the grid. However, consumers want to fully charge their PHEVs as fast as they can in the most economical way. Using smart grid applications such as variable rate pricing schedules, demand response and load management, and vehicle to grid power transfer can overlap the customer and utility benefits.

4.2.2 Smart Grid Applications

The main smart grid applications that can be used in PHEV charging are variable utility rates, smart meters, demand response, load management, and V2G peak shaving and ancillary services. In order to direct costumers to charge their PHEV at the proper times, they need to be offered incentives such as variable utility rate. Only then, PHEVs can help utilize generation capacity of a utility that is usually idle during the off-peak hours.

The variable utility rates are mentioned as real time pricing (RTP) and time of use (TOU) in the literature. RTP defines electricity rate based on actual power generation of the utility and the amount of load consumption. Instead of using a fixed rate, a variable rate depends on each power generation level. Hence, the RTP prices are based on real time data. However, TOU has certain rates for several time ranges. For instance, the utility can prefer to increase the price of the electricity during the peak hours to prevent over loading and to decrease the stress on the grid. For each solution, using smart meters is necessary.

Load management is another smart grid application. It means to manage the residential loads by a computerized energy management system in the house either controlled by the customer or the utility. This application is not currently widely adopted in the U.S.; but seems to be promising for coming years.

4.2.3 Chargers Role in PHEV - Grid Integration

EV chargers are of critical importance to strengthen the interaction between the grid and the vehicle in an appropriate way so that neither vehicle nor grid is harmed in the short and long term. A simple unidirectional charger is sufficient to charge a vehicle battery with suitable voltage and current waveforms. In contrast, an advanced charger is capable of performing several functions whenever connected to the grid to make the grid integration beneficial to the utility and to the owner of the vehicle.

One type of interaction is called demand-side management/demand-response management. It corresponds to responding to utility signals during charging operation to provide continuous adjustment of charging power to keep the electric grid as stable as possible [26]. Secondly, the vehicle can send active and reactive power to the grid when there is a need for support by the utility. This support is called V2G, the acronym for vehicle-to-grid power transfer. It involves using the parked vehicles for distributed energy generation. Usually, a vehicle stays parked during 90-95% of its total lifetime. Therefore, the utility can benefit from this valuable asset and utilize alternative vehicle technologies, an expensive investment. The third outcome of this interaction is to utilize the excess energy produced by RES such as wind turbines, especially during nights when vehicles will be connected for daily charging.

EV chargers can provide the grid with the following services that can be included in V2G: 1) voltage support, 2) reactive power compensation, 3) active harmonic filtering, 4) power factor regulation, 5) load balancing, and 6) peak shaving. Additionally, in the case of a power outage, the charger can be used as an emergency back-up source that is often called vehicle to home (V2H) or vehicle to any load (V2X). Finally, an advanced charger can provide V2V charging to increase the charging availability of the EV even when EV is out of charge without a nearby charging option.

Drawbacks of including the above services to the charger are increased number and size for the components; hence, increased volume/weight and cost for the charger. Coupled with this, each of the objectives should be treated separately to define the net increase in the required size for the components of the charger. Furthermore, the control circuitry and programming needs to be more sophisticated to incorporate these extra functions. The utility will have to provide the required communication signals, and should determine the needed functions in the neighborhood distribution system where the vehicles are plugged-in. In conclusion, PHEV chargers can facilitate the widespread use of PHEVs and charging stations (like gas stations) by including extra functions such as grid conditioning and emergency power.

Chapter 5

Technical Commercial Market Survey of the Grid-Connected Vehicles

The terms charger and charging station may cause terminology confusion. To prevent misunderstandings, a more descriptive term of EVSE is used instead of charging station. The charger is the power conversion equipment that connects the battery to the grid or other power sources while EVSE refers to external equipment between the grid or another power source and the vehicle and it might include conductors, connectors, attachment plugs, microprocessors, energy measurement devices, transformers, communication devices, etc. This chapter aims to explain the market status of the PHEVs and EVs that will be connected to the electric grid.

5.1 PHEV and EV Survey

In this section, a detailed commercial market survey of light-duty passenger PHEVs and EVs that have demonstrated successful market penetration and/or that will be in mass market in upcoming years have been presented. The concept or demonstration vehicles and heavy duty/commercial vehicles are not included in the survey. The survey separated the analysis into three sub-sections: a) energy storage (type of battery, electrical specifications, mechanical design of the battery pack, and intended driving range), b) charging (charging type, charging time, and rated power output of the charger), and c) power-train (ICE/electric motor rated power and torque output). The vehicles are listed in alphabetical order and introduced in Table 5.1.

Table 5.1: List of the vehicles analyzed in this section.

#	Vehicle Make and Model	Type	Sales Location	Current/expected market availability*
1	BMW Mini E	EV	USA, Europe, Japan, and China	2009 - today
2	BMW Active E	EV	USA, Europe, and China	Starting in 2012
3	BYD F3DM	PHEV	China	2010 - today
4	Coda Sedan	EV	USA	Starting in 2012
5	Fisker Karma	PHEV	USA	2011 - today
6	Ford Focus Electric	EV	USA and Europe	Starting in 2012
7	Ford Transit Connect EV	EV	USA and Europe	2010 - today
8	GM Chevrolet Volt	PHEV	USA, Canada, Europe, and China	Late 2010 - today
9	GM EV1	EV	USA	1996 - 1999
10	Mitsubishi MiEV	EV	USA, Europe, Canada, Japan and, other countries	2010 - today
11	Nissan Leaf	EV	USA, Europe, Japan, and other countries	2010 - today
12	Renault Fluence Z.E.	EV	Europe, Turkey, Israel, and Australia	Starting in 2012
13	Renault Kangoo Z.E.	EV	Europe	Starting in 2012
14	Smart Fortwo ED	EV	USA	Starting in 2012
15	Tesla Roadster	EV	USA	2009 - today
16	Tesla Model S	EV	USA	Starting in 2012
17	Think City	EV	Europe and USA	2008 - today
18	Toyota Prius Plug-in Hybrid	PHEV	USA, Europe, Canada, and Japan	Starting in 2012
19	Toyota RAV4 EV- 1^{st} Generation	EV	USA	1997 - 2003
20	Toyota RAV4 EV- 2^{nd} Generation	EV	USA	Starting in 2012

5.1.1 BMW Mini E

Mini E is an EV produced by BMW and shown in Fig. 5.1. It is currently not on sale in any market. However, 500 Mini E have been delivered to selected customers under special agreements in the U.S. in a customer satisfaction test program. This test program is a part

Figure 5.1: BMW Mini E.

of a project called Project-i. It is an initiative of BMW to survey the satisfaction behavior of EV customers in the U.S. market. These vehicles are leased to customers in a one-year contract.

Energy Storage

Mini E has a Li-ion battery storage with 35 kWh energy capacity out of which approximately 28 kWh is utilized [81]. The battery is comprised of 48 modules in series. Each module has two serially connected units. 53 cells connected in parallel constitute a unit. Therefore the connection is 96-series and 53-parallel which is in short 96s53p. The total number of cells is 96×53=5,088. The terminal pack voltage is 380 V nominal. The driving range under ideal operation conditions is 156 miles.

Charging

Mini E uses an integrated charger as shown in Fig. 5.2 developed by AC propulsion. The details of this topology were described in section 4.1.5. Due to using an integrated charger, there are three different options of on-board charging available: a) Level 1: 120 V-12 A (full charging in 26.5 h), b) Level 2: 240 V-32 A (full charging in 4.5 h), and c) Level 2: 240 V-48 A (full charging in 3 h).

Figure 5.2: AC Propulsion integrated charger under the hood (Photo credit: BMW).

Power train

Mini E uses an AC induction motor with 150 kW maximum mechanical power and 220 Nm maximum torque capability.

5.1.2 BMW Active E

Active E is the next step in the Project i framework. Active E is scheduled to be deployed in the U.S., Europe, and in China in 2012 to limited number of customers as the continuation of the field tests. The vehicle is shown in Fig. 5.3.

Energy Storage

Active E comes with 32 kWh Li-ion battery. It has a driving range of 100 mi. The pack is comprised of a total of 192 cells with each cell having a 40 Ah capacity.

Charging

Active E uses a 7.7 kW on-board charger. Level 1 and Level 2 charging are available. Using a 120 V outlet, the battery charges in 16-20 h. Using the higher power Level 2 charging with 240 V-32 A outlet rating, it takes 4-5 h to fully charge the vehicle [82, 83].

Figure 5.3: BMW Active E.

Power train

Active E uses a synchronous motor with 125 kW power output and 250 Nm of torque capability.

5.1.3 BYD Auto F3DM

F3DM is the first commercially available modern PHEV in China and in the world. It is shown in Fig. 5.4. DM stands for dual-mode. F3DM is a series-parallel hybrid electric vehicle. The controller runs the vehicle in electric mode at start-up. When the vehicle needs more power during acceleration, vehicle operates in parallel hybrid mode; the gasoline engine and the electric motor drive the wheels together. The engine also serves as a range extender and works in series hybrid mode similar to Chevrolet Volt. The F3DM has been sold for 149,800 Yuan ($21,900) in China starting in 2010, and it had been slated to go on sale in EU and the U.S. in 2011. However, the reported sales of the F3DMs in China have been decreasing since August 2010 [84].

Energy Storage

F3DM has 40 to 60 mi (64 to 97 km) all-electric range. It uses a Li-ion battery with LFP cathode and with 16 kWh energy capacity. It is reported that F3DM uses 100 li-ion cells with each having a 3.3 V nominal voltage.

Figure 5.4: BYD F3DM (Photo credit: The New York Times).

Charging

The on-board charger allows charging the vehicle in less than 7 h.

Power train

There are two permanent magnet ac synchronous motors with 25 kW and 50 kW output power respectively. Also, F3DM has a 50 kW, 1 L and 3-cylinder gasoline engine placed in the vehicle; therefore a total of 125 kW is available to drive this 4-door midsize sedan vehicle.

5.1.4 Coda Sedan

Coda Automotive is an American car manufacturer established for only EV production similar to Tesla and Fisker that are introduced later in this chapter. The car is expected to be in the market in early 2012 and is shown in Fig. 5.5.

Energy Storage

Coda Sedan has 150 mi (241 km) of range achieved by 36 kWh lithium-ion battery with lithium iron phosphate cathode composition. The pack is comprised of 728 cells with 104s7p connection. It has a nominal terminal voltage of 333 V.

Charging

Coda carries a 6.6 kW on-board charger. It charges the battery fully in six hours using a 240 V connection. It also has a back-up charging mode where the charger is connected to a

Figure 5.5: Coda Sedan (Photo credit: Coda Automotive).

120 V Level 1 outlet. The charging power with this option is 1.3 kW and the charging time increases to around 28 h.

Power train

Coda has 100 kW traction motor with 300 Nm maximum torque capability.

5.1.5 Fisker Karma

Karma is a PHEV and is produced by Fisker Automotive (a joint venture of Quantum Technologies and Fisker Coachbuilt LLC). It is shown in Fig. 5.6.

Energy Storage

It has 50 mi (80 km) of all-electric drive range for 20.1 kWh battery capacity. It uses a Li-ion battery with nanophosphate technology. The battery terminal voltage is 336 V nominal [85]. Karma can come with optional 130 W solar roof that provides 0.5 kWh peak daily energy production. This means maximum 4 to 5 mi (6 to 8 km) free cruising for a continuously sunny week.

Figure 5.6: Fisker Karma (Photo credit: Fisker Automotive).

Charging

It has both Level 1 and Level 2 charging options using an on-board 3.3 kW battery charger. Fisker Automotive also sells customers off-grid solar panel chargers for households with an additional cost.

Power train

The dual motor traction system uses two electric motors. Total mechanical power of the electric motors can reach up to 300 kW with 1300 Nm torque capability. The vehicle also has 2.0 L turbocharged direct injection 4-cyl gasoline engine. Sport-hybrid mode can drive vehicle for 300 mi (483 km) continuously for a combined charge depleting and charge sustaining energy consumption mode. Maximum vehicle speed is 125 mph.

5.1.6 Ford Focus Electric

Focus Electric is expected to be available in the US market in 2012. The vehicle is shown in Fig. 5.7.

Energy Storage

Focus Electric uses a 23 kWh Li-ion battery supplied by LG Chem Ltd. It has a 100 mi (161 km) driving range.

Figure 5.7: Ford Focus Electric (Photo credit: Michael Gil).

Charging

Full charge occurs in 3-4 h using 240 V outlet. It takes around 20 h using 120 V outlet. Ford Focus Electric carries a 6.6 kW charger [86].

Power train

Focus Electric uses a permanent magnet electric traction motor rated at 92 kW power output. It has 246 Nm torque capability.

5.1.7 Ford Transit Connect EV

Ford has partnered with Azure Dynamics to build Transit Connect EV which is a commercial vehicle type based on the popular Ford Transit Connect van platform from Europe. The vehicle is shown in Fig. 5.8. Ford began shipping them to customers in North America and Britain in December 2010. It costs $57,400.

Energy Storage

It has a 28.3 kWh Li-ion battery pack supplied by Johnson Controls Saft. The battery pack has 16 modules in which each module has 12 cylindrical Li-ion cells. Total number of cells is $12 \times 16 = 192$. Each cell has 41 Ah capacity rating. Depending on the SOC, the terminal voltage of the battery pack changes from 215 V to 390 V. The EV range of the vehicle is 80 mi (129 km) [87, 88].

Figure 5.8: Ford Transit Connect EV by Azure Dynamics (Photo credit: Mario Roberto Duran Ortiz).

Charging

Transit connect can be charged in 6-8 h using a 240 V outlet. It also has the option to be charged using a 120 V outlet. The charger power rating is 3.3 kW.

Power train

Transit Connect EV has a Siemens model 135, 3-phase ac induction motor, which has a 300 V nominal input voltage. It has 117 Nm continuous and 292 Nm peak torque capability. The continuous power output of the motor is 52 kW and the peak power output is 105 kW [87].

5.1.8 GM Chevrolet Volt

Chevrolet Volt is the first mass-market PHEV produced by GM in the U.S., and it is shown in Fig. 5.9. GM launched the Volt in limited numbers in November 2010. It is scheduled to be on sale in Europe in 2011 and in Australia in 2012. The list price is announced $41,000 without $7,500 federal tax credit available for plug-in vehicles in the U.S.

Energy Storage

It has a 16 kWh lithium-ion battery with around 10 kWh usable capacity. It consists of 288 cells and has a weight of 437 lb (198 kg) . The total pack is comprised of 96 battery modules each connected in series. Each module has 3 parallel cells. Batteries are manufactured by LG Chemical. The battery provides approximately 35 mi (56 km) all electric range for

Figure 5.9: GM Chevrolet Volt.

the vehicle which is estimated by the EPA. This range changes depending on the driving conditions from 25 to 50 mi (40 to 80 km). To reduce capacity degradation, Chevy Volt employs only an SOC window of 30%-80% of the available capacity.

Charging

The charger of the Chevrolet Volt is compatible with a standard electric outlet and uses SAE J1772 standard connector. The charger can either charge the battery using a Level 1 or Level 2 charging levels. With Level 1 charging it takes about 10 h to fully charge the vehicle while with Level 2 charging this time is reduced down to 4 h. The charger is rated at 3.3 kW.

Power train

Chevrolet Volt uses 111 kW (150 hp) electric motor with 273 Nm rated torque and 370 Nm maximum torque capabilities. It has a 53 kW generator that is powered with a 4-cylinder gasoline engine. Volt is a series hybrid electric vehicle that can provide extended range by generating extra power from its gasoline engine.

5.1.9 GM EV1

GM EV1, one of the first EVs introduced into the market in mid-1990s and shown in Fig. 5.10. Gen I is released in 1996 and Gen II is released in 1999. This vehicle was discontinued in 2002.

Figure 5.10: GM EV1 (Photo credit: GM).

Energy Storage

The Gen I EV1 used a lead-acid battery pack with 312 V terminal voltage and 16.5 kWh energy capacity. It provided a range of 60 mi (97 km) per charge. Gen II vehicles came with 18.7 kWh at 312 V, and increased the EV1's range to 100 mi. Later, the car was updated with NiMH batteries, and the new pack retrofitted to earlier cars. The NiMH batteries were rated at 26.4 kWh and had 343 V of terminal voltage. The range of the car increased up to 160 mi (257 km) per charge.

The lead-acid battery pack of Gen II included 26 serially connected 12 V batteries with a total of 312 V pack terminal voltage. The NiMH packs had 26 battery cells each having 13.2 V output voltage with a total of 343 V pack voltage [89].

Charging

EV1 used both Level 1 and Level 2 charging methods. The Level 2 charger, which is a Magne Charge inductive charger as shown in Fig. 5.11, was actually split between the vehicle and the charging station with a high frequency (HF) transformer. It connected ac grid to vehicle indirectly via the take-apart HF transformer. The term inductive is used because of this design. In this charging concept, the user charges the EV using a paddle as if using a gas pump. The primary and secondary windings of the transformer are placed in the charging paddle and the vehicle inlet, respectively.

While these stations were user friendly and secure, they were not available everywhere which impeded extending the vehicles range. In Fig. 5.11, the picture shows the dedicated

Figure 5.11: 6.6 kW external inductive charger of GM EV1 [14].

charging circuit of GM EV1 which had two options for charging. First is the 220 V, 6.6 kW single-phase dedicated off-board charging circuit as shown in Fig. 5.11. It is reported that it took approximately 3 h to fully charge the 26 kWh GM EV1 lead-acid battery with 15% SOC always being residual in the battery [14]. The second option had been to fully charge the battery with a trunk mounted charger using 110 V and 1.2 kW in 15 h. This charger was used to increase the availability of charging when there was no off-board charger available.

The input current THD of the charger at rated power was reported to be 4.06%. The result of the power factor test was 0.996 [14].

Power train

GM EV1 used an induction motor with 102 kW output power and 149 Nm torque capability.

5.1.10 Mitsubishi MiEV

Mitsubishi Innovative Electric Vehicle (MiEV) technology is a subcompact all-electric vehicle that is available in Japan and the United Kingdom. It will also be on sale in the U.S. in early 2012. Fig. 5.12 shows the U.S. version. The vehicle is also called “Mitsubishi i. It has a starting price with equivalent of $48,800 in UK, and $42,130 in Japan. The U.S. market price is $21,625 with the tax rebate. The 2012 Mitsubishi i has been selected to be the best fuel economy vehicle for sale in the U.S. market, with an official miles per gallon equivalent (MPGe) rating of 112 [90].

Figure 5.12: Mitsubishi Miev (Photo credit: Mitsubishi Motors).

Energy Storage

MiEV has 100 mi (161 km) of range with Japan 10-15 mode driving pattern [91]. The EPA rated mileage is 62 mi (100 km) for the U.S. version. Using the U.S. national-average electricity rates, the i will cost just over $2.50 per full charge from zero. It uses a 16 kWh lithium-ion battery pack. The pack consists of 22 modules and each module has four cells. There are a total number of 88 cells. Nominal terminal voltage of the pack is 330 V.

Charging

Level 1 charging with a 120 V outlet and with a charging current rating of 8 A charges the battery full in 22.5 h. Optional home charging dock gives a full charge in 6.5 h using a 240 V and 15 A outlet. Mitsubishi i can also be equipped with an optional fast charging port. Using 50 kW fast chargers of CHAdeMO protocol, it can receive 80% SOC in 30 min [91].

Power train

It uses a 49 kW permanent magnet ac synchronous motor placed on the rear axle of the vehicle. The maximum torque capability is 180 Nm. The car's top speed is limited to 130 kilometers per hour (80 mph).

5.1.11 Nissan Leaf

Nissan Leaf is an all-electric vehicle mass-produced in the U.S. and is shown in Fig. 5.13. It was launched in December 2010 in Japan and the United States, early 2011 in Europe, and it will be mass-marketed globally from 2012. It is a compact 5-door family car with a maximum of 87 mph (147 km/h) vehicle speed. The announced price in the US is $32,780

Figure 5.13: Nissan Leaf (Photo credit: Richard Kelly [15]).

without \$7,500 federal tax credit. Additionally, State of California has a \$5000 tax credit for all-electric vehicles that would be applied for Nissan Leaf as well.

Energy Storage

Leaf's all-electric range is 73 mi (117 km) based on Environmental Protection Agency (EPA) tests, and it uses a 24 kWh battery. The battery consists of 48 modules connected in series with each module containing four cells. Each module has two parallel cells connected in series with each other. Therefore, the total number of cells is 192. Each cell has 33.1 Ah discharge capacity based on a 1/3C discharge current rating. The average voltage of each cell is 3.8 V. Therefore, the terminal voltage of the pack is $(3.8{\times}2){\times}48{=}364.8$ V. The voltage vs. discharge capacity of the cells manufactured by Automotive Energy Supply Corporation is given in Fig. 5.14 [16]. The total weight of the battery pack is 660 lb (300 kg).

Charging

Nissan Leaf has three types of connections to the grid. The first two ac connections are Level 1 and Level 2. Level 1 is called trickle charge while Level 2 refers to normal charge in the operation manual. Level 1 corresponds to 120 V and 12 A, and Level 2 240 V and 18 A. Trickle charge approximately takes 21 h and normal charge lasts about 7 hours. The third charging option is dc or quick charging with a 400 Vdc connection with up to 50 kW of power. It takes approximately 30 min to charge the Li-ion battery from discharged to 80% charged. The rated output power of the on-board charger is 3.3 kW.

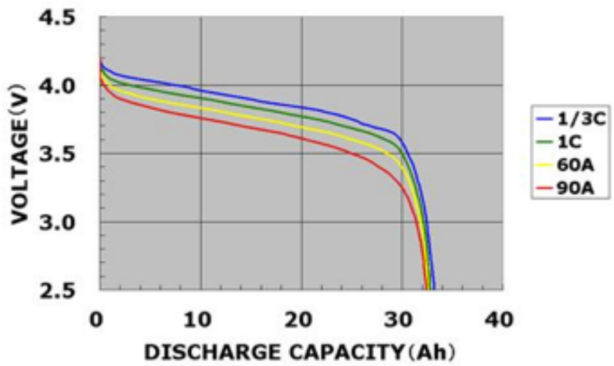


Figure 5.14: Discharge data of Nissan Leaf Cells (Figure credit: Automotive Energy Supply Corporation) [16].

Figure 5.15: Renault Fluence Z.E. (Photo credit: Renault).

Power train

Nissan Leaf has an 80 kW permanent magnet electric motor with 280 Nm torque capability.

5.1.12 Renault Fluence Z.E.

Fluence Z.E. shown in Fig. 5.15 is the electric version of the Renault Fluence that is currently in the market in Europe. Fluence Z.E. is expected to hit the market in Europe in Fall 2012.

Energy Storage

Fluence Z.E. has 22 kWh of Li-ion battery energy storage. It has a driving range of 100 mi (161 km) measured with New European Driving Cycle (NEDC).

Figure 5.16: Renault Fluence Z.E. ready to switch its battery pack (Photo credit: Project Better Place).

Charging

Fluence Z.E. has several charging options. It can be charged full in 10 h using standard outlet in Europe that is rated with 220 V and 10 A. If a special wall-box is installed, the charging time reduces to 6-8 h using a 220 V and 16 A circuit. It is reported that the on-board charger output power rating is 3.7 kW [92]. It also has accelerated 1 h charging, and fast 30 min charging options using public charging stations. Fluence Z.E. will be the first electric vehicle complying with the Better Place battery-switching network that utilizes battery-swapping stations as explained in section 3.2.3. Using Project Better Place infrastructure, shown in Fig. 5.16, charging time reduces to less than five minutes with the demonstrated projects in Israel, Denmark, and Australia.

Power train

Fluence Z.E. uses a 70 kW output power synchronous electric motor with 226 Nm torque capability.

5.1.13 Renault Kangoo Z.E.

Another electric vehicle from Renault Z.E. series is Kangoo Z.E. that is the electric version of its mini cargo van Kangoo. It is illustrated in Fig. 5.17. Its debut in the market is expected to be in October 2011.

Figure 5.17: Renault Kangoo Z.E. (Photo credit: Renault).

Energy Storage

Kangoo Z.E. has an electric range of around 100 mi (161 km). It is powered by a 22 kWh Li-ion battery pack.

Charging

Kangoo Z.E. has also a 3.7 kW on-board charger as Fluence Z.E. has. Moreover, the charging options are the same as Renault Fluence Z.E.

Power train

Kangoo Z.E. has a 44 kW synchronous electric motor output power with 226 Nm torque capability.

5.1.14 Smart Fortwo Electric Drive

Daimler produces Smart Fortwo electric drive, Smart ED for short, expected to be in the U.S. auto market in 2012. The vehicle is shown in Fig. 5.18.

Energy Storage

Smart ED uses a 16.5 kWh lithium-ion battery and has 84 mi (135 km) of range measured with NEDC cycle.

Figure 5.18: Smart ED (With consent from [17]).

Charging

Smart ED carries a 3.3 kW on-board charger. Level 1 charging takes 12 h for a full charge. Using a 240 V outlet the full charging time reduces to around 8 h.

Power train

The electric motor has maximum 30 kW mechanical power and it can reach up to 70 mph (112 km/h) maximum vehicle speed. Peak torque output is 120 Nm.

5.1.15 Tesla Roadster

The Tesla Roadster is an EV sports car produced by Tesla Motors and shown in Fig. 5.19. It is also the first production automobile that uses a lithium-ion battery. The sale price of the Roadster is $109,500 in the U.S. without any federal tax credits. In 2009, Tesla Motors provided a 3-year/36,000 mi (58,000 km) battery warranty and an optional 4-year/50,000 mi (80,500 km) extended warranty available at an additional cost.

Energy Storage

Tesla Roadster has 53 kWh battery energy capacity and 244 mi (393 km) of driving range. The battery contains 6,831 lithium-ion cells and it has an output voltage of 375 V for the electric motor. The battery weight is 992 lb (450 kg).

Figure 5.19: Tesla Roadster.

Charging

Full charging of the battery requires 3 to 4 h using Level 2 charging that supplies 70 A, 240 V electricity. Tesla uses a special charging connector, and it is compatible with a TS-70 EVSE from Clipper Creek.

Power train

The electric motor is a 185 kW (248 hp) 3-phase induction motor with 270 Nm torque capability, and weights less than 70 lb (32 kg).

5.1.16 Tesla Model S

Very similar to Fisker Karma, Tesla Model S is a luxury sports sedan vehicle announced for mass production in 2012. The vehicle is shown in Fig. 5.20. The Tesla Model-S will be assembled at NUMMI plant in California, and will be available in 2012.

Energy Storage

Model S has various battery options based on the user needs which are a) 42 kWh, b) 65 kWh and c) 85 kWh. The number of cells used in each these designs are 5000, 8000 and 8000, respectively. For these battery specifications, Model-S can drive up to 160 mi (258 km), 230 mi (370 km) or 300 mi (483 km), respectively.

Charging

Model S uses the unique Tesla connector for battery charger. The battery is compatible for back up (Level 1), normal (Level 2) and quick chargers (Level 3). The 42 kWh battery can

Figure 5.20: Tesla Model S (Photo credit: Tesla Motors).

be fully charged in 45 min by using a Level 3 charger system. Also the company announced that Model-S would be compatible with battery swapping stations.

Power train

Tesla Model S uses an ac induction motor with 228 kW output power and 415 Nm maximum torque capability.

5.1.17 Think City

Think has been producing electric vehicles since the early 1990s. The 5^{th} generation of Think City, shown in Fig. 5.21, was prepared in 2007. Currently, it is produced in Finland. Think City is an urban electric car.

Figure 5.21: Think City.

Energy Storage

There are two options of battery energy storage that comes with the vehicle. One is using a Zebra battery and the other is using a Li-ion battery. The battery storage capacity is 24 kWh and the vehicle range is 100 mi (161 km) [93, 94].

Charging

Think City accepts a 230 V outlet with a current rating of 10 A-16 A. Zebra battery reaches to 80% SOC from a depleted charge state in seven hours and it takes four more hours to fill up the battery from 80%-100%. However, to charge the Li-ion battery 0%-100% takes eight hours.

Power train

Think City uses an electric motor with 37 kW peak output power.

5.1.18 Toyota Prius Plug-in Hybrid

Toyota Prius plug-in hybrid, as shown in Fig. 5.22, is based on the third generation Toyota Prius hybrid electric vehicle. Its anticipated market debut is mid-2012.

Energy Storage

Toyota Prius Plug-in Hybrid uses a 4.4 kWh Li-ion battery and has 15 mi (24 km) electric-only operation mileage range. The battery pack voltage is 346 V nominal. Each battery cell used in the pack has a 3.6 V cell voltage, and they are designed using 96 series 3 parallel (96s3p) connection [95].

Charging

Prius PHEV can be charged fully in 3 h using a 120 V, 15 A Level 1 outlet. It takes about an hour to fully charge with 240 V Level 2 outlet. It carries a 2 kW on-board battery charger.

Power train

The hybrid system includes a 1.8 L DOHC 16-valve VVT-i gasoline engine that develops 73 kW at 5200 rpm, and 142 Nm at 4000 rpm. The system uses two high-output electric

Figure 5.22: Toyota Prius Plug-in Hybrid (Photo credit: Ralf Roletschek).

motors, one 60 kW unit that mainly works to power the compact, lightweight transaxle, and another smaller electric motor rated at 42 kW that works as the electric power source for battery regeneration and as a starter for the gasoline engine.

5.1.19 Toyota RAV4 EV

The first generation of Toyota RAV4 EV, shown in Fig. 5.23, was leased to customers between years 1999 and 2003. The vehicle was discontinued in 2003 but sold to customers who would like to keep their vehicles. However, Toyota plans to launch the second generation RAV4 EV, shown in Fig. 5.24, in 2012 collaborating with Tesla Motors Company.

Energy Storage

First generation RAV4 EV had 130 mi (210 km) city driving range with a total of 27 kWh of NiMH battery energy storage. It used 24 serially connected battery cells each having 12 V cell voltage. It makes a total of 288 V nominal pack voltage [18]. The second generation RAV4 EV will have 96 mi (155 km) driving range with a total of 37 kWh of Li-ion battery energy storage [96].

Charging

The first generation of RAV4 had models with either conductive or inductive charging. It has a single-phase, 240 V and 40 A Level 2 charger. The charger draws a rated current from the grid with 2.1% TDD [18]. The vehicle and the EVSE are shown in Fig. 5.25. Notice

Figure 5.23: Toyota RAV4 EV first generation.

Figure 5.24: Toyota RAV4 EV second generation.

that the charger is actually in the vehicle and the picture shows the EVSE of the conductive charging system.

The second generation RAV4 EV has two options of conductive charging. First is Level 1 charging using 120 V outlet that charges the vehicle battery full in 28 h. The second option is Level 2 charging using 240 V outlet that charges the battery full in 12 h.

Power train

First generation RAV4 EV motor had 50 kW maximum power and 190 Nm maximum torque. It used a permanent magnet ac electrical motor. The second generation RAV4 EV motor has a maximum of 133 kW power output and 233 Nm maximum torque.

Figure 5.25: Toyota RAV4 EV charging with a conductive charger inside the vehicle (EVSE is also shown outside the vehicle here) [18].

5.2 Summary

Table. 5.2 lists the important specifications of the surveyed vehicles. As shown in this table, the battery pack voltage has an increasing trend compared to older versions of the vehicles. Most of the vehicles have more than 330 V nominal pack voltage. However, mechanical configuration of cells differs from vehicle to vehicle. The on-board dedicated charger output power rating generally stays between 3 kW to 7 kW. However, the vehicles with integrated chargers (BMW Mini E and Tesla Roadster) have higher on-board charging power capability ($>$ 11 kW).

Table 5.2: Specifications for commercially available PHEV/EVs.

#	Vehicle Make and Model	Type	Battery Size (kWh)	Electric range (mi)	Battery voltage (V)	Charger power (kW)	Level 2 charging time(h)	EM power (kW)	EM torque (Nm)
1	BMW Mini E	EV	35	156	380	11.5	3 - 4.5	150	220
2	BMW Active E	EV	32	100	N/A	7.7	4 - 5	125	250
3	BYD F3DM	PHEV	16	40 - 60	N/A	N/A	7	75	N/A
4	Coda Sedan	EV	36	150	333	6.6	6	100	300
5	Fisker Karma	PHEV	20.1	50	336	3.3	6	300	1300
6	Ford Focus Electric	EV	23	100	N/A	6.6	3-4	92	246
7	Ford Transit Connect EV	EV	28.3	80	390 (max)	3.3	6-8	105	292
8	GM Chevrolet Volt	PHEV	15	35	N/A	3.3	4	111	273
9	GM EV1 (NiMH version)	EV	26.4	160	343	6.6	3	102	149
10	Mitsubishi MiEV	EV	16	62	330	3.3	6.5	49	180
11	Nissan Leaf	EV	24	73	365	3.3	7	80	280
12	Renault Fluence Z.E.	EV	22	100	NA	3.7	6-8	70	226
13	Renault Kangoo Z.E.	EV	22	100	NA	3.7	6-8	44	226
14	Smart Fortwo ED	EV	16.5	84	NA	3.3	8	30	120
15	Tesla Roadster	EV	53	244	375	16.8	3-4	185	270
16	Tesla Model-S	EV	42,65, and 85	160, 230, and 300	N/A	N/A	N/A	228	415
17	Think City	EV	24	100	N/A	3.3	8	37	N/A
18	Toyota Prius Plug-in Hybrid	PHEV	4.4	15	346	2	4	60	N/A
19	Toyota RAV4 EV- 1^{st} Gen.	EV	27	130	288	6	N/A	50	190
20	Toyota RAV4 EV- 2^{nd} Gen.	EV	37	96	N/A	N/A	12	133	233

Chapter 6

PHEV/EV Charger Connection to the Grid: Components and Standards

6.1 Electrical Vehicle Supply Equipment

EVSE is a particular term that refers to any device related to external vehicle equipment such as conductors, the EV connectors, attachment plugs, power outlets, or apparatuses installed specifically for energy transfer from the grid to the EV. An EVSE may include connectors, transformers, computer network, and sensors etc. The main concerns for the EVSE include efficiency, compactness and robustness, compliance of standards and codes, and user friendliness.

Efficiency of the EVSE is important for overall system economy, and the connectors should provide high power transfer efficiency. Compactness of the EVSE is another important consideration. High power charging stations can be designed by using smaller bulkhead, coolant system and high efficient transformers.

Longer life of an EVSE system decreases the maintenance and operation costs of the system. Therefore, design of the EVSE should be convenient with long operating time and high/low temperature conditions. Moreover, its lifetime should not be less than the lifetime of the vehicle.

The compliance of EVSE with universal/local standards, official codes, and original equipment manufacturer (OEM) requirements is another crucial consideration during the design process. Charger voltage, connectors, mounting schemes, input voltage and frequency, communications and battery compatibility, and environmental concerns are some of the primary factors. The standards and codes will be explained in section 6.3 in more detail.

6.2 General Considerations for Charger Standards

In this section safe, reliable, and convenient charging related equipments, and their related standards/codes are explained in detail. The following lists the primary concerns on charger standards:

- safe, robust and unique connector for conductive and inductive coupling of charger with battery,
- the wiring methods, design and construction process of the connectors,
- location of the EVSE to prevent hazardous situations, especially high power charging stations for safe, secure and weather proof operation,
- digital communication of charger with utility and battery controller for safety, pricing, and customer/business applications,
- personal protection of consumers due to high voltage power electronics, fault current detection and over current protections,
- using chargers as distributed energy sources, smart grid compatibility, V2G capabilities and related communication procedures, and
- electromagnetic compatibility limitations for safe EV environment.

6.3 Standards and Codes for PHEV Chargers

The society of Automotive Engineers is the leading institution for any kind of vehicle standards including PHEV/EVs. As of November 2011, many standards are under development such as charging infrastructure and grid communications, charger interface systems, and electric utility interface for smart grid applications. In addition to technical requirements of SAE, UL safety standards and EV standards of IEC are also presented.

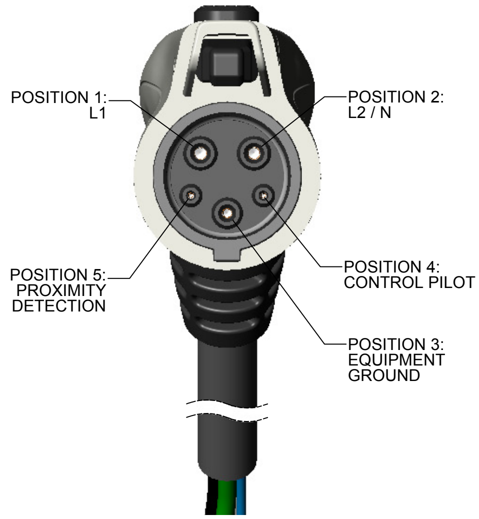


Figure 6.1: SAE J1772 Connector (Photo credit: Methode Electronics).

6.3.1 SAE EV/PHEV Charging Power Transfer Standards

SAE J1772: Electric Vehicle Conductive Charge Coupler Standard

SAE J1772 is the common standard used by most of the vehicle manufacturers, especially those in the U.S., mentioned in chapter 5. The current version, given in [38], has been effective since January 2010. It comprises general physical, electrical, functional, and performance requirements for Level 1 and Level 2 conductive charging connection between EVSE and the on-board charger. The current version does not include the dc off-board charger connection standards.

The J1772 connector has five connection wires listed in the below Table 6.1. The visual representation of the connector is also shown in Fig. 6.1.

Table 6.1: Explanation of J1772 connection plugs.

Connection cable	Description
AC power connector-L1	Power connector for Level 1 and Level 2 connection
AC power connector-L2/Neutral	Power connector for Level 1 and Level 2 connection
Ground connection	Connects EVSE equipment ground to EV/PHEV chassis ground
Control pilot	Control input
Proximity detection	Detector of the presence of the charger connection

The below sequence roughly summarizes the operation principle of the connection as it is described in [38]:

- When the user inserts the connector to the vehicle inlet, the proximity detection causes a state change in the EVSE control electronics.
- If the EVSE is working and ready to supply energy, it sends a square wave signal using the control pilot to the charger.
- The charger determines the current rating of the EVSE by measuring the duty ratio of the square wave signal sent by the EVSE. Therefore, charger controller board sets the available maximum current transfer rating.
- EVSE energizes the system by closing its main power relays, and the charging begins.

Pilot control can also transmit digital information for further functions for Level 1, Level 2 charging, and this data communication is required for dc charging. The status of the standard is active and it is published on January 15, 2010.

SAE J1773: Electrical Vehicle Inductively Coupled Charging

Although SAE J1772 is the dominant charger coupling standard in the industry, SAE reaffirmed the inductive coupling standard in 2009. The J1772 standard was originally developed in 1995. The inductive coupling standard covers manual connection of Level 1, Level 2, and high power Level 3 charging. The automatic connection methods are not the scope of this standard. The inductive coupling occurs at higher frequencies (130 kHz to 360 kHz). Therefore, grid frequency coupling is also out of scope.

In addition to the inductive coupling, it includes a coupler detection for connection check, and 2-way communication using an infrared (IR) communication interface. The inductive charging system manufacturers are in the process of replacing radio frequency (RF) communication to IR interface, but the standard also allows the use of RF communication interface. This standard was reaffirmed on May 28, 2009.

SAE J2894: Power Quality Requirements for Plug In Vehicle Chargers - Part 1 (requirements) and Part 2 (test methods)

SAE J3894 standard was initiated in 2009. Part 1 (requirements) aims to determine a) ac grid characteristics that impact the charging equipment, b) parameters of the charging equipment to preserve the quality of the ac utility service, and c) target values for power control and quality parameters.

Part 2 (test methods) will address topics such as bidirectional power flow, total power factor, power conversion efficiency, total current harmonic distortion, current harmonic distortion at individual frequencies, charger input voltage range, surge, or sag limits, input frequency variations, inrush current, and momentary outage ride-through capability. Part 2 will help EVSE and charger manufacturers and utility companies to make reasonable design decisions. Both parts of the standard are currently under development.

SAE J2293: Energy Transfer System for Electric Vehicles Part 1 and 2

SAE J2293 defines directly or by reference, all requirements and characteristics of the total EV energy transfer system (EV-ETS) to guarantee the functional interoperability of an EV/PHEV charger and the EVSE. This system is responsible for the conversion of utility ac energy into the dc energy to charge the EV/PHEV battery. The first part of this standard was published on July 7, 2007 and part 2 was published on July 8, 2008.

SAE J2954: Wireless Charging of Electric and Plug-in Hybrid Vehicles

The SAE J2954 standard "establishes minimum performance and safety criteria for wireless charging of electric and plug-in vehicles" [97]. Furthermore, it "defines acceptable criteria for minimum performance, safety and testing for wireless charging of electric and plug-in electric vehicles. It establishes ac Level 1, ac Level 2 and dc Level 3 charge levels and specifies a location for wireless charging. Adoption of a standard for wireless power transfer based on charge level will enable selection of an appropriate charging based on vehicle requirements thus allowing for better vehicle packaging, reduced cost, and ease of customer use." as stated in [97]. This standard is currently under development.

SAE J551/5: Performance Levels and Methods of Measurement of Magnetic and Electric Field Strength from Electric Vehicles

The SAE J551/5 covers "the measurement of magnetic and electric field strengths over the frequency range 9 kHz to 30 MHZ and conducted emissions over the frequency range 450 kHz to 30 MHZ" as stated in [98].

Conducted emission requirements in this document are only applicable to on-board conductive battery chargers switching at a frequency higher than 9 kHz. Off-board or inductive chargers are not in the scope of this standard. This standard was revised in January 22, 2004.

SAE PHEV/EV Communication Standards

The following sections present a summary of the current SAE PHEV/EV charging communication standards. As shown in Fig. 6.2, J2836 and J2847 include the core standards, and J2931 and J2953 complete and verify the core components [19].

SAE J2847 and SAE J2836: Communication between Plug-in vehicles and the Utility Grid

SAE J2847 establishes the requirements for communications and SAE J 2836 presents the use cases for those communications. The list of the relevant parts of the standards is shown in Table 6.2.

SAE J2931: Communications for PHEVs/EVs

SAE J2931 covers requirements for several systems that need to communicate within each other during the PHEV/EV charging. These systems include PHEV/EV, EVSE, home area network (HAN), energy management system (EMS), and the utility grid. These standards also intend to assure smart grid interoperability compliance. The titles of all the seven parts

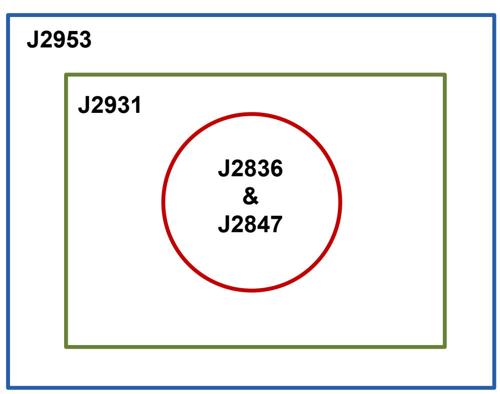


Figure 6.2: Interrelation of SAE EV/PHEV charging communication standards [19].

Table 6.2: SAE J2847 and J2836 standards.

Part	SAE J2847 (detailed info)	SAE J2836 (use cases)
1	Communication between PHEV/EV and utility grid (Published on May 9, 2011)	Use cases for communication between PHEV/EV and utility grid (Published on April 8, 2010)
2	Communication between PHEV/EV and off-board charger (Published on October 21, 2011)	Use cases for communication between PHEV/EV and off-board charger (Published on September 15, 2011)
3	Communication between PHEV/EV and utility grid for reverse energy flow (in progress)	Use cases for communication between PHEV/EV and utility grid for reverse energy flow (in progress)
4	Diagnostics between PHEV/EV and EVSE (in progress)	Use cases for diagnostics between PHEV/EV and EVSE (in progress)
5	Communication between PHEV/EV, customers, and home area network (in progress)	Use cases for communication between PHEV/EV, customers, and home area network (in progress)
6	Wireless charging communication between PHEV/EV and utility grid (in progress)	Use cases for wireless charging communication between PHEV/EV and utility grid (in progress)

are listed in Table 6.3. As shown, it shows various requirements as various protocols are available for customers and the utility. All parts of the standard are in progress.

SAE J2953: Plug-In Electric Vehicle (PEV) Interoperability with Electric Vehicle Supply Equipment (EVSE)

As there are many different PHEV/EV manufacturers and the number of EVSE manufacturers is increasing rapidly, the SAE recommended practice J2953 "establishes the interoperability requirements and specifications for the communication systems between PHEVs/EVs and EVSE for multiple suppliers" as stated in [99]. The standard is in progress.

6.4 Protection and Design Related Standards

The next section highlights some of the safety standards dedicated to EV/PHEV charger, EVSE, and other equipments. The remaining standards will be listed for further information.

Table 6.3: Summary of the parts of the SAE J2931 standards.

Part 1	Power Line Carrier Communications for Plug-in Electric Vehicles
Part 2	Inband Signaling Communication for Plug-in Electric Vehicles
Part 3	PLC Communication for Plug-in Electric Vehicles
Part 4	Broadband PLC Communication for Plug-in Electric Vehicles
Part 5	Telematics Smart Grid Communications between Customers, Plug-In Electric Vehicles (PEV), Energy Service Providers (ESP), and Home Area Networks (HAN)
Part 6	Digital Communication for Wireless Charging Plug-in Electric Vehicles
Part 7	Security for Plug-in Electric Vehicle Communications

6.4.1 UL 2202: Electric Vehicle Charging System Equipment

UL 2202 covers conductive and inductive EV/PHEV charging system equipments with a rating of 600 V or less. The UL 2202 is applicable for on/off board charging equipment, which are installed according to American National Standards Institute (ANSI)/National Fire Protection Association (NFPA) 70 of NEC. These requirements do not cover battery chargers for charging engine-starter batteries, and industrial battery chargers.

6.4.2 UL 2231: Standard for Safety of Personnel Protection Systems for EV Supply Circuits Part 1 and 2

The main concern of UL 2231 is "to reduce the risk of electric shock to the user from accessible parts, in grounded or isolated circuits for charging electric vehicles. These circuits are external to or on-board the vehicle" as stated in [100] which also includes general requirements, and the standards for personnel protection systems for EV supply circuits.

6.4.3 UL 2251: Plugs, Receptacles and Couplers for Electric Vehicles

The UL2251 standard covers requirements for plugs, receptacles, vehicle inlets, and connectors up to 800 A and up to 600 V ac or dc for use with conductive EV/PHEV charging systems in accordance with NEC, ANSI/NFPA-70 for either indoor or outdoor safe locations.

6.4.4 NEC Article 625

Similar to any electrical infrastructure installation, EV charging infrastructure is concerned for some federal, state, and local building codes as well as electrical codes. In this section, as a federal code institution, only the NEC will be discussed. The state codes and local permits depend on the places where charging infrastructure will be installed.

The NEC defines safety codes for electrical construction and operation. The Article 625 is the common code for all over the US that covers EV charger installation. The Article 625 published by the NFPA and it is revised every other 3 years. Key requirements of Article 625 include the following:

- Wiring methods, including electric vehicle coupler design, construction, and functionality
- EVSE coupler requirements, including polarization, non-interchangeability, construction and installation, unintentional disconnection, and grounding pole requirements
- EVSE construction requirements, including rating, markings, means of coupling, cable, interlock, and automatic de-energization of the charge cable
- EVSE control and protection, including over current protection, personnel protection, disconnecting means, loss of primary source, and interactive systems
- EVSE location requirements, including hazardous locations, indoor sites and ventilation requirements for indoor installations, and outdoor site requirements.
- The basic requirements are as follows. EV charging receptacles/coupler should be stored or located between 18 in (46 cm) and 48 in (1 m and 22 cm) above the floor for indoor applications, and 24 in (61 cm) above the grade for outdoor applications. Explosive materials such as flammable vapors, liquids and gases, combustible dust or fibers, and materials that can ignite on contact with air should be kept away from all EVSE.

Different from previous versions, 2005 version of Article 625 includes:

- NEC 625.2, “The Neighborhood Electric Vehicles” are assumed as a type of regular electric vehicles, so the main requirements need to be met for neighborhood EVs as well.

- NEC 625.26, “Interactive Systems” allows bidirectional power transfer between EV and the power source. When EVs are connected to the electrical power supply, they can serve as an optional standby system or an electric power back-up source.

6.5 Other Standards

There are a wide range of standards that affect the design and manufacturing of the EV/PHEV charging components. All other related standards are listed in 6.4.

Table 6.4: Other standards for EV/PHEV charging.

UL 2594	Electric Vehicle Supply Equipment
UL 1741	Inverters, converters, controllers and interconnection system equipment for use with distributed energy sources
UL 62	Standard for Safety of Electric Vehicle Cable
UL 2735	Subject Standard for Safety of Electric Utility (Smart) Meters
UL 458A	Subject Standard for Safety of Power Converters/Inverters for Electric Land Vehicles
UL 2580	Subject Standard for Safety of Batteries for Use in Electric Vehicles
UL 2733	Subject Standard for Safety of Surface Vehicle On-Board Cable
UL 2734	Subject Standard for Safety of Connectors for Use with On-Board Electrical Vehicle (EV) Charging Systems
IEC 61851-1	Electric vehicle conductive charging system - Part 1: General requirements
IEC 61851-21	Electric vehicle conductive charging system - Part 21: Electric vehicle requirements for conductive connection to an ac/dc supply
IEC 61851-22	Electric vehicle conductive charging system - Part 22: AC electric vehicle charging station
IEC 62196-1	Plugs, socket-outlets, vehicle connectors and vehicle inlets - Conductive charging of electric vehicles - Part 1: General requirements
IEC 62196-2	Plugs, socket-outlets, vehicle connectors and vehicle inlets - Conductive charging of electric vehicles - Part 2: Dimensional compatibility and interchangeability requirements for a.c. pin and contact-tube accessories
IEEE P2030	Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads (Published on September 10, 2011)
IEEE P2030.1	Guide for Electric-Sourced Transportation Infrastructure Working Group (In progress)
IEEE P2030.2	Guide for the Interoperability of Energy Storage Systems Integrated with the Electric Power Infrastructure (In progress)
IEEE P2030.3	Guide for Test Procedures for Electric Energy Storage Equipment and Systems for Electric Power Systems Applications (In progress)
IEEE P1547	Standard for Interconnecting Distributed Resources with Electric Power Systems
IEEE P1547.1	Standard Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems
IEEE P1547.2	Application Guide for IEEE Std 1547, IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems
IEEE P1547.3	Guide for Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems
IEEE P1547.4	Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems
IEEE P1547.6	Recommended Practice for Interconnecting Distributed Resources with Electric Power Systems Distribution Secondary Networks
IEEE P1547.7	Guide to Conducting Distribution Impact Studies for Distributed Resource Interconnection (In progress)
IEEE P1901	Standard for Broadband over Power Line Networks: Medium Access Control and Physical Layer Specifications

Chapter 7

Conclusion and Summary of the Report

EVs/PHEVs are already in the market and their number is increasing each year. Each grid connected vehicle is equipped with two important assets: a larger energy storage unit (battery) and an ac-dc conversion device. They can be controlled to support grid energy storage services. This report focuses on the integration of the grid connected vehicles to the grid by explaining EV/PHEV technology, vehicle traction batteries, charging terms and definitions, charger topology selections, and charger related standards and codes. It also provides a market survey for grid connected vehicles in terms of their energy storage capacity and charging circuitry.

The report explains the battery technologies and related charging requirements. The definitions of vehicle battery charging terminology are presented. The chargers have been classified in terms of their different features such as location, topology, connection type to the vehicle, electrical waveform of the charging coupler, and the direction of power flow.

V2G operation changes the topology of the charger in a great deal. There are different operation modes that can yield different topological structures. Currently, almost all of the market vehicles employ PFC unidirectional chargers. However, a two-quadrant unidirectional charger can also supply limited amount of reactive power while the vehicle is under charging operation. A four-quadrant bidirectional charger can operate in all of the power quadrants without any limitation. It is also possible to combine the charging circuitry with the traction-drive power electronics that yields integrated charger topologies.

Report lists the grid charging related specifications of the vehicles that have been introduced into the market by the following auto manufacturers (by alphabetical order): BMW, BYD, Coda, Fisker, Ford, GM, Mitsubishi, Nissan, Renault, Smart, Tesla, Think, and Toyota. Last, all the vehicle battery charging related standards are listed.

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