Chapter 14
Advanced Electric Vehicles

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Abstract This chapter primarily aims at addressing the practical issues for commercialization of current and future plug-in hybrid electric vehicles (PHEVs), and focuses primarily on power electronics based solutions for both current as well as future electric vehicle (EV) technologies. New PHEV power system architectures are discussed in detail. Key EV battery technologies are explained as well as corresponding battery management issues are summarized. Advanced power electronics intensive charging infrastructures for EVs and PHEVs are also discussed in detail.

14.1 Introduction

Conventional vehicles (CVs), which use petroleum as the only source of energy, represent majority of the existing vehicles today. As shortage of petroleum is considered as one of the most critical world-wide issues, costly fuel becomes a major challenge for CV users. Moreover, CVs emit greenhouse gases (GHG), thus, making it harder to satisfy stringent environmental regulations.

One of the most attractive alternatives includes electric vehicles (EVs) or zero emission vehicles (ZEVs), which only consume electric energy. However, due to the limited energy densities of the current commercially available battery packs, the performance of EVs is restrained as neighborhood vehicles, with limitations of low speed, short autonomy, and heavy battery packs. As a successful example,

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S. Chakraborty et al. (eds.), *Power Electronics for Renewable and Distributed Energy Systems*, Green Energy and Technology, DOI: 10.1007/978-1-4471-5104-3_14,

Canada-based ZENN's commercialized EV has an average speed of 25 mph and 30–40 miles driving range per charge.

Currently, the most promising and practical solution is the hybrid electric vehicles (HEVs). Its propulsion energy is usually from more than two types of energy storage devices or sources, and one of them has to be electric. HEV drive trains are basically divided into series and parallel hybrids. Series hybrids are electric-intensive vehicles, as the electric motor is the only traction source, and the internal combustion engine (ICE) merely works at its maximum efficiency, as an on-board generator, to charge the battery.

Keeping in mind the goals of creating an energy wise, cost-effective, and overall sustainable society, plug-in hybrid electric vehicles (PHEVs) are recently being widely touted as a viable alternative to both conventional as well as regular HEVs. PHEVs are equipped with sufficient on-board electric power, to support daily driving (an average of 40 miles/day) in an all-electric mode, only using the energy stored in batteries, without consuming a drop of fuel. This, in turn, causes the embedded ICE to use only a minimal amount of fossil fuel to support further driving beyond 40 miles, which further results in reduced GHG emissions.

PHEVs can reduce fuel consumption by charging its battery from the grid. It is, thus, a valid assumption that moving into the future, a large number of PHEV users will most definitely exist, and the overall influence of charging the on-board energy storage system (ESS) cannot be neglected. Related literature firmly states that by the year 2020, the market share of PHEVs will increase to about 25 %. Based on this data, the additional electric energy demanded from the distribution grid for 5 million PHEVs would be roughly about 50 GWh per day. Also, the typical charging time would be 7–8 h, which might make it hard to accommodate these additional loads in the load curve without increasing the peak load. Also, the required additional charging energy would have a possible impact on the utility system.

Expanding the electric system the conventional way, with large generating plants located far from the load centers, would require upgrading the transmission and distribution systems too. Besides the high costs, this can take many years before obtaining the right of way. Alternatively, smaller power plants based on renewable energy, such as wind energy, which is a cost-effective renewable energy addition to many utilities. Also, solar energy can be installed in a fraction of that time on the distribution system, which is commonly referred to as "distributed generation (DG)." Photovoltaic (PV) presents a modular characteristic and can be easily deployed in the roof top and facades of residences and buildings. Many corporations are adopting the green approach for distributed energy generation. For instance, *Google* has installed 9 MWh per day of PV on its headquarters, Googleplex, in Mountain View, California. At the moment, it is connected to Mountain View's section of electricity grid. Alternatively, it could be used for charging PHEVs during work hours, being a great perk for environmentally concerned employees. The energy stored in the batteries could also be used for back-up during faults. In Canada, the latest projections (2000) indicate that by 2010, renewable DG sources will represent at least 5 % of the total energy produced and 20 % of cogeneration, from the actual figures of 1 and 4 %, respectively. Therefore, from the environment point of view, charging PHEVs with solar power will be the most attractive solution.

This chapter primarily aims at addressing the practical issues for commercialization of current and future PHEVs, and focuses primarily on power electronics based solutions for both current as well as future EV technologies. New PHEV power system architectures are discussed in detail. Key EV battery technologies are explained as well as corresponding battery management issues are summarized. Advanced power electronics intensive charging infrastructures for EVs and PHEVs are also discussed in detail.

14.2 Electric, Hybrid Electric, and Plug-In Hybrid Electric Vehicle Topologies

14.2.1 Electric Vehicles

The EVs are powered only by electricity. Therefore, they include electric motors for propulsion, batteries and/or fuel cells for long-term storage, and sometimes ultra capacitors for transient stabilization, making a combination called hybrid energy storage system (HESS). The technology of EVs is retrofit to other EVs such as electric bikes, electric boats, and electric airplanes. and so on. EVs supplied from batteries (the most common) are called battery electric vehicles (BEVs). Historically, the very first cars by the middle of the nineteenth century were BEVs because of the simplicity of electric motors compared to ICEs. However, ICE cars replaced BEVs due to the low range of BEVs and low specific energy batteries when compared to gasoline.

Batteries must be properly sized for achieving a given driving range. Therefore, many cells should be put in series and parallel in a battery pack to provide suitable voltage and rating for driving the EV motors. Various issues must be considered in designing battery packs, such as charging methods for improved battery lifetime as presented in Sect. 14.3.1.4.

14.2.2 Hybrid Electric Vehicles

A hybrid vehicle utilizes two or more sources of energy for propulsion e.g., gasoline, natural gas, hydrogen, liquid nitrogen, compressed air, wind, solar, electricity, or any other. If one of these sources is electricity, this vehicle is called HEV. This electricity is usually provided by a battery pack or a fuel cell. HEVs generally combine ICEs with electric motors to run the vehicle. They may include vehicles other than cars but hybrid electric cars are the most common ones. The main purpose of using HEVs, the same as EVs is to reduce the amount of emissions and fuel consumption. This can be achieved in different ways, the simplest could be turning off the ICE during idle times such as during the waiting time at stop lights (called by stop–start control strategy). Another possibility is by converting the car kinetic energy to electric energy during breaking, instead of wasting such energy as heat in the brakes. This can improve the gas efficiency (mile per gallon range) to approximately 15 %. This efficiency increases as the efficiency of the wheel to battery path components are improved by better design. Different configurations of ICE and electric motor are possible in a HEV. They will be described in the following section as follows.

14.2.2.1 Hybrid Electric Vehicles Topologies [1, 2]

Series Hybrid

In a series hybrid, the ICE acts as a prime mover to run a generator. This generator charges a battery pack and this battery pack will supply power to the electric motors. In fact, the ICE is the main primary source of power; however, the HEV runs by the direct mechanical coupling of the electric motor and not from the ICE. The benefit rises from the fact that the ICE engine can be smaller compared to a standard car. In addition, the ICE in a series hybrid operates at the most efficient operating point most of the time, resulting in improved overall efficiency of the system. In terms of power flow analysis, the power from generator may supply the electric motors directly, however, to smooth the power transients or variable power demand from electric motors, the battery pack is necessary to act as an energy buffer. Depending on the design, in order to minimize the stress on the battery pack leading to improved life cycle of the battery pack, banks of ultra capacitors may also be used to supply highly transient currents. As mentioned before, during the vehicle braking the kinetic energy can be transformed to electrical energy using a generator; therefore, the electric machine and the motor drive in a series hybrid is designed to act as a motor generator. Generally, series hybrids are more

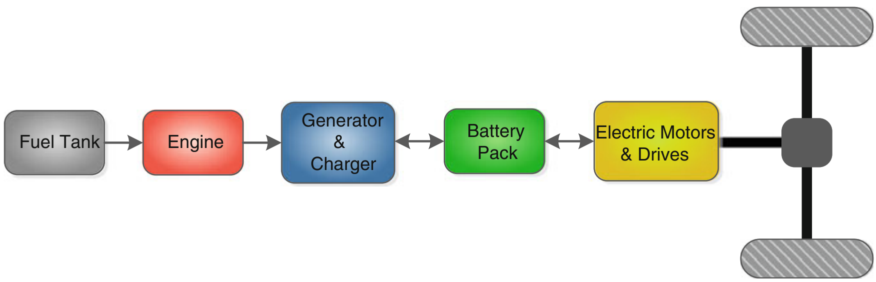

Fig. 14.1 Typical series-hybrid topology

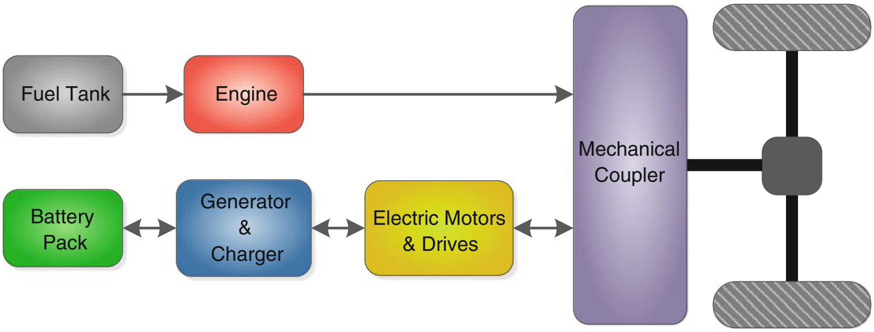

Fig. 14.2 Typical parallel-hybrid topology

efficient for low-speed range and urban areas. A typical series hybrid power train is illustrated in Fig 14.1.

Parallel Hybrid
In a parallel hybrid, the ICE can directly run the HEV in parallel to the electric motor. In other words, the transmission is governed by ICE, electric motors, or both of them at the same time depending on the driving condition and control strategy. The typical configuration of parallel hybrid is shown in Fig. 14.2. In general, parallel hybrid is more efficient for high-speed ranges, i.e., highways. In today's parallel HEV market, the electric motors are low power and usually rated less than 30 kW with a relatively small size battery pack since in parallel hybrid the electric motor is accompanied by ICE and does not supply all the power. Regenerative braking can be supported in parallel hybrids also.

Series–Parallel Hybrid
This configuration is shown in Fig. 14.3, it is also known as power split topology and combines the features of series and parallel hybrid. As shown in the figure, a power split is utilized to share the output mechanical power from ICE to the drive shaft or to the electric generator. This ensures the battery pack is always

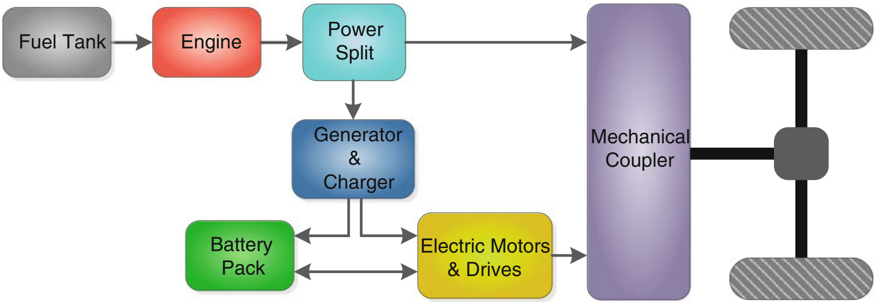

Fig. 14.3 Typical series–parallel hybrid architecture

maintained charged to be able to run the electric motors when needed. A series–parallel hybrid can operate in series hybrid mode or in parallel hybrid mode, depending on the driving conditions and supervisory control strategy. A series–parallel hybrid benefits from advantages of both series and parallel hybrid, so it is efficient in both urban areas and highways.

14.2.3 Plug-In Hybrid Electric Vehicles

A PHEV is the combination of a HEV and an EV which can be recharged using an electric plug. In fact, a PHEV benefits from both the hybrid nature of a HEV and the noticeable all-electric range (AER) of an EV. AER simply shows the distance that the PHEV or EV can go only using the batteries. For instance, PHEV-30 means that the PHEV can go 30 miles only on electricity. In a simple HEV, the AER is relatively small because of the small capacity of the battery pack. However, in a PHEV the vehicle can run long ranges only on batteries. The battery pack of a PHEV is much bigger than a HEV to be able to store the required amount of energy. The overall efficiency of PHEVs is much higher than ICE cars. The final usage cost highly depends on the price of electricity, since PHEVs require a relatively significant amount of input electric energy to get charge. To get a rough idea, it can be mentioned that charging a PHEV once per day doubles the electrical energy consumption of a mid-size home. Besides, the reduction amount of pollutants depends on the source of electricity, i.e., fossil fuel, natural gas, hydro, wind, and solar.

PHEVs have same three main topologies as HEVs, i.e., series, parallel, and series parallel. PHEVs can operate in three different modes of operation: charge depleting, charge sustaining, and blended mode. If the battery has enough charge, PHEV can operate using only electricity until it reaches the minimum state of charge (SOC), this is called charge-depleting mode. The battery pack cannot provide enough energy and power for acceleration if its SOC is low. In contrast, the battery pack cannot absorb available energy from regenerative breaking if it is fully charged. Thus, it is desired that the SOC of the battery pack is kept in a range from 60 to 80 %. If the control strategy operates the ICE and other subsystems to achieve this, it is called charge-sustaining mode. In some PHEVs, the control strategy operates in such a way that for low speeds, e.g., less than 60 km/h the vehicle works in charge-depleting mode and for high speeds it works in charge-sustaining mode. This is called blended mode. In other cases, the PHEV may operate in different modes of operation for different speed ranges depending on the driving condition and control strategy, this mode is called mixed mode of operation.

14.3 EV and PHEV Charging Infrastructures

14.3.1 EV and PHEV Batteries and Charging Regimes

Replacing the conventional ICE vehicles with EVs and PHEVs in a large scale can result to tremendous prosperities in saving our world from the dangerous ever-increasing rate of pollutants. The majority of benefits such as pollution reduction and decrease of oil consumption resulting from moving toward using EVs and PHEVs are mainly based on using batteries as a green source of energy. The electrochemical nature of batteries has a highly nonlinear behavior and dependant on many factors such as materials, temperature, aging, load profile, and charging algorithm. A very important concern is related to storage, because in order to have a given amount of energy for a reasonable AER, tens or hundreds of cells should be connected in series and parallel for the desirable voltage and current ratings of the battery pack. This causes the nonlinear behavior of cells to be more prominent. Furthermore, there are some phenomena that are observed only in battery packs and not in single cells, such as thermal unbalance among the cells in pack.

EV and PHEV battery packs are relatively expensive compared to the price of the whole car, because of high number of cells, chemistry types such as Lithium-based, and protection circuits. Accordingly, the life cycle of these battery packs are very important for a cost-effective user's point of view. Therefore, lower cost for final customer can be achieved with increasing the battery pack life cycle, resulting in less frequent replacements of the whole pack. As a real example related to Honda Civic: recently, there has been news [3] about Honda Company regarding the battery packs of Honda Civics produced during 2006–2008. Apparently, some of the battery packs in the second-generation Honda Civic hybrids are failing prematurely after five years. According to regulations in California, there is a 10 year, 150,000 mile warranty requirement on the components of the hybrid system. Although Honda Company took recall actions, some customers were not satisfied and preferred to change themselves the battery packs. It has been reported that those battery packs cost about $2,000 excluding shipping and installation.

This case shows the importance of the battery packs price in the commercialization of EVs and PHEVs in a large scale. A factor that highly impacts the life cycle of battery packs is the charging algorithm. There are other factors also involved such as the charging time that plays an important role in high attraction to EVs and PHEVs. These topics and all other ones related to this area should be mainly handled with a multi-level control and power system called battery management system (BMS) which takes care of all or some of the aspects affecting batteries in any way. The more accurate and comprehensive the BMS is the more reliable, safer and faster the charging procedure can be done. Designing a high efficient BMS needs very good understanding of the behavior of single cells according to the variations of different parameters and also parameter variation and behavior change in a packed large number of cells.

The following section describes basic definitions of battery technology and appropriate charging algorithms that optimize the life cycle of batteries. Such definitions help understanding the applications in HEVs.

14.3.1.1 Battery Parameters

(1) *Battery Capacity*: This parameter indicates the amount of charge that can be drawn from a fully charged battery until it gets fully discharged. An important effect in batteries is that the higher amount of current drawn from a battery, the lower capacity the battery will have. Hence, theoretically, battery capacity is defined as the amount of current drawn from a battery that completely discharges it in exactly 1 h; for example, a battery capacity of 10 Ah means that a constant current of 10 A is drawn from the battery will discharge completely the battery after 1 h. However, in practice, battery manufacturers specify a table showing the amount of time the battery runs with several constant current loads and several constant power loads. In practice, this table provides much more practical information rather standard definitions, because after production different loads with different characteristics may be connected to the battery. Nevertheless, the amount of time that a battery runs is not exactly predictable, because in general the loads are not necessarily constant current or constant power loads. In addition, these manufacturer tables are valid for new batteries and they change with aging. Therefore, in many design methodologies just estimates of battery runtime calculated. The battery capacity is shown with variables defined as "C" or "Q" or similar notations. The main unit for battery capacity is Ampere-hour (Ah), but based on the battery size other units such as mAh or even mAsec (for very small batteries) can be used.

(2) *C Rate*: This parameter is used to show the amount of current used for charging the battery. For example, for a 10 Ah battery, when it is mentioned to terminate the charging process while the charging current falls below C/10 rate (10 h rate), it means the charging should be stopped when current becomes less than the amount of current with which the battery is discharged after 10 h, or specifically 10 Ah/10 h = 1 A.

(3) *State of Charge*: State of charge (SoC) is the percentage of charge available from a battery to the whole capacity of the battery. SoC is very difficult to measure because a complex electrochemical model is required, and there are other effects such as relaxation (described in the following section). Besides, according to aging the rated capacity of the battery reduces over time, hence, for determining SoC, the rated capacity should be measured or calculated regularly.

(4) *Depth of Discharge*: Depth of discharge (DoD) is defined as (100 − SoC) in percentage, i.e., how much from the total energy of the battery has been utilized. This parameter is usually used in discharge patterns

recommendations. For example, the battery manufacturer may recommend the user not to go over 70 % DoD according to lifetime.

(5) *Energy Density*: Energy density can be defined based on volume or weight, i.e., Wh/L or Wh/Kg. The "Volumetric Energy Density", which is defined as the amount of available energy from a fully charged battery per unit volume (Wh/Litre). The unit Litre is mainly used for measuring the volume of liquids. Mostly, the batteries have liquid electrolyte, so in such cases it easily makes sense, however, even for solid-state electrolytes such as Lithium Polymer batteries, the same unit is usually used. The other way of defining the energy density is "Gravimetric Energy Density" which is also referred as "Specific Energy" and defined as the available energy from a fully charged battery per unit weight (Wh/Kg). Based on application and based on the importance of the volume or weight, either definition can be used. In the case of EVs and PHEVs usually weight is a more important factor than volume, so, mostly specific energy is seen in the literature for EVs and PHEVs.

(6) *Charging Efficiency*: The chemical reactions inside the battery during charge and discharge are not ideal and there are always losses involved. Therefore, not all the energy used to charge the battery, is available during discharge. Some of this energy is wasted as heat dissipation. The charging efficiency can be defined as the ratio of available energy from the battery in a complete discharge to the amount of energy needed to completely charge the battery. This parameter may be mentioned by other names such coulombic efficiency or charge acceptance. The types of losses that reduce coulombic efficiency are mainly losses in charging process due to chemical reactions, such as electrolysis of water or other redoxation reactions in the battery. In general, the coulombic efficiency for a new battery is high, however, reducing as the battery ages.

Next section discusses some aspects of batteries of EVs and PHEVs regarding charging battery packs. This will help in designing more efficient and flexible chargers based on battery behaviors which will finally lead to improvement of battery packs lifetime.

14.3.1.2 Main Characteristics of Commonly Used Batteries

There are hundreds types of batteries described in reference books [4] and technical literature.

Most of them are demonstration prototypes, working under laboratory conditions and still under investigation, not commercialized maybe because of costs, nonmature technology, low energy density, safety, toxic components, and so on. The most widely available batteries are Pb–Acid, Ni–Cd, Ni–MH, Li–ion, and Li–polymer.

Batteries can be mainly divided into primary batteries and secondary batteries. Primary batteries are those which can be used only once and after a full discharge they are no longer used, because the internal chemical reactions are irreversible.

Secondary batteries can be used many times by recharging such as the ones used for automotive and traction applications and as energy storage for renewable energy systems.

Here, we will only consider secondary type batteries and when we are talking about batteries we mean secondary batteries, otherwise stated.

(1) *Lead–Acid (Pb–Acid) Batteries*: For over one century, lead–acid batteries have been utilized for various applications including traction. Their well-improved structure has led to valve regulated lead–acid (VRLA) batteries which can be considered as maintenance free batteries, which is a desirable characteristic for PHEVs. In terms of efficiency they have a high efficiency in the range of 95–99 %. The main disadvantage of lead–acid batteries is their weight, in other words, they have a low specific energy (30–40 Wh/Kg) compared to their counterparts.
(2) *Nickel–Cadmium (Ni–Cd) Batteries*: Considering low power applications Nickel–Cadmium (Ni–Cd) batteries also benefit from a mature technology but considering traction applications their specific energy is low as well. The typical specific energy for this type is 45–60 Wh/Kg. The main applications are in portable devices, but they are also recommended when high instantaneous currents must be provided. They are typically used when long life and reasonable costs are desired. However, they have environmental concerns for recycling because they contain toxic metals [5].
(3) *Nickel–Metal Hydride (Ni–MH) batteries*: Comparing to previous types they have higher specific energy at the expense of lower cycle life. In general, for the same size batteries, Ni–MH batteries can have up to two or three times more energy than a Ni–Cd type. The typical value for the specific energy of the present technology Ni–MH batteries is in the range of 75–100 Wh/Kg. This type is widely used in EV and PHEV applications.
(4) *Lithium–Ion (Li-Ion) batteries*: This type has noticeably high specific energy, specific power, and great potential for technological improvements providing EVs and PHEVs with perfect performance characteristics such as acceleration performance. Their specific energy is in the range of 100–250 Wh/Kg. Because of their nature, Li–ion batteries can be charged and discharged faster than Pb–Acid and Ni–MH batteries, making them a good candidate for EV and PHEV applications. Besides all, Li–ion batteries have an outstanding potential for long life if managed in proper conditions, otherwise, their life can be a disadvantage. One of the main reasons is almost the absence of memory effect in Li-based batteries. A weak point of Li-based batteries is safety since they are highly potential for explosion due to overheating caused by overcharging. They can almost easily absorb extra charge and get exploded. The use of advanced BMS can ensure reliable range of operation of Li–ion batteries even in cases of accidents. Another advantage is that Li–ion batteries have environmentally friendly materials when compared with Ni-based batteries.
(5) *Lithium–Polymer (Li-Po) batteries*: Li–Po batteries have the same energy density as the Li–ion batteries but with lower cost. This specific chemistry is

one of the most potential choices for applications in EVs and PHEVs. There have been significant improvements in this technology. Formerly, the maximum discharge current of Li–Po batteries was limited to about 1 C rate; however, recent enhancements have led to maximum discharge rates of almost 30 times the 1 C rate, which greatly improves and simplifies the storage part of the EVs and PHEVs in terms of power density, since this can even eliminate the need of ultra-capacitors. Besides, there have been outstanding improvements in charging times. Recent advances in this technology have led to some types which can reach over 90 % SoC in a couple of minutes which can significantly increase the attraction toward EVs and PHEVs because of noticeable reduction of charging time. Because this type is a solid-state battery, having solid electrolyte, the materials would not leak out even in the case of accidents. One of the other advantages of this type is that it can be produced in any size or shape which offers flexibility to vehicle manufacturers.

14.3.1.3 Basic Requirements of EV and PHEV Batteries

The basic preferred characteristics of PHEV batteries can be summarized as follows [6]:

(1) High specific energy which results in higher AER and less recharge cycles required.
(2) High specific power which results in high acceleration characteristics of the PHEV due to high rates of currents available from the battery without causing any permanent damage to the battery pack.
(3) High number of charge/discharge cycles available and high safety mechanisms built into the battery because of high power ratings of battery packs.
(4) Environmental friendly aspect of the battery, i.e., being recyclable and including low amounts of toxic materials.
(5) Cost is also an important concern for commercializing EVs and PHEVs in a large scale.

14.3.1.4 Charging Methods

Charging in general is the action of putting energy back to the battery i.e., restoring energy. Different chemistries require different charging methods. Other factors affecting choosing the charging method are capacity, required time, or other factors. The most common techniques are mentioned here:

(1) *Constant Voltage Charge*: As it is clear from the name “Constant Voltage” or CV is when a constant voltage is applied to the battery pack. This voltage is a pre-set value given by the manufacturer. This method is accompanied with a current limiting circuit most of the time, especially for the beginning periods

of charging where the battery easily takes high rates of current comparing to its capacity. The current limitation value mainly depends on the capacity of the battery. Depending on the battery type to be charged, this preset voltage value is chosen. For example, for Li–ion cells the value of 4.200 ± 50 mV is desirable. An accurate set point is necessary, since overvoltage can damage the cell and under voltage causes partial charge which will reduce life cycle over time. Therefore, the circuit used for charging, which can be a simple buck, boost or buck–boost topology depending on the voltage ratio of input and output, should be accompanied with a controller to compensate for source and load changes over time. When the cell reaches the preset voltage value, this causes the battery to be in a standby mode, ready for later use. The amount of this idle time should not be very long and should be limited based on the manufacturer recommendations. This method is usually used for lead–acid batteries, also for Li–ion batteries while using current limiter to avoid overheating the battery especially in the first stages of the charging process [7].

(2) *Constant Current Charge*: Constant current charging simply means applying a constant current to the battery with a low percentage of current ripple independent of the battery SoC or temperature. The abbreviation for this method is CC in the literature. This is achieved by varying the voltage applied to the battery using control techniques such as current mode control to keep the current constant. CC technique can be implemented using a “Single Rate Current” or “Split Rate Current”. In single rate only one preset current value is applied to the battery which is useful in balancing the cells. However, backup circuits must be used to avoid overcharging. In the split rate, CC different rates of current are applied based on time of charge, voltage, or both in different stages of charging. This gives more accurate and balanced charging and circuits should be used to avoid overvoltage of the cells. In some cases, for prolonging dead batteries, CC method with high rates and low duration can be utilized to extend the lifetime of the battery. But, this is a very cautious procedure and must be done carefully. Ni–Cd and Ni–MH batteries are charged using this method. Ni–MH batteries can be easily damaged due to overcharging, so they should be accurately monitored during charging [8].

(3) *Taper Current Charge*: This method can be used when the source is a non-regulated DC source. It is usually implemented with a transformer with a high output voltage comparing to the battery voltage. A resistance should be used to limit the current flowing to the battery. A diode can also be used to ensure unidirectional power flow to the battery. In this method, the current starts at full rating and gradually decreases as the cell gets charged. As an example, for 24 V 12 A battery, the charging begins with 12 A when the battery voltage is 24 V, then 6 A when the voltage reaches 25 and then 3 A for 26 V and finally 0.5 A for 26.5 V. (This is just a hypothetical example and the values are not necessarily valid). This technique is only applicable to sealed lead–acid (SLA) batteries. Taper charging has other disadvantages. As mentioned before, this technique uses transformers which adds to the weight of charger and generates heat.

(4) *Pulse Charge*: This technique involves using short-time current or voltage pulses for charging. By changing the width of pulses the average of the current or voltage can be controlled. Pulse charging provides two significant advantages, (1) it reduces charging time, and (2) the conditioning effect of this technique highly improves the life cycle. The intervals between pulses called rest times play an important role, they provide some time for chemical reactions inside the battery to take place and stabilize. Since in this method high rates of current or voltage can be used, it reduces undesirable chemical reactions that happen at the electrodes, such as gas formation and crystal growth, which are the most important reasons of life cycle reduction in batteries. This technique may remind us pulse width modulation (PWM) technique which is a control technique with very low voltage rates and higher frequency ranges which is different from pulse charging.

(5) *Reflex Charge*: During charging procedure some gas bubbles appear on the electrodes, especially amplified during fast charging. This phenomenon is called "burping". Applying very short discharge pulses or negative pulses which can be achieved for example by short circuiting the battery for very small time intervals compared to charging time intervals in a current limited fashion, typically 2–3 times bigger than the charging pulses during the charging rest period resulting in depolarizing the cell will speed up the stabilization process and hence the overall charging process. This technique is called with other names such as "Burp Charging" or "Negative Pulse Charging". Different control modes of charging along with waveforms and diagrams are described in [9]. There are other charging methods such as current interrupt (CI) which will be thoroughly explained in the charging algorithm section.

(6) *Float charge*: For some applications when the charging process is complete and the battery is fully charged, the batteries should be maintained at 100 % SoC for a long time to be ready for time of use uninterruptable power supplies (UPS) are one of such applications where the batteries should always remain fully charged. However, because of self discharge of batteries, they get discharged over time; for example, they may lose 20 or 30 % of their charge per month. To compensate for self-discharge, a constant voltage which is determined based on the battery chemistry and ambient temperature is applied permanently. This voltage is called "Float Voltage". In general, float voltage should be decreased with the increase of temperature. This causes a very low rate of current, for example C/300–C/100 rate to the battery which continuously compensates for the self discharge rate and also prevents sulfate formation on the plates. This technique is not recommended for Li–ion and Li–Po batteries and it is not necessary for EV/PHEVs which are frequently used every day. In addition, float charging involves a protection circuit which avoids overcharging. This circuit adjusts the float voltage automatically and interrupts charging at some intervals based on battery voltage and temperature.

(7) *Trickle charge*: Mainly, trickle charging is the same as float charging just with small differences. One is the usual absence of protection circuit which avoids overcharging. Hence, it is very important to make sure in the design procedure that the charging current is less than self discharge rate. If so, they can be left connected to the battery pack for long times.

14.3.1.5 Termination Methods

When the charging is in procedure, it is very important to decide when to terminate the charging. This is because of two main reasons. One is to avoid undercharge, i.e., making sure the battery is fully charged, not partially, in order to use the full capacity of the batteries. The other one is to avoid overcharging which is very dangerous, especially in the case of high energy density Lithium-based EV/PHEV battery packs. If not terminated on time, the overcharging of batteries can lead to over gassing of the cells, especially in liquid electrolyte cells which results in increase in the volume of individual cells, a situation that cannot be tolerated in a rigidly packed battery pack. Another issue is overheating of the cells, especially in Lithium-based batteries which can easily lead to the explosion and firing of the whole pack, since; Lithium is a very active material and easily combines with oxygen in the air. The only thing needed to begin the combination is enough heat.

Choosing different termination criteria leads to different termination methods. Selecting the type of termination of charging process depends on different factors such as the application and the environment where the battery is used. The conventional termination methods that can be used are mentioned here:

(1) *Time*: Using time is one of the simplest methods which is mainly used as a backup for fast charging or normally used for regular charging for specific types of batteries. This method is very simple and inexpensive, but because of diminishing battery capacity over time due to aging, the time should be reset for a reduced capacity aged battery to avoid overcharging of old batteries. Therefore, the charger will not work well for new batteries and will lead to life time reduction.
(2) *Voltage*: As mentioned before, voltage can be used as a termination factor, i.e., terminating the charging process when the battery voltage reaches a specific value. This method has some inaccuracies, because real open circuit voltage is obtained when the battery is left disconnected for some time after the charging. This is because chemical actions happening inside the battery need some time to stabilize. Nevertheless, this method is widely used. In addition, this technique is usually used with constant current technique to avoid overheating damage to the battery.
(3) *Voltage Drop (dV/dT)*: In some chemistries like Ni–Cd when charged using constant current method, the voltage increases up to the fully charged state point and then the voltage begins to decrease. This is due to oxygen build-up inside the battery. This decrease is significant, so the negative derivative of the voltage versus time can be measured to indicate overcharge. When this

parameter becomes negative, it shows that we have passed the fully charged state and the temperature begins to rise. After this point the charging method can be switched to trickle, or float charge, or terminated completely.

(4) *Current*: In the last stages of charging, if constant voltage method is used, the current begins to decrease as the battery reaches fully charge state. A preset current value such as C/10 rate can be defined and when the current goes below this value the charging would be terminated.

(5) *Temperature*: In general, increase in temperature is a sign of overcharge. However, using temperature sensors highly adds to the cost of system. Nevertheless, for some chemistries such as Ni–MH, methods such as voltage drop is not recommended, because the voltage drop after full charge state is not significant to be relied on. In this case, temperature increase is a good indication of overcharge and can be used.

14.3.1.6 Cell Balancing

For high power/energy demanding applications such as EV/PHEVs a large number of cells should be connected in series to provide a high voltage stack and connected in parallel in order to provide a high output current. There are some concerns related to a battery stack. Single cells produced by different manufactures can be recharged hundreds of times, but when connected in series the life cycle dramatically decreases. This is because of cell imbalances. Just to get an idea about the significance of this effect, the results of a real experiment from [10] is mentioned here. In an experiment, 12 cells were connected in series. Despite claiming life cycle of 400 cycles by the manufacturer, it reduced to only 25–30 cycles in a string. This shows how devastating cell imbalance can be. To deal with this, the reasons of cell imbalance should be known and managed. Batteries are electro-chemical devices. Even in the case of a simple resistor while manufactured there is a percentage of inaccuracy. In the case of batteries this is magnified. Two different cells produced in the same factory at the same time will have slightly difference in their parameters. One of these parameters is capacity difference. In the case of a battery pack there are different reasons leading to cell imbalance. As mentioned in [11] there are four fundamental factors leading to cell imbalance. They are manufacturing variations, differences in self-discharge rate, differences in cell age, and also charge acceptance variance. Similarly, in [12] cell imbalance is classified as internal sources which include “Variations in Charge Storage Volume” and “Variations in Internal Battery Impedance” and external sources resulting from “Protection Circuits” and “Thermal Differential Across the Battery Pack”.

A simple analogy can be made with water tanks in order to understand how different battery cells, with different capacities, operate when connected in series. By assuming that water tanks have different volumes connected to each other using pipes at the bottom of tanks, if the first tank is supplied with water the level of water in all the tanks evenly rises. After sometime, the tanks with lower capacity get full of water while others with higher capacity are partially filled with water. To completely fill up higher capacity tanks, there is no way other than over filling the lower capacity tanks.

Coming back to the real situation, now it is easy to guess what happens in the case of battery strings. Fully charging the high capacity cells involves overcharging low capacity cells. This will lead to excessive gassing and premature dry out of lower capacity cells and at the same time sulfate formation in partially charged cells leading to lifetime reduction. The only way to manage such situation is with cell equalization circuits and custom control algorithms. An important distinction between batteries for EVs versus PHEVs is that for the first case the batteries are usually charged up to 100 % SoC (cell balancing becomes an important issue), while for PHEVs the batteries are usually kept in the range of 40–80 % enabling them to provide enough energy, while being able to absorb regenerative power at the same time.

It is important to note that in cell balancing SoC is the main factor and not voltage. Measuring actual SoC involves discharging the battery completely and calculating the percentage of charge which is not practical. Hence, usually SoC is estimated. Voltage is correlated with SoC and can be used an indicator of SoC. Accuracy of estimated SoC using voltage depends on battery chemistry and other factors. If other techniques can be used that can determine SoC more accurately, they may be used depending on the allowable cost of the system. Different SoC estimation techniques will be presented in (Sect. 14.3.1.7). Cell balancing in a series string really means equalizing the SoC of the cells which is approximately equivalent to voltage balancing [13].

There are three main cell equalization techniques: (1) charging (2) passive, and (3) active:

(1) *Charging*: Charging method is simply continuing charging the cells until they are all balanced to some degree. This implies overcharging the cells in a controlled manner which leads to the full charge of high capacity cells. This method is applicable to lead–acid and Nickel-based batteries since they can tolerate some overcharge without significant damage. However, this technique should be carefully implemented since extra overcharge leads to overheating of the cells and finally premature drying of the electrolyte. Despite simplicity and low cost of this method, there are disadvantages such as low efficiency and long times required to obtain cell balance. Experimental results [14] show that for complete cell equalization of 48 V batteries of a specific chemistry, a time on the range of weeks is required. Furthermore, results from [10] show that the extra time required for cell balancing of more cells using this method increases with the square ratio of the number of cells added to the string.
(2) *Passive*: In this method, extra energy in lower capacity cells is dissipated in resistive elements connecting two terminals of the cells. This will provide enough time for higher capacity cells to get fully charged. This method has low efficiency because of energy dissipation but has a higher speed than the charging method. Passive technique is inexpensive, easy to implement and the control algorithm can be easily designed.

(3) *Active*: Active cell balancing uses active devices such as transistors, op-amps, and diodes to control the power flow between different cells. This flow can be between groups of cells or single cells. Extra charge is removed from lower capacity cells and transferred to higher capacity cells. This technique highly speeds up the charging procedure and no energy is dissipated. Of course, a small amount of power is dissipated in the circuitry which can be minimized using zero-voltage or zero-current switching techniques.

Lithium–ion batteries are one of the most attractive candidates for EV/PHEVs. Their voltage should be carefully monitored and rigorously controlled in the range of 4.1–4.3 V/cell since the threshold voltage leading to break down of the cell is very close to the fully charged cell voltage rating. Because Lithium batteries do not tolerate overcharging, the charging technique is not applicable to them. According to safety considerations, for Lithium-based batteries the only reliable cell equalization technique is active balancing.

Various types of cell balancing techniques can be found in the literature. Hence, there is a need to categorize them based on a criterion. Based on energy flow they can be classified into four different groups: (1) dissipative, (2) single cell to pack, (3) pack to single cell, and (4) single cell to single cell. It is possible to imagine the operation of each category based on the name with some pros and cons for each group. For instance, dissipative shunting resistor technique is an inexpensive technique and easy to control because of simple structure leading to simple implementation [15].

In addition to energy flow criterion for categorizing, cell balancing techniques can be split into three main groups based on the circuit topology: (1) shunting, (2) shuttling, and (3) energy converter.

Nondissipative techniques like PWM controlled shunting technique have high efficiency but it needs accurate voltage sensing and is somewhat complex to control [16]. Besides, the high number of elements leads to an expensive system. Using resonant converters highly increases the efficiency because of very low switching losses but on the other hand increases further the complexity of the control system [17].

Shuttling techniques work based on transferring extra charge of high capacity cell or cells to an energy storage element such as a capacitor or a group of capacitors, and then transferring it to the low capacity cell or cells [18]. The system would be cheaper using only one high capacity capacitor, but the equalization is faster when a group of capacitors are used. Utilizing a group of low capacity cells instead of one high capacity cell is a good idea, although it increases the complexity of the control system.

Most of the energy converter cell equalization techniques utilize transformers where isolation becomes an advantage at the expense of weight and costs. A model and transfer function of the energy converter cell equalization system is derived in [19] which can be used for control designing purposes.

The above-mentioned cell balancing techniques are all summarized and explained along with circuit topologies in [20]. The question that arises here is that how much the cells should be balanced. The balance should be in the range of volt, mill volt, or some other range? As experiments from [13] show for lead–acid batteries, cell-to-cell voltage matching should be in the range of 10 mV which corresponds to a SoC range that provides reasonable improvement in life cycle. This is an important factor, since, for example if the voltage matching should be in the range of 1 mV, it means that the sensors should be 10 times more accurate and also the algorithm may be needs to be improved for this case. This means more cost and complexity. Therefore, there is a trade-off between cost and life cycle. This parameter should be experimentally verified for different chemistries, environments, and applications.

Since EV/PEHV battery packs do not possess a mature technology and also not many experimental data are available, sometimes contradictory claims may be seen in the literature, one of which is mentioned here. As mentioned before, battery packs used in HEVs are usually controlled to remain in the mid-range of SoC. The principle is that the battery should be in a state with the ability of absorbing regenerative energy while being able to support enough power during acceleration. If the battery is in 100 % SoC, absorbing regenerative current will lead to the overcharge of the battery. Cell overcharge is usually sensed through measuring the cell voltage. Some literature supports that switched capacitor cell equalization technique (shuttling method) is a suitable candidate for applications with no end of charge state like HEVs, because there is no need for intelligent control and it can work in both charge and discharge mode [20]. On the other hand, some researchers support that according to the nearly flat shape of open circuit terminal voltage of Lithium–Ion cells in the range of 40–80 %, the suitability of charge shuttling methods for HEV applications is denied because of the negligible voltage deviation of cells [15], and more complex estimation of SoC should be implemented, as discussed in the next section.

14.3.1.7 SoC Estimation

One of the most important information needed for safe charging is SoC. Charging algorithms is mainly based on SoC directly or indirectly. Hence, the knowledge of SoC value is a key parameter in accurate charging. Unfortunately, directly measuring SoC is somehow impossible or at least very hard and expensive to implement and in some applications does not make sense, so mostly SoC is estimated based on other variables or states of the battery. This involves battery models based on which different estimation methods can be utilized or observers can be designed. Precise estimation of SoC is not an easy task, although in typical applications battery voltage which is a sign of SoC can be used. In the case of high power/high energy EV/PHEV battery packs more accurate methods are advisable, although being more expensive and complex in implementation. The more accurate the SoC estimation is, the better the charging algorithms can be implemented resulting in life cycle improvement.

As mentioned before, SoC is mainly the ratio of available charge to the rated capacity of the cell. One of the important points in SoC estimation to take care of is rated capacity change over time due to aging resulting from degradation of electrolyte, corrosion of plated and other factors. Research in this field is defined as "State of Health Estimation" where the readers are encouraged to study in the specialized literature.

Here we mention and describe some SoC estimation techniques. One of the simplest methods is to completely *discharge* the battery and measure the SoC. Although simple, it is very time consuming and it is not practical to completely discharge a battery just to measure SoC. Knowledge of the SoC is useful for the current situation of the battery, so if the battery is discharged the state of the battery has changed and there is no more use of previous state SoC knowledge. Especially, in the case EV/PHEV this method is not applicable. Although this method is not used online, it may be used periodically after long intervals just to calibrate other SoC methods.

Another method is *Ah Counting* which measures and calculates the amount of charge entering the battery or leaving it by integrating the current over time. This is one of the most common methods used; however, there are some deficiencies and drawbacks. Initially, because there is always inaccuracy in the sensors. Even very small, because it is being integrated over time it can sum up to a considerable value leading to significant errors. Besides, even supposing a very accurate current sensor, because this integration is being implemented usually by the use of digital circuits and numerical methods, there are always calculations errors involved and again can show up in high errors over time. Even if assuming both deficiencies to be solved in some way there is another reason leading to inaccuracy. Even if the amount of charge entering the battery is exactly calculated, because of coulomb efficiency where a certain amount of current entering to charge will not be the same when leaving the battery, this method has some inaccuracy. One way to reduce these inaccuracies is to recalibrate the integration process every time a specific known set point (such as fully discharged state or fully charged state) is reached.

Another method for SoC estimation is called *Measurement of Physical Characteristics of Electrolyte*. Obviously, this method is applicable only to liquid electrolyte batteries, not solid ones like Li–Po. In this method, a chemical fact is used and that is the relation of change of some parameters in electrolyte with change of SoC. One of these parameters is the density of the acid. There is an almost linear relation between changes in acid density versus SoC. This method is very well-known specially in lead–acid batteries. Acid density can be measured directly or indirectly using parameters such as viscosity, conductivity, ion concentration, refractive index, ultrasonic response, and so on.

As discussed before, the *Open Circuit Voltage* of the batteries can also be used as an indicator of SoC. The uncertainty in this method is due to the fact that batteries under operation need some rest time for their open circuit voltage to stabilize. This time for some cases can be up to hours; however, this method is also widely used. The key point in this method is the linear relationship of open circuit voltage versus SoC in a specific range of SoC. This range and its slope are variant for different chemistries which should be taken into account.

There are other techniques categorized under soft computation techniques such as fuzzy neural network [21] or adaptive neuro-fuzzy modeling [22] which can also be utilized for SoC estimation. Other approaches categorized as heuristic interpretation of measurement curves mentioned in [23) such as Coup de Fouet, Linear Model, Artificial Neural Network, Impedance Spectroscopy, Internal resistance, and Kalman filters can also be utilized which are more precise methods but more complicated to implement.

14.3.1.8 Charging Algorithm

Charging algorithm can be defined as the combination of what was mentioned up to here and controlling all or part of the parameters affecting battery performance and life cycle in such a way to achieve charging the battery pack with safety, efficiently, and terminated on time. Managing the charging procedure of a high power battery pack with hundreds of cells involves many issues as already discussed in this chapter. To control all of these parameters, efficient and accurate algorithms with reliable safety and backup circuits are required. The trend toward fast charging with huge amounts of current flowing to the battery pack producing lots of heat requires accurate and reliable supervisory control algorithms to ensure safe charge. Managing such complex task can be handled with advanced control techniques like fuzzy logic, supervisory control, and decentralized control, and so on. In general, each battery chemistry requires a unique charging algorithm. Depending on the algorithm it may be applied to other types as well; however, this should be carefully done according to life cycle and safety issues.

For precise battery charging, the charge/discharge profile of the battery provided by the manufacturer must be used. However, the profile is valid for brand new batteries; hence, some techniques like data acquisition methods must be used to acquire the charge/discharge profile of the battery with deterioration due to aging. Novel techniques regarding this issue is being introduced in the literature every often [24].

As mentioned before, lead–acid batteries have mature technology and infrastructure already exists, but they still have poor life cycles in the order of 300–400 cycles. A lot of efforts have been put into research for increasing the life cycle of lead–acid batteries because of their advantages such as low cost and availability. This chemistry has a common charging algorithm which includes four different stages or three based on the application, as indicated in Fig. 14.4. In the first stage, a predefined constant current is applied to the battery pack which charges the cells rapidly. In this stage, the cell voltages increase gradually because of SoC increase. This stage is called *Bulk Charge* stage. The process is continued until a predefined maximum voltage is reached. These values are all recommended by the manufacturer in the datasheet. In the next stage called *Absorption Charge* stage, a constant voltage is applied to the battery pack. At this stage, the current decreases gradually until it reaches a predefined C rate value and the cells are approximately charged but not equalized because of cell imbalance. At this stage, a relatively higher voltage than constant voltage in absorption stage can be applied to the pack for some time to balance all the cells inside the pack. This stage is called *Equalization Charge* stage. The equalization can also be achieved with other techniques as mentioned before. After some prescribed time, the charger applies a lower constant voltage in order to keep the battery in a ready to use state. This is called *Float Charge* stage and depending on the application it can utilized or omitted.

As the battery ages, its internal characteristics also changes; hence, an adaptive charging algorithm could be used to take into account these parameters variations. Experimental results show that the value of voltage of the third stage should be increased over time to get the same amount of energy as the battery ages [25–27]. The equalization stage is the key part of this algorithm and has great influence on the life cycle of the battery. As mentioned before, the voltage of this stage should be increased but this increases the current and also the heat generated which has negative impact on the life cycle. One way to get the same amount of current with lower heat dissipation is by using pulses of current. Although this technique seems the same as pulse charging, it is actually different, because the time intervals are significantly bigger than pulse charge time periods which are in the range of kilo hertz. This method is called CI. This technique has shown significant life cycle improvements [28]. Using this algorithm, the battery can reach 50 % of the initial capacity after 500 cycles which is a significant improvement in life cycle. Although this algorithm is useful, it puts the battery under stress while it reaches the end of life because of permanently increasing the overvoltage value. This algorithm can be implemented in an alternative way. Instead of using this method for each cycle, which puts high stress on the battery, it can be utilized every 10 cycles. This algorithm is called partial-state-of-recharge cycling (PSOR) [28] and has approximately the same effect with the advantage of less stress on the battery. This algorithm has been claimed to

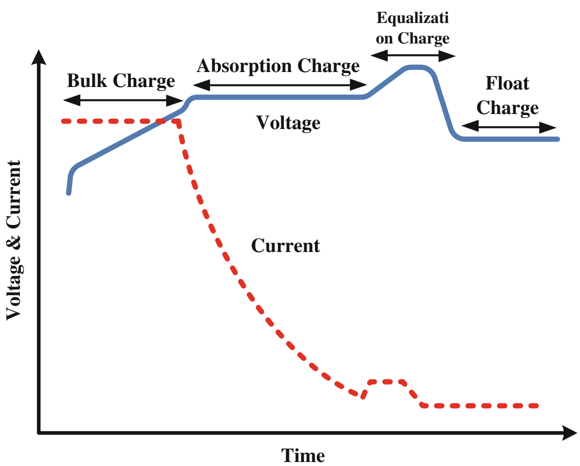

Fig. 14.4 Charging algorithm of a typical lead–acid battery

enable the battery deliver up to 80 % of initial capacity even after 780 cycles [28] which is a really noticeable improvement in life cycle.

As can be seen, these complicated algorithms cannot be done using simple PI, PID controllers. They require DSP-based controllers to be programmable with numerical data dependent on the battery chemistry, state of health, and other factors.

Continuously, different algorithms are being proposed and tested for improving life cycle of the batteries. This is a vast research area and is currently still under development, getting a lot of attention as EV/PHEVs become popular and available in the market.

14.4 Power Electronics for EV and PHEV Charging Infrastructure

In its simplest incarnation, a charging facility for EVs would merely consist of a unidirectional AC/DC converter charger connected to the power grid. Power would simply flow on demand from the power grid through a power conditioner into the vehicle battery pack; once the battery is fully charged, the connection to the grid no longer performs any useful work. This simple set up may have been appropriate for small private commercial vehicle fleets, or where electric cars represented a very small fraction of the active road vehicles. However, as society's efforts to electrify our means of transportation intensify, it is clear that a smarter exploitation of the vehicle-to-grid (V2G) interaction is in order. To the power utility, the bulk of EVs connected to its grid appears as an energy storage agent that is too significant to be left untapped. This view is reinforced by the outcome of several statistical studies [29] that show that more than 90 % of all vehicles are parked at all times, thus potentially connected to the grid. Assuming a 50 % EV market penetration, simple calculations show that, the total storage capacity available would be in the order of thousands of GW-hour! Therefore, the V2G connection should be bi-directional, giving the owner of each vehicle the ability to "sell" back a portion of this stored energy to the utility, presumably at an advantageous rate. The same requirement of

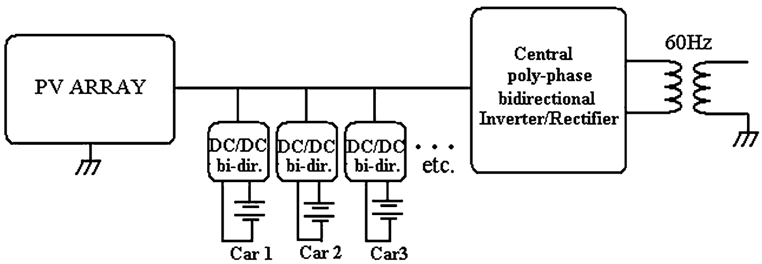

Fig. 14.5 Typical PV-powered gird-tied carport architecture

bi-directionality also applies when the vehicle is connected to a microgrid powered by a distributed resource. In a grid-connected solar carport for instance, many vehicles can be charged by PV panels or by the grid or by both, depending on load and insolation (time of day, meteorological conditions, time of year, etc.). In the case of overproduction, energy from the panels can be fed back to the grid for a profit, while the EV batteries function to buffer the characteristic solar intermittence. Similarly, the DC–DC converters that condition the power from the solar panels to each charging vehicle should also be bi-directional in order to allow the owner of a plugin electric vehicle (PEV) to exchange a portion of his energy with the operator of the micro grid (Fig. 14.5).

These considerations demonstrate that bi-directionality is a highly desirable feature in any power conditioner utilized in vehicle charging–discharging applications, including interactions to and from the grid, microgrid, or residential loads and renewable energy generators. On this basis, the reader should note that the discussion that follows makes no distinction between V2G and grid-to-vehicle communication, both being classified by the acronym V2G. Similarly, V2H will designate either the vehicle-to-home or the home-to-vehicle interface.

Other requirements for the optimal charging infrastructure are harder to identify. This is due to pervasive lack of standardization involving battery technology and nominal voltage, safety strategy, connector configuration, communication protocols, location of charger (on-board or off-board), and more. In the following paragraphs, these issues are treated especially in reference to their impact on local power generation and utilization.

14.4.1 Charging Hardware Strategy

Like any other means of transportation, EV/PHEV's benefit markedly from minimizing their weight. These vehicles are even more sensitive to that issue, considering the unavoidable presence of heavy battery/ultra capacitor energy packs. The electronic power converters intended for the charging function can be bulky and heavy in their own right, and their deployment on-board seems to make little engineering sense. Yet, at the time of this writing, the great majority of PEVs in North America contain their own power rectifier and connect directly to 120 or 240 V household plugs. This can be explained by two considerations. First, while the household AC voltages are fully standardized, at least within a country, the DC nominal battery voltage for PEVs is definitely not. Different manufacturers have adopted ad hoc energy storage technologies and safety strategies, resulting in strikingly different bus voltages and current requirements. An unsophisticated external converter could then be optimized for only one vehicle brand or model.

Second, some techniques have been developed that do not add significant weight to the vehicle. The critical idea is to utilize the power electronic circuitry that is already on-board in order to perform the rectifying function. This charging circuit is commonly referred to as an "integrated charger"; it makes use of the bi-directional inverter that drives the electric motor as well as the windings of the motor itself. Figure 14.6 shows a well-known example of this concept:

With regard to Fig. 14.6, it is important to realize that inductors LS1, LS2, and LS3 are not added magnetic devices, but the actual winding leakage inductances of the electric motor. Thus, the only added components are the two relays K1 and K2, which are activated in order to reconfigure the schematic from a three-phase motor driver, during normal vehicle propulsion operation, to a single-phase boost rectifier, during charging.

The above two considerations are consistent with relatively slow charging strategies. In the first instance, because the amount of electric power available in a residential setting does not usually exceed 10 kW at a household plug. In the second instance, because the electronics that drive a PEV electric machine are sized for its propulsion needs. Thus, the average charging power must be limited to a level comparable to the motor's rated power, which is of the order of 10–50 kW in smaller cars.

Slow charging strategies are commonly referred to as level 1 and level 2. The former is associated with a connection to a regular AC household plug (120 V, 15 A), while the latter involves powers that can be as high as 14.4 kW or 240 V at 60 A, which is also normally available in residential settings. Moreover, these power levels are compatible with the average generating capacity of microgrids and corresponding distributed resources. Then, it would appear that whether a car

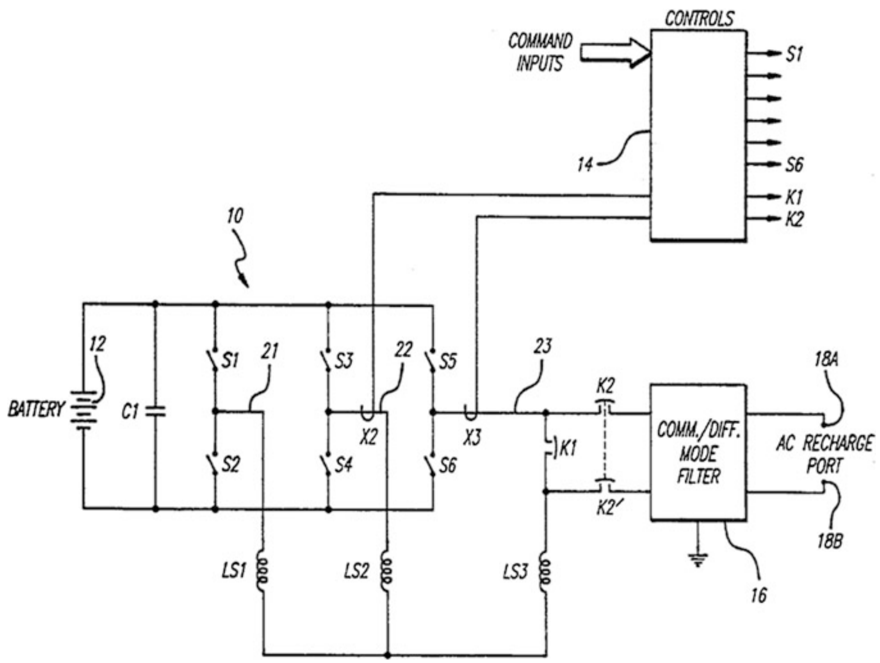

Fig. 14.6 Integrated charger based on boost converter [47]

is charged through a regular residential wall socket, or a microgrid outlet, the available power levels justify the location of the rectifier on-board the vehicle.

On the other hand, EV manufacturers are quickly recognizing that long charging periods may be acceptable to consumers only if quick charging is available as well, albeit at higher cost. Two solutions are presently under consideration. The first solution is the so-called battery swapping, whereby a car owner simply drives to a service station and allows an automated system to safely replace a spent battery with a fully charged one. Along the same lines, the battery could be of the redox flow type. In this case, the battery casing is not replaced; rather, it is drained and then filled with fresh liquid electrolyte. In either forms, the obvious drawback is the need for the exact standardization of battery size, chemistry, and capacity.

The second solution consists of allowing direct access to the battery DC terminals, so that a large off-board rectifier can be connected and re-energize the battery pack using powers of the order of up to several hundred kilowatts. This is known as level 3 charging, allowing an electric “fill-up” service stop to last only a few minutes. In this instance, although the battery itself may not need a high level of standardization, it would be subject to extremely high currents at high voltages. This renders the practical implementation of this second solution strongly dependent on needed improvements to battery and ultra capacitor technologies. Furthermore, a public charging station capable of servicing many cars simultaneously would represent a local load of several megawatts as seen by the grid.

Despite these difficulties, it is highly likely that either the battery swapping or the fast-charging strategy will eventually be universally available to complement, or even replace, the onboard charger.

14.4.2 Grid-Tied Infrastructure

Assuming fast-charging through direct DC connection becomes the method of choice, car owners will have two options. They may still prefer to slow charge their vehicles overnight by plugging to a AC–DC charger [or electric vehicle supply equipment (EVSE)], most probably in their homes. This converter will deliver relatively low powers of the order of 5–10 kW because limited by the residential connection, as mentioned earlier. However, as further explained in Sect. 14.5, this method may involve some financial returns. The alternative method will be to use a fast-charging public facility, corresponding to a familiar service gas station that is capable of multi-megawatt power transfers. Although the cost per kW-hour will be high, the owner benefits from charge times in the order of minutes rather than hours.

In both cases, V2G capability, enabled by smart grid technology will become a standard feature with all EVSE’s, whether they are public, commercial, semi-public, or private. This will allow the subsistence of a very significant distributed storage resource at the disposal of electric utilities. More specifically, the PEV fleet will be optimally positioned to become a significant provider of some ancillary services and play a role in offering dispatchable peak power. These services to the electricity supplier will be analyzed separately:

PEVs as "Peakers"
A peaker is a small but nimble generating units that can supply the grid with relatively fast response. Historically, natural gas turbines or small hydroelectric plants were the devices of choice for this task. They are active for only a few hours every day and therefore provide only limited energy. Thus, a substantial fleet of PEVs can carry out this task as a highly distributed resource without significantly depleting their batteries. Unfortunately, as long as peak power is not considered a "service", the utility operator will compensate the car owner solely for the energy sold, albeit at a higher peak demand rate [30]. This may not constitute a strong enough incentive to the car owner who has to consider other factors, such as the additional battery and power electronic wear and tear for his vehicle. Nevertheless, future adjustments in energy market models are under study to address this among other issues.

PEVs as Spinning and Nonspinning Reserve
One of the most lucrative ancillary service is the spinning and nonspinning reserve. The former consists of generators that are online, but normally run at very low capacity. In the case of a disruption, such as a failure in base load generation or transmission, these generators are commanded to provide the missing power. They must be able to ramp up in less than 10 min and provide power for as long as 1 h or more. Nonspinning reserves are not online and are required to ramp up to full power within 30 min. Because this is a service, the utility company will pay for the availability of the power as well as its amount. In fact, this service is paid even when no power is ever delivered. A PEV owner can provide this service naturally and be reimbursed starting at the time he plugs his vehicle to the grid even if the battery is never discharged. Also, it must be noted that PHEVs have smaller battery capacity than all-EVs, but contain an ICE that can be started on a V2G command to generate electricity and function as a spinning reserve as well.

PEVs as Voltage Frequency Regulation Agents
An ancillary service that is even better tailored for PEVs is regulation. It consists of delivering or absorbing limited amounts of energy on demand and in real time. Normally, the request is automated in order to match exactly the instantaneous power generation with the instantaneous load. Failure to do so results in dangerous shifts in line frequency and voltage. The dispatched amount of energy has short duration—in the order of few minutes—but it is requested relatively frequently. Therefore this is a continuous service. It is important to underline that the amount of energy involved is relatively small and changes direction quite rapidly and regularly, implying minimal PEV battery discharge for any reasonably short-time interval. The near instantaneous response time and the distributed nature of the PEV fleet explains why regulation is probably the most competitive application for V2G from the point of view of the utility operators.

PEVs as Reactive Power Providers [31]
Most electronic topologies used for the inverter/rectifier function in the interface of the PEV to the grid are fully capable of shaping the line current to have low distortion and varying amounts of phase shift with respect to the AC line voltage. This implies that reactive power can be injected into the grid on demand and in real time. Furthermore, since reactive power translates in no net DC currents, this service can be provided without any added stress to the PEV battery.

14.5 The V2G and V2H Concepts

The advantages described in the preceding sections are not presently exploitable due to a general lack of the required hardware infrastructure, as well as the thorny transition to new business models that include the V2G concept. The roadmap toward achieving this goal will probably consist of the following several milestones.

(1) The first milestone is rather rudimentary as it does not yet require bidirectional converters. It will consist of a simple owner-selectable option afforded by the vehicle BMS user interface that allows the grid to schedule when to activate and deactivate charging. In return, the owner pays lower per-kW-hour rates. Communication between the grid operator and the BMS can be done through the existing cell phone technology, requiring no additional infrastructure or hardware.
(2) The straightforward "grid-friendly" charging time-window strategy described above will evolve to include more sophisticated algorithms. For instance, the grid might broadcast any updates to the current per-kW-hour cost and let the vehicles BMS choose whether to activate charging. Some ancillary services, such as regulation "down" could become feasible, while regulation "up" will be limited by the lack of reverse power flow capability of the EVSE at this stage. The use of aggregators will also become widespread. Aggregators are intermediate communication and power distribution nodes between a group of vehicles, located in proximity to each other, and the grid. This allows the grid to macromanage a single installment of several vehicles, corresponding to significant power level blocks with somewhat predictable behavior, akin the other distributed energy resources. Furthermore, because the aggregator's consumption will be in the MW range, it will allow purchases of power on the wholesale market, reducing the cost for each participant vehicle.
(3) Eventually, bidirectionality will become a standard feature for all EVSEs. However, this capability will not be immediately harnessed to achieve controlled reverse power flow to the grid. Rather, the PEV battery will, most likely, initially service the surrounding premises, probably the owner's home. This scenario, called V2H, will probably precede the full implementation of V2G [32], because it effectively bypasses several large infrastructure and

technical issues needed for V2G, while achieving many of the same results. Through pricing incentives, a PEV parked in the residential premises and connected on the customer's side of the meter, can be exploited to absorb energy from the grid during times of low demand, and transfer it to the household appliances, during times of high demand. This will indirectly shrink the power peaking for the grid while reducing the electrical bill to the user. It will also reduce overall transmission losses over the V2G strategy, because line current will flow only in one direction, from grid to vehicle, and will then be consumed locally. Moreover, if the household is geared with renewable source generators, the vehicle can immediately serve as storage and, during blackouts, as backup power. Although one can find some similarities between the concepts of V2H and V2G, there are important distinctions. In practical terms, these differences stem from the fact that V2H cannot take advantage of the high predictability deriving from statistical averages afforded by very high numbers of vehicles available for V2G operations. Simply stated, the real benefits of V2H are not easily estimated, because they are dependent on many exceedingly uncertain variables. Some of these are: the number of available vehicles, commute schedule, time duration and distance, PEV energy storage capacity, presence and quantity of quasi-predictable local generation (example: solar panels), presence and quantity of unpredictable local generation (example: wind power), residence-specific energy consumption profile, and presence of additional storage. Despite the fact that these issues will require complicated management algorithms in order to optimize the use of V2H, some benefits, such as emergency back-up, are available immediately with a relatively minor upgrades to the residential infrastructure. These upgrades consist mainly in the installation of a transfer switch to disconnect the residence from the grid during backup operation, and expand the design of the power converter to detect islanding conditions. Furthermore, the EVSE must be capable of controlling output current into the line when connected to the grid, but reverting to controlling output voltage when acting as a backup generator.

(4) Full V2G implemented with automated options for V2H. The connection will be metered and could also include any locally generated renewable energy management.

14.5.1 Grid Upgrade Strategy

The electric transmission and distribution networks in most industrialized nations must consider changes and upgrades in order to fully benefit from the introduction of PEVs as distributed resources. First we must consider the extent by which the current production capacity will have to be expanded. Various studies [33] have suggested that once the typical charging profile for a PEV is scrutinized and hopefully optimized—charging mostly at night—the installation of new generation will be unnecessary or minimal at most. In fact, it will have the effect of diminishing reliance on more expensive load-following plants, since the overall 24 h demand curve will average closer to the base load. Therefore, the main effort should be in effectively introducing intelligence into the grid. The hardware and communication standards for implementing such intelligence are still under study. Wideband digital interface can take the form of PLC (Power Line Communication) or utilize separate communication channels that have some market penetration already. In either case, the EV will most likely be treated as any other managed load by this smart grid, with the exception of a sophisticated on-board metering device that will have to be reconciled with the utility's pricing model. Presently, the two major obstacles to the utilization of PEVs as distributed resources are the lack of bi-directionality in the power converters and the lack of recognized standards, both software protocols and hardware, for the smart grid function. Of the two, the former is by far the easiest to implement, given the well-established characterization of suitable power electronic topologies.

Renewable and Other Intermittent Resource Market Penetration
Due to recent well-known trends, renewable resources are increasingly prominent in the complex energy market mosaic. As long as their penetration level is low, they can be easily handled by the current infrastructure, but at present incremental rates this will not be the case in the future. The intermittent nature of solar and wind generation will require a far more flexible compensation mechanism than what is available now. Because of this, today's renewable energy installations are invariably accompanied by large battery banks that act as buffers between the generator and the grid. Wind power, in particular, is not only intermittent put has no day-average predictability, as winds can differ hour to hour as easily as night as during the day, adding an extra amount of irregularity to an already varying load. This suggests that PEVs will be called to perform not only the more manageable regulation task, but also aid in providing peak power. As noted earlier, this may not find the approval of the PEV owner unless the pricing model is modified. Nevertheless, it is reasonable to ask whether a large PEV contracted fleet could perform this task on a national (US) level. Studies have shown [34] that the answer is yes. With an overconfident, 50 % estimation for the market penetration of wind energy and 70 million PEVs available, peak power can be provided at the expense of approximately 7 kW-h of battery energy per day or about 10–20 % of an average PEV reserve.

Dedicated Charging Infrastructure from Renewable Resources
The traditional microgrid often relies on diesel generators as a single source of energy. Even in this case, any load fluctuations are quite difficult to negotiate, relying solely on the intrinsically slow ramp up speeds of the generator itself. The new trend toward integrating renewable resources into microgrids greatly amplifies this problem due to their notorious intermittent nature. On the other hand, the dedicated generation from renewables for the explicit purpose of PEV charging is gaining more credibility as a means to eliminate transmission losses and greatly

reduce the overall carbon foot-print associated with EVs. Such installation would fall in two categories: (1) small installations with or without a grid tie, (2) large installation with grid-tie. Small installations can be somewhat arbitrarily defined at less than a total of 250 kW of peak production. This would be sufficient to slow-charge about 20 vehicles and would certainly require local external storage in order to buffer the peaks and valleys in local energy production. This is more evident in the case of islanded installations; if any energy is produced in excess, it cannot be sent back to the grid, so it will need long-term storage capability. Large installation with a grid-tie can inject or draw power to and from the grid as a means to equalize the grid during overproduction and draw from the line. However, depending on the number of vehicles connected, which can be accurately predicted with statistical methods, some of the PEV resource can be utilized to minimize the size of the external storage. Nonetheless, it appears that PEVs can alleviate the inherent issues associated with local renewable production for the dedicated purpose of PEV charging, but not totally eliminate them.

14.6 Power Electronics for PEV Charging

The PEV charging process will be enabled by the sophisticated power electronic circuits found in the EVSE. Such equipment will be optimally designed depending on the different possible sites and types of power connection. We will begin by looking at EVSE connected to the main power grid and then analyze dual-sourced systems such as grid-tied renewable energy installations dedicated to PEV charging. A short discussion on basic safety compliance strategy follows.

Safety Considerations

For off-board chargers there are only a few important safety needs that affect significantly the power converter design. These are (1) isolation of the battery pack with respect to chassis and the grid terminals, (2) ground fault interrupters (GFI) to detect any dangerous leakage current from either the grid or the battery circuit, (3) connector interface, and (4) software.

A typical EVSE and related connections is shown in Fig. 14.7.

Two GFIs detect any breakdown or current leakage on either side of the isolation barrier in order to insure complete protection to the user and disconnect the

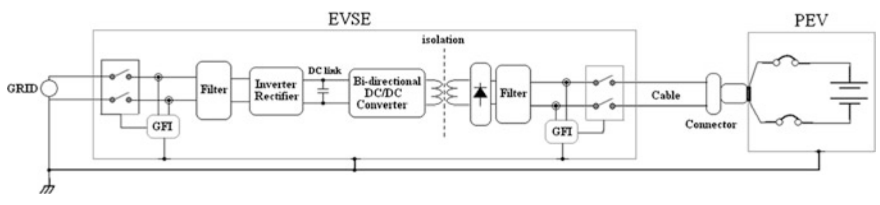

Fig. 14.7 Typical EVSE safety configuration

high-power circuit immediately in case of fault. The battery pack is fully isolated from the chassis since it cannot be grounded properly during charging without heavily over sizing the connector cable. In fact, some existing safety recommendations require that an active breakdown test be performed on the battery pack prior to every charging cycle. At the time of writing, the de facto standard for level 3 DC charging is the CHAdeMO standard developed by the Tokyo Electric Power Company. Although competing standards may eventually overtake it in popularity, the description the CHAdeMO connector demonstrates the safety concerns involved. The connector itself will have mechanical means to lock itself onto the car receptacle in order to prevent accidental removal when energized. It will carry the power leads, but also communication wires that include a CAN bus digital interface as well as several optically isolated analog lines for critical commands such as on/off, start/stop, etc. Every analog signal sent by the PEV to the charger (or vice versa) is received and acknowledged through the analog lines. This analog interface is sturdier than a digital one and less susceptible to electromagnetic interference. The CAN bus is activated only when more complex information is exchanged. Prior to the start–charge command, the EVSE communicates its parameters to the PEV (maximum output voltage and currents, error flag convention, etc.), and the PEV communicates its parameters to the EVSE (target voltage, battery capacity, thermal limits, etc.), and a compatibility check is performed. During charging, the PEV continuously updates the EVSE with its instantaneous current request (every 100 ms or so) and all accompanying status flags. Once charging is finished, the operator can safely unlock the connector and drive away.

As can be seen, the presence of safety devices, such as the GFIs as well as a sturdy method of analog and digital communications renders the charging process extremely safe, leaving the power electronic designer of the EVSE with the relatively simple task of ensuring only the isolation barrier between the grid voltage and the PEV floating battery. In fact, the utilization of an isolation transformer can actually simplify some designs due to the added voltage amplification capability afforded by the transformer's turns ratio. This could prove very beneficial if much higher battery voltages become necessary in order to increase storage capacity.

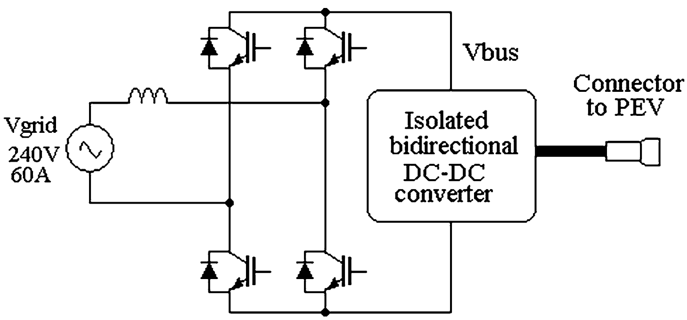

Fig. 14.8 Canonical single-phase EVSE configuration

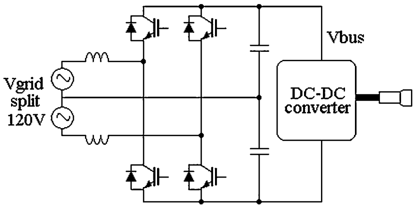

Fig. 14.9 Split phase sourced EVSE configurations

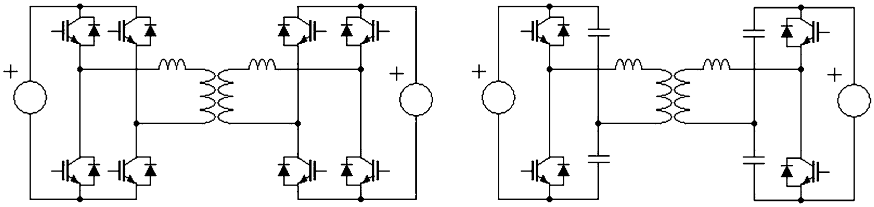

Fig. 14.10 Typical isolated bidirectional buck–boost DC–DC converter topologies

Grid-tied Residential Systems
As noted earlier, only level 1 and level 2 are feasible within the confines of a residential setting. This can be accomplished through integrated chargers when available or an external EVSE. In the latter case, the most obvious circuit configuration is a single-phase bi-directional rectifier/inverter powered by a 60A/240 VAC circuit that is readily available from the distribution transformer. The DC-link voltage is then processed by a bi-directional DC–DC converter that performs the isolation function. This simple topology shown in Fig. 14.8 can be called the canonical topology as will be repeated, with minor changes, for most grid-tied system irrespective of power rating.

In North America, the 240 V from the residential distribution transformer is in the form of a split 120 V supply, suggesting small modifications to the canonical topology. Figure 14.9 shows two possibilities:

The two topologies in the figure are similar, but the one on the right has better voltage utilization and is better equipped to counter unbalanced loads on the split supply [35].

For the DC–DC converter, many bi-directional isolated circuit topologies have been proposed [36]. Typical circuits are shown in Fig. 14.10.

When the two controlled bridges are independently driven in phase-shift modulation (PSM), these are generally referred to as dual active bridge (DAB) topologies. In their simplest operation mode, when power needs to be transferred from the left-side circuit to the right-side circuit, for instance, the right-side IGBT switches are left undriven, leaving their antiparallel diodes in the form of a regular diode bridge. Under these circumstances, the topology becomes identical to a regular PSM converter, which is simple to operate, but not very flexible in terms of voltage gain. On the other hand, when both bridges are modulated, power transfer

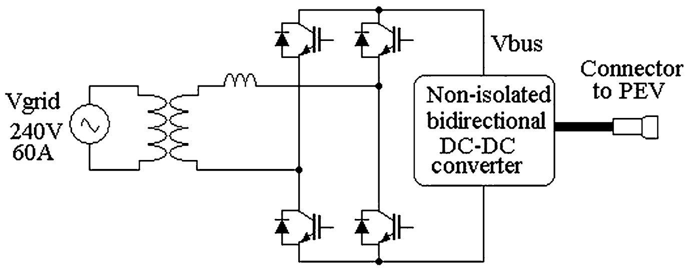

Fig. 14.11 Configuration with isolation at the grid

can be accomplished in both directions and with great variability ranges on the input and output voltages. In addition, zero voltage switching (ZVS) can be assured for all switches for reduced switching loss and generated electrical noise (EMI).

Other topologies [37, 38] based on the DAB have been proposed with purported additional benefits, such as better switch utilization, extended ZVS operating range, and more flexible voltage amplification.

Grid-tied Public Systems

A public parking/charging installation would deliver only level 2 power, given the relatively long plugin times. Because there are several parking locations in close proximity, the power configuration used for residential use may not optimal. Rather, a single transformer can be installed at the grid, delivering isolated power to all vehicles in the facility. This way, cheaper and more efficient nonisolated DC–DC converters can be used without violating safety rules.

Figure 14.11 illustrates this configuration for each charging station. For the whole installation, the architectures shown in Fig. 14.12 are possible:

In the centralized architecture [39] a single, large poly-phase, 50/60 Hz step-down transformer connects to the grid, providing isolation for the whole facility. This is followed by a large bidirectional rectifier that produces a single high-voltage DC bus. Each parking station uses inexpensive high-efficiency nonisolated DC–DC converters to process this bus voltage into the appropriate charging current for the individual PEVs. Because isolation is either desirable or required, especially on PV panels depending on local electrical codes, additional storage or generating resources, such as wind turbines and fuel cells, can also benefit from simpler interface to the DC bus. Moreover, the single transformer connection guarantees that no DC current is injected into the grid, doing away with complicated active techniques to achieve the same purpose.

The advantages just noted for centralized configuration are somewhat offset by the following drawbacks: (1) the need for a bulky and usually inefficient line-frequency transformer, (2) an expensive high-power polyphase inverter/rectifier, (3) single-fault vulnerability in the transformer and central inverter rectifier, and

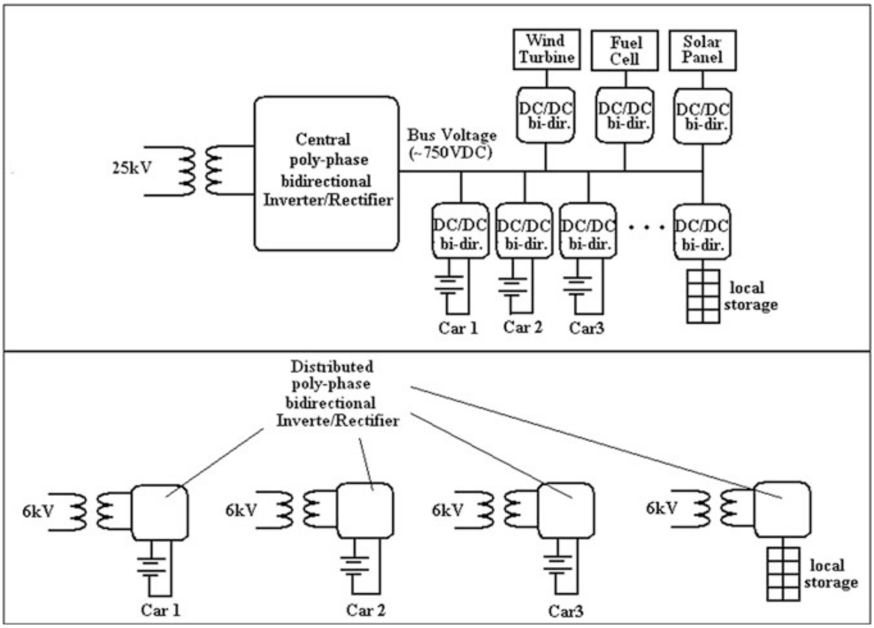

Fig. 14.12 Central architecture (*top*). distributed architecture (*bottom*)

(4) lack of voltage amplification in each non-isolated DC–DC converter (otherwise afforded by the turns ratio of the high frequency transformer in isolated topologies).

In a level 3 (fast charging) public facility, other technical challenges must be considered. For instance, with battery pack rated voltages in the range of 200–600 V, the overall currents required for fast charging will be of the order of thousands of amps. These currents must necessarily flow through cables and especially connectors, causing local thermal issues and loss of efficiency due to ohmic loss. In addition, the charging stations will appear as a concentrated loads to the grid, so that any power transients produced by the stations are very likely to cause local sags or surges.

The first issue can be partially countered by brute force methods such as the development of advanced sub-milliohm connectors and minimizing cable lengths by placing the grid step-down transformer in physical proximity of the vehicle. It is obvious that any intervening power conditioning electronic circuit should be added only when absolutely necessary. This immediately suggests that the architecture of the charging station should be distributed rather than central. As can be seen from Fig. 14.12 (bottom), a distributed architecture could potentially reduce the number of processors from grid to battery from two to one. To be fair, this single stage may not be feasible when managing large input–output voltage ranges, especially if buck–boost operation is required (see discussion on the Z-converter later in this section). Nevertheless, if an additional DC–DC stage should prove necessary, it will be easily integrated locally with the inverter for improved efficiency. Furthermore, a central processor, besides constituting a single point of failure as already noted, would have to be rated for the full service station power, which could be of the order of a megawatt. On the contrary, a distributed architecture benefits from repeated circuitry (economies of scale), redundancy for higher reliability, and the possibility of power conditioning in physical proximity to the vehicles, reducing ohmic loss.

The issue of power line quality deterioration caused by the service station operating transients has only been studied for specific geographic locations [40], but possible voltage fluctuation of up to 10 % have been reported depending on the length of the feeding high-voltage transmission line. The obvious and perhaps sole approach to mitigate this problem is the integration of flywheel, battery, or ultracapacitor banks into the charging station. This storage will smooth out the load transients by delivering local power when needed and storing power during periods of lower demand. Moreover, it will average out the draw from the grid, so that the distribution equipment can be rated at much lower peak powers (as much as 40 % [41]).

The task of discriminating between the various available electronic topologies is made easier when considering the sheer power handled by fast chargers; to wit, up to 250 kW. Obviously, a good candidate must be very efficient, inherently low noise, with low component count and capable of high-frequency operation in order to control physical size. For the inverter/rectifier section, we must also add the requirement that no significant harmonic content should be present in the line current. In order to obtain input currents that are sinusoidal and free of ripple noise, several methods of increasing complexity exist.

One method uses a three-phase thyristor bridge. The devices are very rugged and efficient in terms of conduction loss and have enough controllability to roughly regulate the DC bus [15]. In order to remove unwanted current harmonics, an active filter is added. This filter is based on IGBT devices, but only processes a small portion of the total power. A second method uses a fully controlled IGBT bridge in order to achieve excellent input current shaping for extremely low input current distortion and well regulated, ripple-free DC bus voltage.

Moreover, fewer components and much higher switching frequencies can be achieved resulting in smaller magnetic components. On the other hand, IGBTs

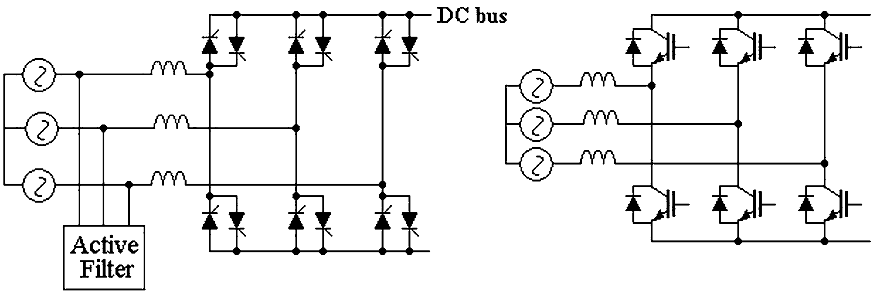

Fig. 14.13 Thyristor bridge and active line filter (*left*), IGBT bridge (*right*)

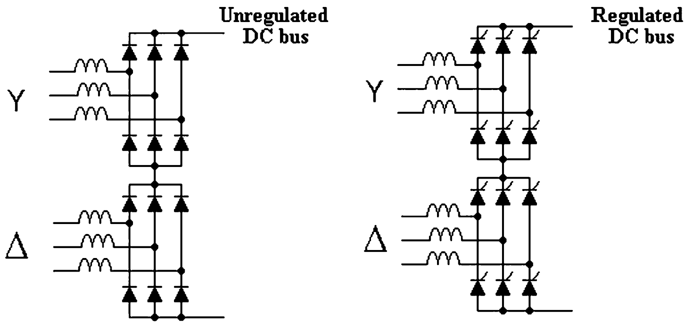

Fig. 14.14 12-pulse rectifier circuits

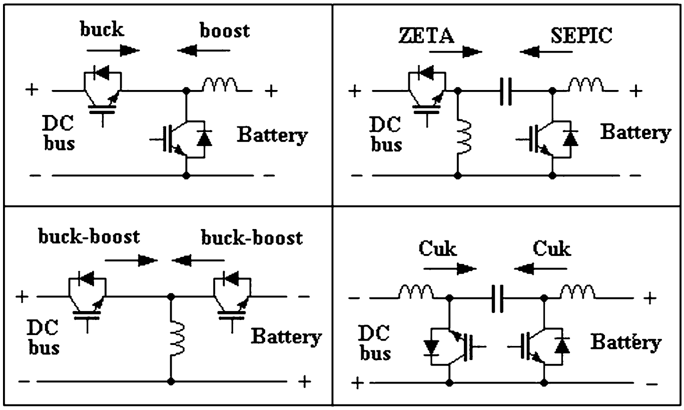

Fig. 14.15 Basic bidirectional nonisolated topologies

have switching losses and more significant conduction losses than thyristors. Yet other techniques, although less sophisticated, have the potential of realizing the required low current distortion limit without the addition of an active filter. The uncontrolled 12-pulse rectifier shown in Fig. 14.13 (left) can certainly do this, albeit with the addition of significant inductive filtering. Because the output DC bus will not be regulated, the subsequent DC–DC converter design cannot be optimized. Using thyristors can achieve regulation of the bus and possibly still achieve the required input current shaping.

It is important to note that of the four topologies mentioned here, only those in Fig. 14.14 are bidirectional, and therefore,, the only choice if V2G is to be implemented.

For the final DC–DC converter, all common basic topologies, that is, boost, buck boost, buck, Cuk, SEPIC, and ZETA can be used so long as they are rendered bi-directional by replacing the diode with a transistor device. In this case, these

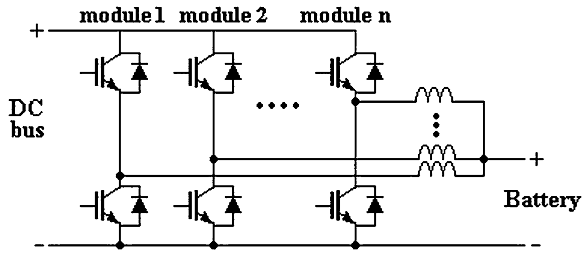

Fig. 14.16 Interleaved modular approach for the DC–DC converter

topologies function differently depending on the direction of power flow (see Fig. 14.15).

Different design requirements might suggest different topologies [39], but some of these are objectively more difficult to justify. For instance, using the buck boost/ buck boost (bottom left in Fig. 14.15), produces a voltage inversion from positive to negative that may be undesirable. It also places higher electrical stress on the switches; it requires a more sophisticated design for the inductor and draws pulsed current from the battery. Similarly, the ZETA/SEPIC topology has a higher part count, including a capacitive, rather than inductive energy-transferring element. On the other hand, as long as the DC bus is guaranteed to exceed the battery voltage—a requirement that is assured by the use of the controlled bridge discussed earlier—the buck–boost topology (top left in the figure) is quite attractive. Furthermore, this topology is readily modified in order to divide the task of handling a very large power flow among paralleled modules [40].

This is shown in Fig. 14.16; the amount of converted power can be split among n identical sections and the battery ripple current greatly reduced by the well-known technique of phase-shift interleaving. Using this circuit with n = 3 and a switching frequency of 2 kHz, for a typical 125 kW application, efficiencies as high as 98.5 % have been reported.

Grid-tied Systems with Local Renewable Energy Production

As noted earlier, when relatively large energy production from intermittent sources is to be tied to the grid, a statistically predictable PEV presence could serve the purpose of minimizing on-site dedicated storage. This would be the case for municipal carports powered by wind and/or solar generation and where the vehicles must be able to interact intelligently with both locally generated and grid

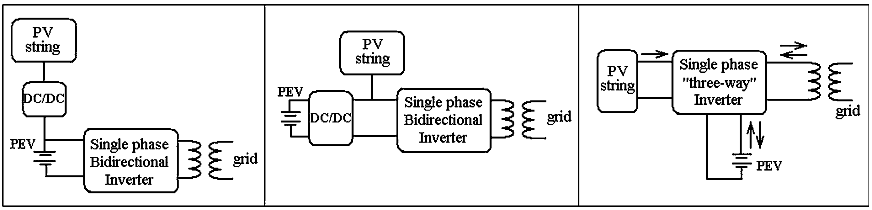

Fig. 14.17 Possible configurations for solar carport

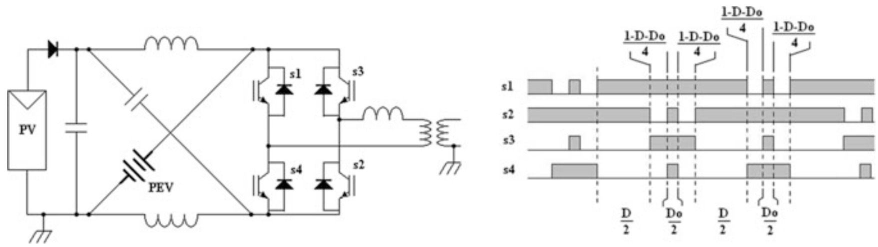

Fig. 14.18 Z-loaded rectifier (*left*), gating pattern (*right*)

distributed power at the same time. The possible scenario described in Fig. 14.12 (top) may not be ideal when the renewable resource is meant to generate the dominant share of PEV charging energy. Rather, by realizing the advantages of the distributed configuration, as in Fig. 14.12 (bottom), one stage of conversion can be eliminated so long as a conversion topology with wide input–output voltage range capability can be found.

Figure 14.17 shows some possible configurations for one of the several charging stations in a solar carport. The architecture depicted on the left has the disadvantage of inserting a DC–DC converter into the main intended power flow, from PV to battery. Moreover, the power drawn from a single phase connection is pulsed at twice the line frequency. This pulsating power takes the form of an undesirably high ripple current into the battery. The configuration shown in the middle of Fig. 14.17 removes the ripple issue, but adds an additional conversion stage between the grid and the battery. The configuration on the right requires a converter that is capable of bidirectional flow between the PEV and the grid, as well as steering of PV power to either the PEV or the grid in a controlled fashion. Furthermore, this should ideally be achieved by a single conversion stage for all power flow paths and with wide voltage range capability. A good candidate for this task is the Z-loaded inverter/rectifier topology shown in Fig. 14.18.

The operating characteristics of the Z-loaded converter have been described extensively in the literature [42–44]. The most salient feature of this conversion topology is its controllability through two distinct modulation modes within the same switching cycle, designated by duty cycle D and “shoot-through” duty cycle Do. The gating patterns shown in Fig. 14.18 describe the meaning of D and Do. As can be seen, during period Do, all four switches are closed simultaneously, causing the inductors to charge and ultimately boost the voltage across the capacitor, the battery, and the grid terminals. Thus, Do can be understood as the duty cycle associated with operation akin to that of a current sourced inverter. During period D, on the other hand, the bridge operates in a manner similar to that of a voltage sourced inverter, which is essentially a buck. Therefore, with the appropriate utilization of D and Do, both buck–boost operation can be achieved, so that the battery voltage can be either higher or lower than the peak of the line voltage. This allows a wide line and battery voltage range. Most significantly, due to the double modulation, both the grid and the battery current can be controlled precisely in

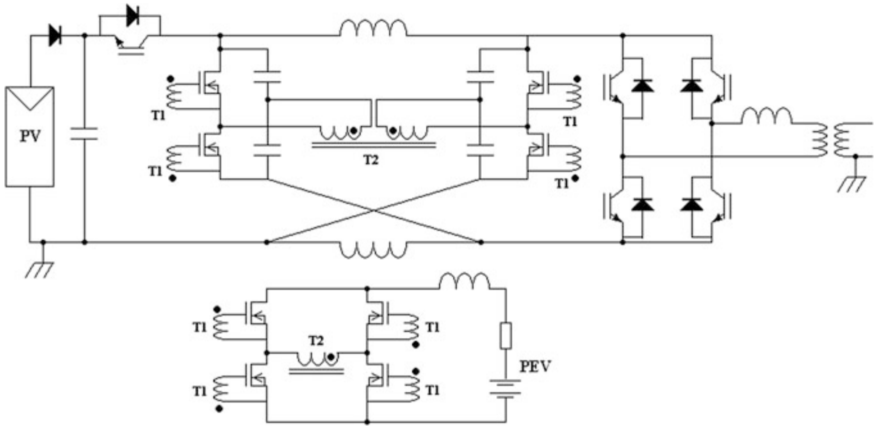

Fig. 14.19 Z-converter application to single phase, grid tied PV charging station

amplitude and shape (sinusoidal for the line current and ripple-less DC for the battery). The maximum power point tracking (MPPT) function for the PV string can then be achieved by managing the simple addition of these two power flows.

The topology shown in Fig. 14.18 must be modified in order to achieve isolation of the battery pack. Therefore, the DAB converter shown in Fig. 14.10 (right) can be integrated resulting in the detailed schematic of Fig. 14.19. The apparent complexity of the isolation stage is deceptive; in fact, this is a simple bidirectional converter that uses a small and inexpensive high-frequency transformer and that runs in open loop at full duty cycle and where all eight switches are driven by the same signal. In addition, since the duty cycle is always 100 %, ZVS is assured, resulting in efficient operation executed by relatively small devices.

With the inclusion of the isolated DC–DC converter, the need for the 50/60 Hz isolation transformer may be called into question. In North America, the grounding of one side of the PV panel has traditionally been the required norm. Although recent conditional exceptions to this safety regulation have been allowed by the National Electric Code, utility companies have resisted this change, mainly because a direct connection to the AC–DC bridge converter can inject dangerous

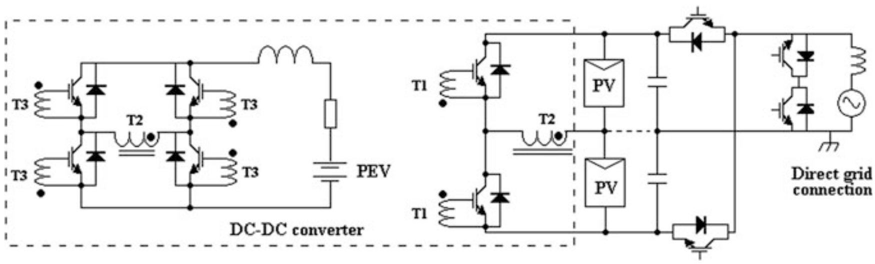

Fig. 14.20 Transformerless topology

levels of DC current into the distribution transformer. On the other hand, should this constraint become less binding in North America, as it is currently in Europe, other circuits could be proposed that could prove more reliable and efficient. Many so-called transformer less topologies have been proposed [45, 46] and Fig. 14.20 depicts a simplified schematic for one such possibility.

In this case, the DC–DC conversion and the rectifier/inverter section are controlled separately, rendering the control strategy much simpler. On the other hand, the DC–DC converter is now governed by a feedback loop, meaning that it no longer takes advantage of the low switching loss normally associated with 100 % duty cycle operation. With allowances from the regulatory safety agencies, the PV panels can be floating as long as the circuit has additional protection afforded by GFIs and that it produce no leakage currents to ground during normal operation. The last requirement is attained only if the topology guarantees very little common mode voltage on the PV panels during normal operation (note that this cannot be achieved with the Z-converter). Nevertheless, the mid-point can still be grounded, as indicated by the dashed line in the figure, but at the expense of performance.

Whichever architecture is chosen it is clear that the energy transfer cannot be controlled to fully satisfy any arbitrary current demands of the PV, the grid and the PEV battery simultaneously. In fact, many renewable resources are themselves subject to MPPT control, so that the simple power balance in Eq. (14.1) must be satisfied:

$$P_{\mathrm{MPPT}} = P_{\mathrm{PEV}} + P_G \tag{14.1}$$

where P_{MPPT} is the power draw requested by the distributed resource. It has to equal the sum of the power absorbed by the grid and the PEV battery (PPEV and PG respectively). Since P_{MPPT} is determined by external factors, such as clouding in the case of PV, either P_{PEV} or P_G can be controlled independently, but not both. Which of these is controlled will depend heavily on how the PEV owner decides to utilize his vehicle storage resource. Thus, in installations where charging power comes primarily from intermittent sources, the need for a significant presence of additional storage on the premises will be diminished, but not eliminated.

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