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ARE ELECTRIC VEHICLES SAFER THAN COMBUSTION ENGINE VEHICLES?

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INTRODUCTION

Replacing conventional vehicles using internal combustion engines with electrified vehicles (EV) is a challenge in many respects. Introduction of new technical solutions, especially those produced for a mass market, may substantially change and possibly increase the risks associated with the products. On the other hand, electric vehicles have clear advantages concerning safety as they do not carry conventional fuels onboard such as petrol or diesel, both of which are flammable and toxic. Without a combustion engine onboard, the risks of fire and explosion are thus decreased. Therefore, the introduction of electric vehicles promises a transition to a clean, non-polluting, healthy and safe means of transportation (see also Chapter 6 on life cycle environmental impact).

While there is a potential for electric vehicles to be safer than conventional ones we still need to consider what possible new risks this technological transition will bring, as the risks associated with conventional vehicles are well known to most people and thus easily dealt with in daily life. What risks are associated with a large onboard chemical energy storage? What kind of battery failures may occur and what will the consequences of such failures be? Will the hazardous traction voltage of the electrical system pose a danger to the passengers or to rescue personnel in case of an accident? How can eventual risks be diminished in traffic, when vehicles are parked and maintained? Does the silent electrical drive introduce a risk for pedestrians? All these aspects and more need to be considered when designing the vehicle.

Safety issues for electric vehicles considered here include mainly battery powered vehicles including vehicles which have the battery as the only means to store energy (BEVs) or range extended vehicles where the battery is the main source of energy but an extended range can be obtained using a combustion engine, for example plug-in hybrid vehicles (PHEVs).

Another type of electric vehicle is the fuel cell powered car, using hydrogen gas as fuel. In this case, safety aspects mainly concern the safe handling and storage of hydrogen. While EVs are on the market in rapidly increasing numbers today, the fuel cell car has not reached true commercial introduction yet. Compared to conventional fuels hydrogen has both advantages and disadvantages, but again, the risks are different to those we are familiar with and other safety practices are needed. Fuel cell and hydrogen safety issues are however not covered in this chapter.

Lithium-ion (Li-ion) batteries have high energy and power densities that make it possible to build BEVs and PHEVs with acceptable electric driving range with zero tail pipe emissions. This type of battery has therefore become the preferred choice for manufacturers of these types of vehicles. This chapter focus primarily on the lithium-ion battery while other battery types are discussed more briefly. Other technologies for energy storage, e.g. flywheels, compressed air and supercapacitors might be used in future electric vehicles. Presently, they are used to a very limited extent and are therefore not included in the discussion here.

BATTERY SYSTEM DESCRIPTION

The traction battery system in an electric vehicle consists of many parts. Figure 4.1 shows the principle layout for a traction battery system. The basic building block in the battery pack is the battery cells. The cells are connected in series in order to increase the voltage. Cells can also be connected in parallel, in order to increase capacity. Typically a battery pack for an electric vehicle consists of 100-400 cells, although some manufacturers use a significantly larger number of smaller cells.

A number of cells form a module which at present (2016), typically has a voltage below 60 V and is thus not a particular electrical hazard. A battery pack usually consists of several such modules. To monitor and control cells, modules and pack, each battery system has a master Battery Management System (BMS), often in combination with one or several slave management systems (e.g. one per module). The BMS has a number of functions essential for safe operation of the battery system: (*i*) parameters such as cell voltage, current and temperature are monitored in order to ensure that the battery operates within the allowed limits, (*ii*), balancing of cells is performed in order to keep all cells on the same level regarding state of charge (SOC), (*iii*) contactors placed inside the battery pack in order to connect and disconnect the battery to the rest of the vehicle are controlled, (*iv*) the status of the electrical insulation of the traction voltage system is monitored and (*v*) the BMS communicates with the other parts of the vehicle as well as supplies information to the driver. As an independent means of electrical safety the battery often has one or several fuses, for short circuit protection. Furthermore, the thermal management system of the battery could both heat and cool the cells in order to maintain a temperature within an efficient and safe temperature range. A mechanical housing, the battery box, is used to enclose and protect the battery pack. It has several functions and a suitable tightness-class.

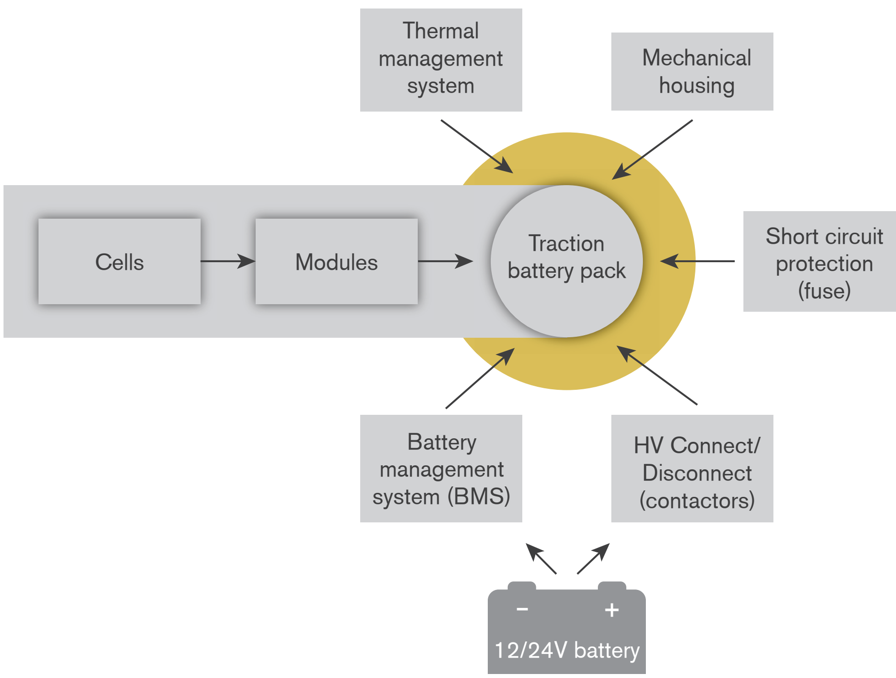

Figure 4.1. The traction battery system overview.

Typically the battery pack for a car uses an external 12 V supply from the vehicle's 12 V-battery, e.g. a conventional lead-acid battery. The 12 V supply is used to power up the BMS and to close the contactors. In principle, the battery could supply its own 12 V by an internal DC/DC converter but an external supply is a simple solution that is commonly used. Heavy-duty vehicles instead use a 24 V lead-acid battery, otherwise the function is basically the same.

BATTERY TYPES

Lead-acid batteries (PbA) have been used for more than 150 years and are still produced in large quantities as 12 V and 24 V vehicle batteries. Several types are available, e.g. free ventilated or recombination cells (e.g. AGM, GEL). The lead-acid technology is fully mature and therefore cost-optimized but has lower power and energy densities and a significantly shorter cycle lifetime than nickel-metal-hydride and Li-ion batteries. Lead-acid batteries also require a long charging time, typically 10 hours. However, due to its high weight and large volume it is not a real option for PHEVs or EVs, even though it was used experimentally in EVs during the

1990s. Presently lead-acid batteries are considered only for micro-hybrid electric vehicles (start and stop techniques). The safety concerns are small and related mainly to the risk of hydrogen gas production during operation. Hydrogen gas can potentially ignite and explode but the buoyancy of hydrogen gas makes it relatively easy to ventilate the battery in order to avoid the formation of an ignitable mixture with air. Since lead acid batteries is a mature technology the battery design is very well developed to avoid these problems.

Nickel-metal-hydride batteries (NiMH) are presently (2016) dominating the HEV-market and are being used in e.g. the Toyota Prius. NiMH offers significantly improved energy and power densities compared to lead-acid batteries. Further, it offers a high cycle life time and safety concerns are small. They do not, however, have the same energy storage capacity as Li-ion batteries.

Lithium-ion is the dominant battery technology today (2016) for PHEVs and EVs due to its high energy and power densities, combined with a long life time. The safety concerns are however larger than for NiMH and lead-acid batteries due to the chemistries used for lithium-ion cells together with the large size of the battery systems needed for these types of vehicles which makes the consequences of a malfunction potentially more serious.

A lithium-ion cell consists essentially of anode, electrolyte, separator and cathode. During battery charge and discharge, lithium ions are shuttled back and forth between the anode and cathode through the electrolyte. Even though a large number of different lithium-ion chemistries are possible within the Li-ion battery family, only a few lithium-ion chemistries are used to any larger extent commercially today (2016). The anode is commonly based on lithium intercalated natural or synthetic graphite but lithium titanate (LTO) is also used. The first cathode material used in Li-ion batteries was lithium cobalt oxide (LCO), however, the use of LCO is decreasing due to e.g. safety and raw material costs. Today cobalt is often mixed with other metals; nickel, manganese and aluminum, forming mixed-oxide cathode materials; NMC (or NCM) is lithium nickel-manganese-cobalt oxide, NCA is lithium nickel-cobalt-aluminum oxide. Lithium manganese oxide (LMO) is another cathode material. Phosphates are also used as cathode material and the most used one is lithium iron-phosphate (LFP). Electrode materials for higher cell voltage and thus increased energy density are under development, however, the increased cell voltage makes safety more challenging and is more demanding regarding electrolyte stability. The electrolyte is flammable and toxic and typically consists of organic solvents, lithium salt and additives. The exact composition differs between the manufacturers and is usually a commercial secret, especially regarding the additives. The separator is a porous polymer where the pores are filled with the electrolyte; its primary function is to avoid direct contact between anode and cathode. In some cases the separator may also have the function of shutting down the ion transport in case of overheating.

It takes a long time to develop new battery technologies, typically more than 20 years. Potential future battery storage technologies is a very active field of research and one of the most interesting future battery technologies is the *lithium-air battery*, which has a huge potential compared to Li-ion batteries, e.g. the energy density is projected to be more than 10 times that of Li-ion batteries.

There are, however, several challenges to be solved for the lithium-air technology, e.g. regarding life time and safety. One safety concern is how to prevent air from reaching the free lithium-metal. Metal-air batteries may, on the other hand, offer an additional safety technique to shutdown battery voltage, by stopping the air supply to the battery[1]. Li-air batteries are, however, not likely to be commercialized within the near future[2].

SAFETY ISSUES WITH LI-ION BATTERIES

The risks involved with the use of lithium-ion batteries are closely related to the chemistries used, the design of cell and system, the handling of the battery when in use and the quality of the production. The choice of cell chemistry is, in turn, determined by the demands regarding energy and power density as well as cost and safety for the specific application. Small size lithium-ion batteries have been used for more than a decade in consumer products, such as laptop computers and mobile phones. During this time, battery fire incidents have been reported in portable computers, cargo planes and electric vehicles[3]. However, the conditions and requirements for lithium-ion batteries in automotive applications are different and more demanding than those for consumer electronics. Lithium-ion cells for the automotive industry are, for example, characterized by increased quality, safety and life time compared to that of small consumer cells, and generally use more advanced materials with higher degree of purity.

Lithium-ion batteries have many advantages but the window of stability is relatively small (both regarding temperature and voltage). The cells must therefore be monitored and controlled, by BMS. Overheating may cause a severe malfunction; if the temperature exceeds typically 120-150 °C, exothermal reactions within the cell can start. The exothermal reactions will increase the temperature further, which can trigger additional exothermal reactions. If the overall cell reaction creates a rapid temperature increase, it could result in a so called thermal runaway[4,5,6,7]. A thermal runaway consists usually of one or a combination of the following events: rapid gas release, electrolyte leakage, fire, rapid disassembling/explosion. The reason for the initial overheating may be an external short circuit, overcharge, overdischarge, deformation of the battery by external forces, external heating or an internal short circuit. The latter may be caused by dendrite growth, unwanted particles in the cell, manufacturing deviations, etc. If the overheating spreads to adjacent cells a large part of the battery system may be affected. Figure 4.2 shows how a thermal

1 F. Larsson, A. Rytinki, I. Ahmed, I. Albinsson, B.-E. Mellander, "Overcurrent abuse of primary prismatic Zinc-Air battery cells studying air supply effects on performance and safety shut-down", *Batteries*, 3 (1) (2017).

2 Girishkumar, G., McCloskey, B., Luntz, A.C., Swanson, S., Wilcke, W. (2010) Lithium-air battery: Promise and challenges. *Journal of Physical Chemistry Letters* 1(14):2193-2203.

3 Wang, Q., Ping, P., Zhao, X., Chu, G., Sun, J., and Chen, C. (2012) Thermal runaway caused fire and explosion of lithium ion battery *Journal of Power Sources* 208:210-214.

4 D. Doughty, E. P. Roth, "A general discussion of Li ion battery safety", *The Electrochemical Society Interface*, summer 2012 (2012) 37-44.

5 F. Larsson, B.-E. Mellander, "Abuse by external heating, overcharge and short circuiting of commercial lithium-ion battery cells", *Journal of the Electrochemical Society*, 161(10) (2014) A1611-A1617.

6 A. W. Golubkov, D. Fuchs, J. Wagner, H. Wiltsche, C. Stangl, G. Fauler, G. Voitic, A. Thaler, V. Hacker, "Thermal-runaway experiments on consumer Li-ion batteries with metal-oxide and olivin-type cathodes", *RSC Advances*, 4 (2014) 3633-3642.

7 F. Larsson, P. Andersson, B.-E. Mellander, "Lithium-ion battery aspects on fires in electrified vehicles on the basis of experimental abuse tests", *Batteries*, 2 (9) (2016).

event on the cell level could develop to the system level. In order to obtain a high level of safety such a chain of events must be hindered, or at least, its propagation be delayed[8]. It may be pointed out that events like e.g. gas release and electrolyte leakage can also occur in non-thermal runway situations, that is at temperatures lower than those where a thermal runaway is initiated.

The outcome of these reactions varies with cell design and chemistry, particularly with the electrode and electrolyte composition. The combination of reactive materials and flammable components in the cell pose a risk, the electrolyte is flammable and the oxide materials may release oxygen at elevated temperatures, thus both fuel and oxidant needed for a fire might be present inside the cell.

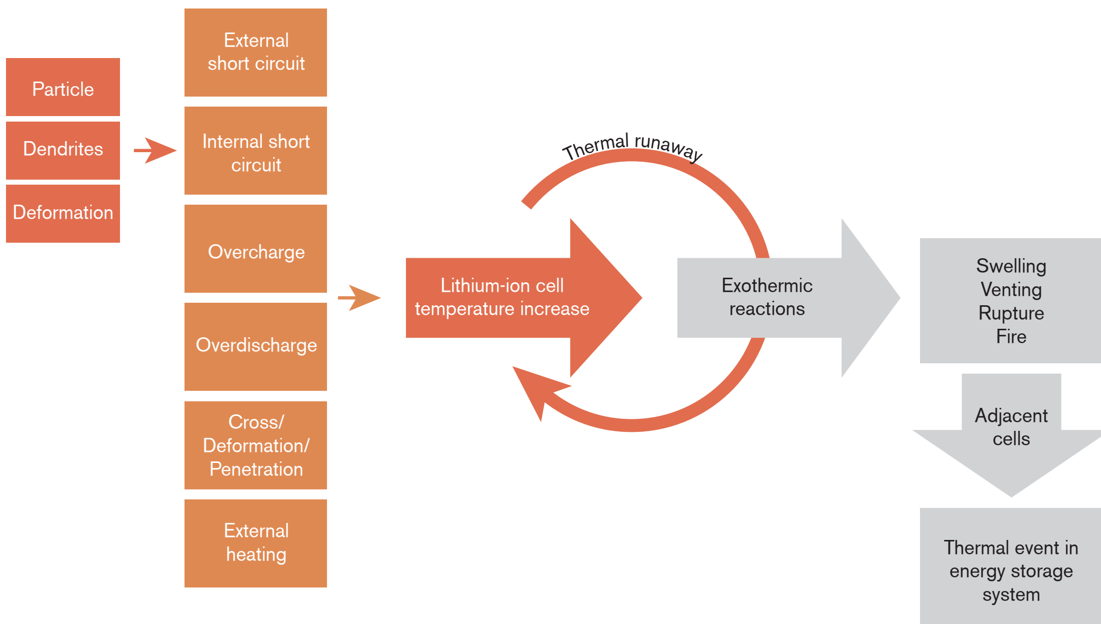

Figure 4.2. Potential chain of events for a thermal event on the cell level developing to system level.

In order to meet the demand of the automotive industry, improved battery materials have been produced. The selection of the active electrode materials (anode and cathode) strongly affects the thermal runaway and its onset temperature. Lithium iron phosphate is for example a more stable cathode material than the cobalt-based lithium oxides that are commonly used in consumer Li-ion batteries. Other electrode materials, for example mixed oxides with cobalt in combination with other metals (e.g. Ni, Mn, Al), have been developed in order to improve safety and other aspects (e.g. life time, cost, energy and power densities)[9].

The electrolyte composition and its additives, e.g. flame retardants, redox shuttles and gas release controllers (shutdown additives), are also important for the overall safety of the battery. The organic solvents involved, e.g. ethylene carbonate (EC)

8 F. Larsson, J. Andersson, P. Andersson, B.-E. Mellander, "Thermal modelling of cell-to-cell fire propagation and cascading thermal runaway failure effects for lithium-ion battery cells and modules using fire walls", *Journal of the Electrochemical Society*, 163 (14) (2016) A2854-2865.

9 Wang, Y., Jiang, J., Dahn, J., (2007) The reactivity of delithiated $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$, $Li(Ni_{0.8}Co_{0.15}Al_{0.05})O_2$ or $LiCoO_2$ with non-aqueous electrolyte. *Electrochemistry Communications*, 9:2534-2540.

and dimethyl carbonate (DMC) are volatile and flammable. The boiling temperature of DMC is, for example, 90 °C. The mechanical packaging, cylindrical, soft or hard prismatic can or pouch-prismatic, also affects the cell behavior during a thermal event. For example, a cylindrical can cell could build up a much higher pressure than a pouch cell. There are both pros and cons associated with each type of cell packaging. For example, with a cylindrical cell it can be easier to control the venting direction by the placement of the safety vent but higher internal cell pressure build up can be potentially more dangerous, especially in case of safety vent malfunction. Thus, there are a number of safety mechanisms that can be included into a lithium-ion cell construction by its manufacturer depending both on the chemistry and physical design of the battery. Safety mechanisms for Li-ion cells were originally developed for use in consumer products, i.e. a low voltage Li-ion battery consisting of one or a few cells. Some safety mechanisms, e.g. PTC and CID, will not work with larger voltages such as in a traction battery pack for electric vehicles.

FIRES, GASES AND EMISSIONS

The energy stored in the battery in an electric vehicle is essentially released once you connect the two battery poles while the energy in a conventional vehicle requires the fuel to be mixed with air at the right proportion and pressure and then the gas mixture needs to be ignited by a spark or by exposure to high temperatures. The higher voltages and currents used in an electric vehicle may be a risk for fires and lithium ion batteries pose a special risk as the electrolyte is combustible, with properties similar to gasoline or LPG. Furthermore, the battery might progress into thermal runaway as described above. One of the safety mechanisms used in these cells to prevent a more severe incident (e.g. explosion) to occur is venting. The gases released in a venting situation are, however, highly toxic and flammable. In particular, a venting cell would release hydrogen fluoride (HF) which is highly toxic. Venting would also release many other fluorinated substances, e.g. POF_3, that have a potential of being toxic, but the toxicity of these are to a large part unknown. The source of the fluorine in the Li-ion cells comes from the use of Li-salt (e.g. $LiPF_6$) in the electrolyte but can also come from the use of fluorine in the binders (e.g. PVdF) used in the electrodes.

If a fire starts, many of these substances might be consumed in the fire but the knowledge in this field is still limited and more research is needed regarding evolved gases from battery fires. Limited fire test studies on commercial Li-ion battery cells and electrolyte solvents have recently shown that the potential concentration of HF emissions could be high[10,11,12]. Emissions of HF and other toxic gases in other abusive situations, e.g. overcharging, and with or without ignition, have to our knowledge not been studied this far. HF is a gas that evolves in many different types of fires as can be seen in e.g. the study conducted by INERIS in France in

10 F. Larsson, P. Andersson, P. Blomqvist, A. Lorén, B.-E. Mellander, "Characteristics of lithium-ion batteries during fire tests", Journal of Power Sources, 271 (2014) 414-420.

11 P. Andersson, P. Blomqvist, A. Lorén, F. Larsson, "Using Fourier transform infrared spectroscopy to determine toxic gases in fires with lithium-ion batteries", Fire and Materials, 40 (8), 999-1015, 2016.

12 A. Lecocq, G. G. Eshetu, S. Grugeon, N. Martin, S. Laruelle, G. Marlair, "Scenario-based prediction of Li-ion batteries fire-induced toxicity", Journal of Power Sources, 316 (2016) 197-206.

2012[13] in which two different electric vehicles and two similar conventional ICE vehicles were set on fire and the heat release rate during the fire as well as gases evolved, including HF, were measured. They found that the heat release rate was of the same order of magnitude, independent of vehicle type. High concentrations of HF were emitted in the beginning of the fire for all four vehicles. This might have been caused by the air-conditioning system using a new coolant medium. However, the concentration of HF emission created in a Li-ion battery fire and in other failure situations has to be further investigated in order to evaluate the associated risks.

Anecdotal evidence exists that electric vehicles burn fiercely and that the fire is difficult to extinguish. The INERIS experiment does not confirm this burning behavior but the fire was started by a gas burner in one of the seats in these experiments. Other means of starting the fire might give another result but there are at present a very limited number of investigations, if any, available on this topic.

Research for firefighters was in the beginning mainly focusing on extrication of people from crashed cars and it is only recently that also extinguishing advice has started to be developed. In 2012 DEKRA in Germany published a study where batteries were extinguished using water and different additives[14]. They conclude that more water was needed for the EV fires than for vehicles with conventional internal combustion engines. In 2013 NFPA conducted a study[15] about firefighting of electrified vehicle batteries and found that large amounts of water applied during long time were needed to cool down the battery in order to prevent re-ignition. A recent NFPA study[16] concludes however that more research is needed concerning firefighting tactics for Li-ion batteries.

The EV users would like to be able to charge their vehicle fast in some situations, similar to filling fuel into a conventional vehicle, or at least to have a significantly shorter charging time than that of overnight charging. Today (2016) the grid of electric vehicle fast chargers world-wide is constantly increasing, yet far from being fully built-up. Fast charging requires high currents and one would therefore intuitively associate this with larger fire risks. The high current would result in a higher risk of overheating or other malfunctions in the charging station or in the vehicle itself and thus careful design is important. These risks are well known and actions have been taken to minimize associated risks.

VOLTAGES, CURRENTS AND ELECTRICAL HAZARDS

Traction voltage components and cables carrying a hazardous voltage are usually very well insulated and protected. The risk that a human, e.g. driver, passenger,

13 A. Lecocq, M. Bertana, B. Truchot and G. Marlair (2012) Comparison of the Fire Consequences of an Electric Vehicle and an Internal Combustion Engine Vehicle. *Proceedings of FIVE 2012*. Chicago, USA, Sep. 27-28, P. Andersson, B. Sundström, eds, SP Technical Research Institute of Sweden, Borås, Sweden, 2012, 183-193.

14 http://www.prnewswire.com/news-releases/lithium-ion-batteries-demonstrate-their-safety-in-fire-tests-176338721.html (accessed 2016 03 24).

15 R. T. Long Jr, A. F. Blum, T. J. Bress, B. R. T. Cotts, "Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results", Fire Protection Research Foundation, Quincy, MA, USA, June 2013.

16 A. F. Blum, R. T. Long Jr, "Hazard Assessment of Litium Ion Battery Energy Storage Systems", Fire Protection Research Foundation, Quincy, MA, USA, February 2016.

rescue personnel or firefighter, would be exposed to an electrical shock is in general very low. Both DC (direct current) and AC (alternating current) voltages are present in EVs (see also Chapter 3). The DC voltage comes from the traction battery or other components (e.g. charger, DC/DC converter) and the AC voltage is used by the power electronics (inverter) and electric motor/generator. The definition of hazardous voltage is that it is potentially dangerous for humans, and it is usually stated as > 60 VDC (voltage direct current) and > 30 VAC (voltage alternating current), although this limit varies in different countries and also in different electrical safety standards valid for the vehicle.

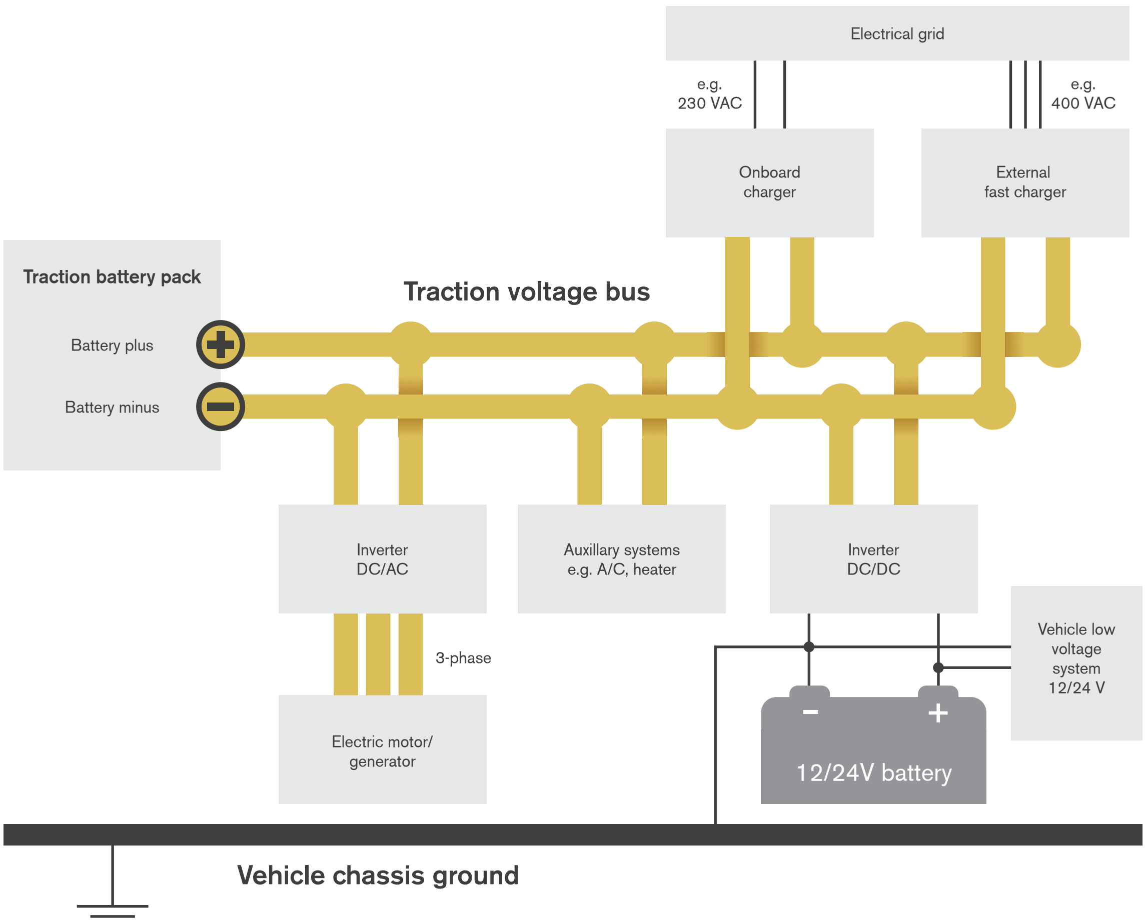

Figure 4.3. Schematic overview of a traction voltage system in an electrified vehicle connected to the electrical grid. The traction voltage bus (with DC voltage) with floating ground principle is shown.

The traction battery has a so called floating ground, meaning that there is no electrical connection between the traction battery poles and the vehicle chassis ground. The 12V/24 V vehicle battery on the other hand (for both conventional ICE vehicles and EVs) uses the vehicle chassis ground as the current return path to the negative 12V/24 V battery pole. Figure 4.3 shows a schematic overview of a traction voltage system in an electrified vehicle connected to the electrical grid. The floating ground principle is also shown, where the traction voltage bus/battery poles have no contact with vehicle chassis ground. Figure 4.4 shows a close-up of the traction battery as well as the current path and floating ground principle.

Both DC and AC voltage pose a danger for humans in case of an electric shock caused by either a direct touch of the traction voltage/battery poles, or indirectly by touching the metal chassis. In order for such exposure to occur, two insulation faults are required (one at each pole of the traction voltage/battery) and the victim must touch metallic parts with the different potentials at the same time. Figure 4.5 shows the principle of a double insulation fault. The vehicle chassis ground is usually constructed to electrically act as one pole of the 12/24 V system by having most metal parts connected to each other. In the situation of a double insulation fault there will be a short circuit through the chassis. Since the current takes the easiest path (i.e., the conducting path with the lowest resistance), the human body will hardly be affected by touching the chassis ground. On the other hand, there could be a potential risk for service personnel repairing a damaged electric vehicle, since they can, during disassembly, have two chassis ground, one with minus traction voltage/battery potential and the other with positive traction voltage/battery potential. There are however, protection means for this, e.g. insulation measurements, electrically insulated gloves (typically marked for safe use up to 1000 V), and knowledgeable maintenance staff should be able to minimize this risk. With an increasing number of electric vehicles on the roads the experience and techniques/routines will grow for their users (e.g. driver, service and rescue personnel) resulting in developing safer handling by time. A similar adaptation has occurred in the past learning how to handle flammable gasoline/diesel fuel, as well as hazards associated with the electrical grid.

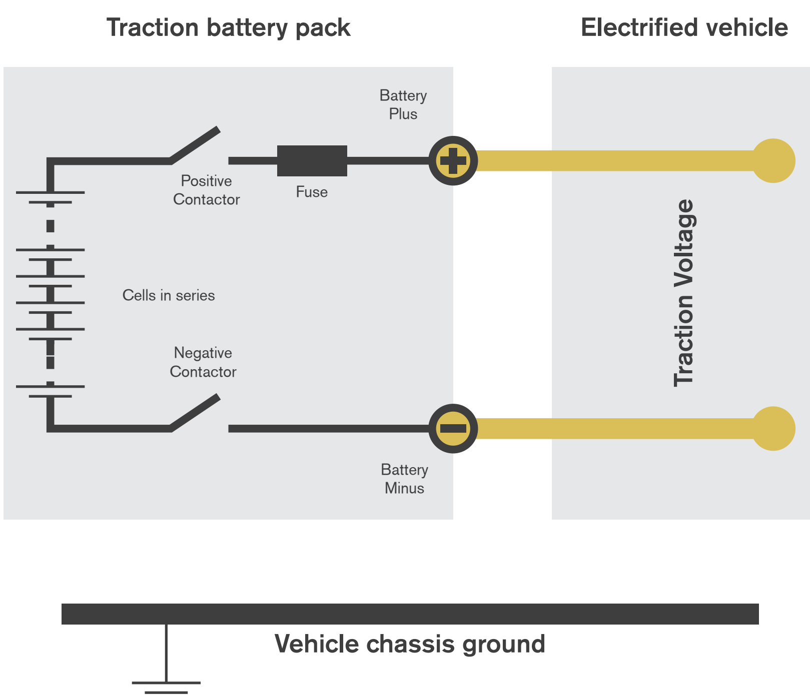

Figure 4.4. Traction battery pack current path and the floating ground principle. If there are no insulation fault(s), there are no electrical connections between vehicle chassis ground and the battery poles.

It could be mentioned that hazardous voltages, both DC and AC, inside the components in an EV, sometimes are referred to as "high voltage". From the automakers perspective, this term conveniently separates the 12/24 V system ("low voltage") and the e.g. 300-600 V system ("high voltage") for the electric drivetrain and the traction battery, However, to name the hazardous traction voltage as "high voltage" is somewhat misleading since there is already a definition and a long time tradition to use the term "high voltage" within the mains (electrical grid), for voltages over 1000 VAC or over 1500 VDC. The term "HV" is actually in automotive industry sometimes interpreted as "hazardous voltage" (instead of "high voltage").

An electrified vehicle still contains electrical energy in the battery when it is shut-down and parked. The hazardous battery voltage is, however, kept inside the battery pack and insulated from the rest of the vehicle by design. This means that, for a shut-down and parked vehicle at rest without charging connection to the electrical grid, all parts except the inside of the battery system can be considered as voltage free (provided there are no electrical insulation failures). It is however important to understand that also an "empty" battery, meaning fully discharged, 0% SOC, still has a considerable voltage. For an electric vehicle this is still to be considered as a hazardous voltage.

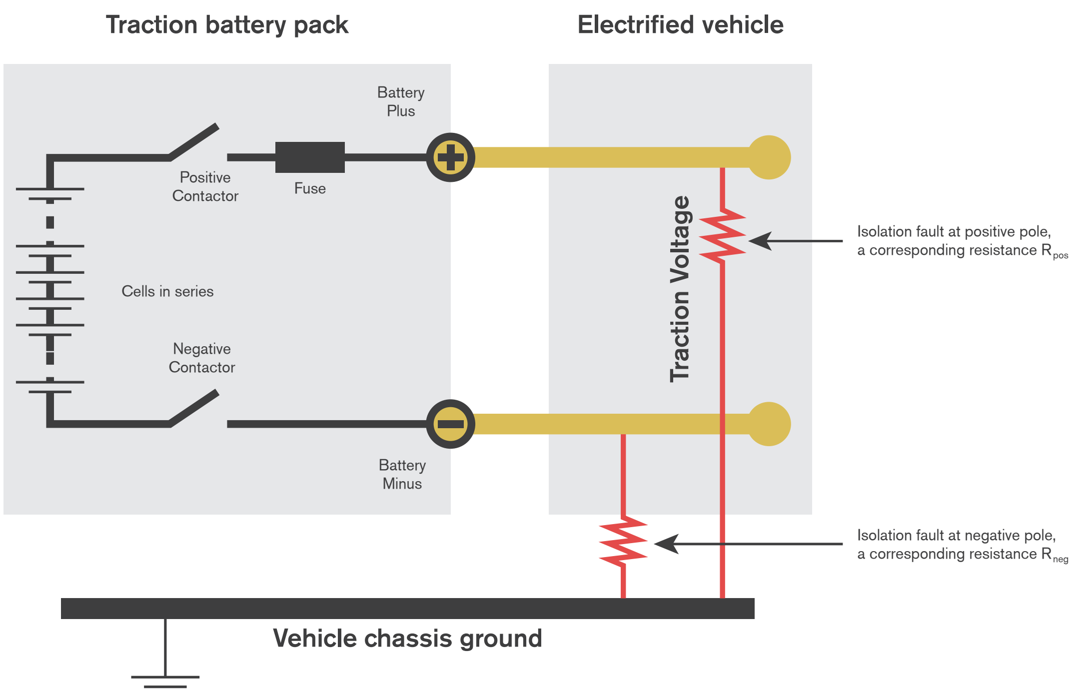

Figure 4.5. Principle figure that shows a double insulation fault. This means one insulation fault at the plus and one at the minus pole. They are shown as two resistances, R_{pos} and R_{neg}, connected to ground. This creates a current path between battery plus and battery minus through the vehicle chassis ground.

As seen in Figure 4.3, the battery pack is not the only source of hazardous traction voltage. When the battery pack is disconnected (open contactors) a hazardous voltage can still be present in the vehicle originating from other sources such as the electric motor, charger and DC/DC inverter. For example, in case a wheel of the vehicle is rolling when the battery pack is in shut-down mode (open contactors), e.g. by manual movement of the vehicle by service personal, a hazardous electrical voltage is induced in the electric motor. This voltage is however insulated by design, and the electric charge is typically designed to discharge/deplete within a few minutes. Also, service personnel typically use a work instruction including short circuiting/discharging any potential voltage prior to doing maintenance/repair on the vehicle. Another example is the charger, which can be located onboard the vehicle or externally as a charging station. Fast chargers are typically placed externally while smaller chargers (e.g. 230 VAC, 10-16 A) are placed onboard the vehicle. The charger is mainly used to recharge the battery pack but could also be used for other purposes energizing the vehicle, thereby energizing the traction voltage system. This could for example be the case using the charger, taking its power from the electrical grid, to give power to an on-board vehicle heater/cooler, without using the energy from the battery pack. The DC/DC inverter between the 12/24 V battery and the traction voltage is also a potential source of electrical hazards when activated.

Vehicles with internal combustion engines have had a remarkable increase in vehicle safety during the last 10-20 years. Active safety is now starting to be introduced in some cars, e.g. lane departure warnings. The passive safety, e.g. crash protection, has evolved greatly over the years with e.g. the Euro NCAP testing. Computer simulations and crash tests have fostered the development of crash deformation structures significantly and increased crash and collision protection. Electrified vehicles are likely to have the same level of passive and active safety as conventional vehicles. In order to ensure this, the safety techniques must be adapted for this new technology, e.g. during a crash, crash detection sensors inside the vehicle, also used for activation of airbags, can disconnect the traction voltage from the battery before the crash is complete. This means, that even if the electrical insulation of the traction voltage, containing the hazardous voltage, would be damaged, this voltage will be turned off. Of course, in severe crashes, there is always a risk that this might not be the case.

Presently (2016), car manufacturers crash protect the battery pack so that no short circuit may occur in its electronics and that no lithium-ion cell can be deformed during pre-defined crash scenarios. In principle, this is done by putting the battery inside a crash protected box. This adds weight, volume and costs. The battery is usually placed outside the deformation zone. For a passenger car, this generally results in a battery placement inside or beneath the passenger compartment. In the future, it is likely that the battery pack instead becomes a part of the crash structure. Battery packs of today can handle some small deformation; this is a matter of design, which today varies depending on cell chemistry, cell design and packaging. In the future, it is likely to have safer lithium-ion cells and battery systems which could to a higher level stand a deformation. In that case the battery can to a larger extent by used in the vehicle's crash structure. The deformation protection design criteria are given by load-cases. This means that for a severe crash, which is outside the design criteria, a deformation which is larger than expected can occur. It is unrealistic and just not possible to design the crash protection for all types of extreme collisions.

INCIDENTS

Despite the manufacturers efforts to produce safe batteries some events have occurred that have reached media attention. One of the major media events in June 2011 was the fire that started in a PHEV, GM Chevrolet Volt, three weeks after a crash test. The incident was thoroughly investigated by NHTSA and the chain of events was reproduced. The reason was found to be that the cooling media had leaked over the battery and then dried; leaving crystals that finally short circuited the battery through the metallic belt around it. Changes have since been made to the design, e.g. to avoid leakage of cooling media.

Another event that has drawn some media attention is the fires that occurred after hurricane Sandy hit the Atlantic coast in the New York area in October 2012. At the harbor of Newark, New Jersey, thousands of parked vehicles were flooded. The cars were brand new shipped in from abroad. The water wave that followed Sandy immersed the parked vehicles in 1.5-2.5 meters of seawater during several hours. It has been reported that sixteen Fisker Karma PHEVs and a few Toyota Prius HEV and PHEV burned. Unconfirmed statements from Fisker and Toyota blame the fires on short-circuits in the 12 V vehicle electronics. To be submersed in 1.5-2.5 meter deep seawater for several hours is a very severe test for an electrical system in general which can only be met with IP68 class or equal water-tightness level. Seawater is a good electrical conductor and can cause short circuits, for both low voltage (e.g. 12/24 V vehicle voltage) systems and for the traction voltage in electrified vehicles.

At the end of 2013 mass media attention was also drawn to the incidents of three burning Tesla Model S electric vehicles within a six week time period. In one of them the driver crashed into a concrete barrier and a tree resulting in significant damage to the vehicle. In the other two, road debris were hit at highway speed. It is natural that large external forces can lead to deformation and penetration of the battery pack resulting in short circuit and fires. The incidents were investigated by NHTSA and no defect trends were found. However, Tesla voluntarily choose to improve underbody protection of the vehicle using armed plates. Up to now (May 2016), the authors are aware of three more fires with Tesla Model S, possibly caused by electrical faults (e.g. charger) outside of the vehicle. Today there is very limited statistics available of fires in electric vehicles and no statistics is available for potential aging effects on electric vehicle safety. At present slightly more than 100 000 Model S have been sold, that gives a fire in about every 1/20 000 Model S cars. This number potentially indicates a high safety for this type of electric vehicles since the comparable number for combustion engine vehicles is about 1/1000[17]. One should keep in mind however that this number include all types of fires including those that are intentionally lit.

More than 200 000 Nissan Leaf electric vehicles have been sold during the last 5 years of production. So far the authors are only aware of one vehicle fire incident which indicates a very low fire risk for Nissan Leaf. Even if data still is very limited there seems to be a potential that electric vehicles can be less prone to fires than combustion engine vehicles.

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17 M. Ahrens, "Automobile Fires in the U.S.: 2006-2010 Estimates", *Conference Proceedings of Fires in Vehicles (FIVE) 2012*, P. Andersson, B. Sundström, eds, SP Technical Research Institute of Sweden, Borås, Sweden, 2012, 95-104.

OUTLOOKS FOR THE FUTURE

The electrical drive train is made safe by several means. The battery cells used are in general safe since judicious choice of Li-ion technology ensures that an unsafe lithium-ion cell would not be chosen. The battery safety is ensured by the manufacturer by adding layer by layer of safety, schematically shown in Figure 4.6. Safety issues are of major concern in any introduction of a new product into the market as negative publicity might have a very negative impact of the general public's perception of a product and the product's potential to succeed. Key aspects here are to design safe products and be very open about events that have occurred as ample correct information is the best way to avoid rumors. One threat to a safe introduction could be home-converted vehicles as these, with their limited budget, would have difficulties reaching the same high safety levels as commercially built vehicles.

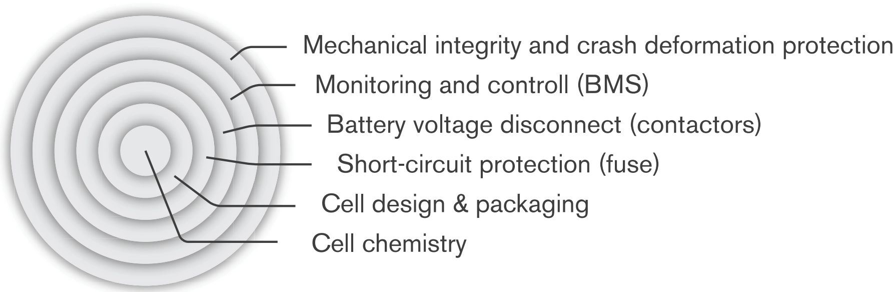

Figure 4.6. An example of battery safety layer by layer.

Lithium-ion batteries for automotive use have shown an increased safety regarding fires through e.g. improved electrode and electrolyte materials. The choice of materials for future batteries is thus a fundamental issue including possible scarcity problems. New materials that are introduced in order to improve battery performance or safety may, however, result in new risks which will need to be addressed. As an example, the choice of different additives to obtain sufficient safety, e.g. flame retardants, or other necessary battery characteristics can result in negative environmental impact issues and battery life-cycle issues which will be untenable.

Electric vehicles can have several benefits for the overall safety; the largest fire risk is removed with the absence of gasoline/diesel fuel (or less amount in case of PHEV), lower center of gravity (with a large battery pack underneath), increased freedom in vehicle design, potentially larger front deformation zone since no space is needed for a large combustion engine and the electric motor is small. Electric vehicles might however have less deformation capabilities for some crash angles, strongly depending on battery size and placement, since the battery has to be protected from deformation. Electric vehicles with Li-ion batteries also have other disadvantages, e.g. release of toxic and flammable gas emissions and electrical hazards. As long as there are no intrinsically safe Li-ion cells, there will always be a small risk of cell failure, therefore it is essential to lower the probability of a single cell failure and to limit its consequences, i.e. early warning detection, handling of its effects (e.g. gas release) and limited propagation by design of battery pack and vehicle integration.

The number of EVs on the road is still too low to conduct reliable statistical studies of incidents and accidents. Anyhow, the limited data on incidents up to now, presented in this chapter, give an indication that electric vehicles might be less prone to fire incidents than vehicles with internal combustion engines. The numbers of EVs sold are steadily increasing and with that also the possibility to conduct different safety studies which will foster development of even safer EVs. Focus on battery safety has to a large extent been on the cells as such and much progress has been made in this respect. The traction voltage parts of the system are also subject to many protection steps. It is important, however, to take into account that the cells are part of a large system with a lot of electronics that needs to be functioning in a harsh environment as vehicles are subject to many different situations.