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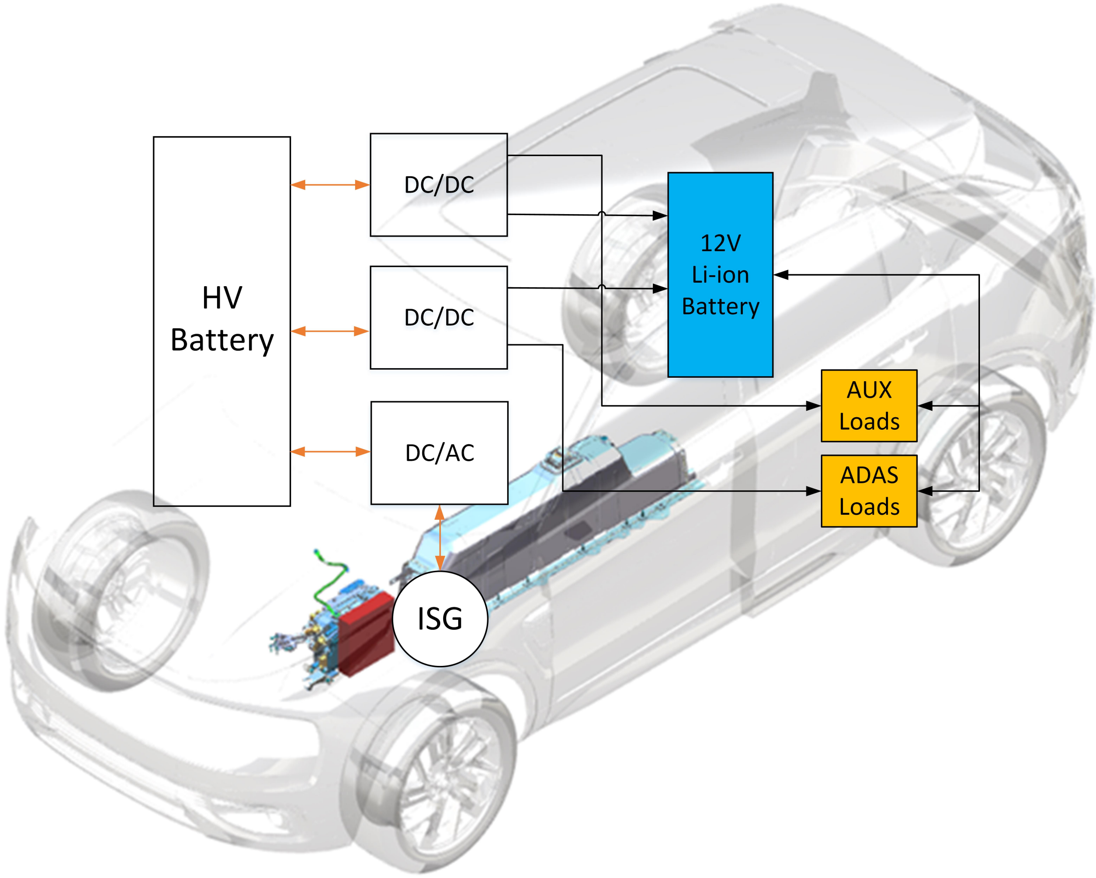

Study of a 12V Li-ion Battery Solution for Hybrid Vehicles

Master's thesis in Electric Power Engineering

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Abstract

Nowadays, the typical 12 volt battery chemistry in cars is lead-acid. There is the possibility to replace this chemistry with a Li-ion technology in hybrid vehicles, due to its potential beneficial features. Besides, there is a need of an extremely reliable 12V electric system in hybrid cars, not only for the current electric distribution system in the car, but also due to the introduction of autonomous drive. Moreover, since packaging space is a big issue in modern cars there is also a need to reduce the number of components. Therefore, it is important to study the impact when integrating the 12V Li-ion battery to be a part of the electric system as a power source, including the power distribution system and loads, in order to improve the utilization and performance of the battery. In this project the 12V Li-ion battery of the hybrid vehicle is taken in to account to find a suitable battery available on the market that can fulfill the specific requirements of the 12V electric system.

Keywords: Plug-in Hybrid Vehicle, 12V Li-ion Battery, Battery Management System, High Voltage, Battery Pack

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Daniel Cela
Gothenburg, Sweden. 2018

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Patrik Alerman
Gothenburg, Sweden. 2018

Definitions

Ampere hour (Ah), or amp hour for short, is the energy capacity of the battery. It defines the number of amps or electric current that flows from a battery during one hour [1].

C-rate describes the amount of charged/discharged-rate (current) which is relative to the capacity of the battery for a certain time within specific voltage range [2].

Cold Cranking Amps (CCA) is a measurement which tells the capability of the battery to start an engine in a cold environment. If a battery can maintain a minimum voltage of 7.2 V during 30 seconds at -17.78 °C, the number of amps from the battery can be measured [3].

Curb weight is the weight of fuel tanked vehicle without any passengers, cargo or other loads [4].

Gross weight is the total weight of the vehicle with passengers, cargo and other loads [4].

Regenerative braking. A conventional vehicle's kinetic energy is transformed into heat loss during braking. Regenerative braking (or regeneration of braking energy) allows some of these losses be captured, converted into electricity through the electric motor and stored in a battery. This stored electricity can provide extra power for the electric motor during acceleration [5], [6], [7].

Reserve Capacity (RC) describes how long the battery will operate, in minutes, for a fully charged battery to give 25 amps until the voltage reach 10.5 V at 26.67 °C when the alternator is disconnected/failed [8], [9].

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Introduction

1.1 Background

Nowadays, there is an increasing demand of low emissions and environmentally friendly vehicles. Thus, hybrid vehicles such as Hybrid Electric Vehicles (HEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) have been under development the last years which consume less fossil energy. According to Navigant Consulting, the HEVs represented three percent of the total number of passenger vehicles in 2017. The vehicle's auxiliary system has a voltage level of 12 V, that is powered up by a Lead-acid (PbA) battery, which today is the most common battery in any vehicle including HEVs and PHEVs. Not only current, but future generations of HEVs and PHEVs include more electric loads and the vehicle electrification demands better requirements from the 12V battery. Therefore, there is a need of a reliable 12V system in hybrid vehicles for the present electric distribution system and new electric loads such as: autonomous drive. Moreover, since packaging space is a big issue in modern vehicles there is a need to reduce the number of components, the total vehicle weight and the overall vehicle energy consumption. Hence, there is a possibility to replace PbA battery with a Lithium-ion (Li-ion) battery and to integrate the 12V battery within a future platform of HEVs/PHEVs.

1.2 Aim

The aim of this project is to find a suitable 12V Li-ion battery that can replace the traditional Lead-acid battery in the low voltage system, analyze and estimate a 12V Li-ion solution for the electric system when the autonomous drive is introduced, and study the integration of a 12V battery in the future platform for HEVs & PHEVs.

1.3 Problem Description

The 12V electric system is an important part of the vehicle. Currently, more requirements are needed for the vehicle's low voltage battery system to be fulfilled, such as the autonomous drive system and present loads. Inside the vehicle there is a space limitation together with the need of decreasing the vehicle's total weight. Therefore, the technology, size, weight and location of the 12V battery play a key role in the vehicle's performance.
In order to investigate and evaluate this project the next three sub-tasks are investigated:

- Study the availability on market of the 12V Li-ion batteries for vehicles.
- Analysis of the 12V system requirements with respect to power sources and auxiliary loads including the introduction of the autonomous drive.
- Integration of a 12V Li-ion battery solution.

First, a market research is done to determine the availability of 12V Li-ion batteries. Using market information of batteries and current offers from different suppliers, the technical specifications of this type of battery are analyzed. The main advantage of using Li-ion battery is the low weight and size compared with the traditional Lead-acid battery. However, Li-ion battery is more expensive than PbA, thus the cost of the solution is taken into account.

Furthermore, a benchmark analysis is performed in order to determine which cars in the current market had adopted the 12V Li-ion battery technology. On the other hand, the current requirements of the 12V system in hybrid vehicle are collected and analyzed to perform a study of the electric power consumption of the loads including technical data such as: rated voltage, current, power and working conditions.

Critical loads must be determined in order to find their energy requirements for the worst driving scenario. It is important to find the limitations of the usage of the 12V battery along with the electric distribution system.
It is also important to analyze the power consumption of the low voltage system when introducing the vehicle into autonomous drive mode. This study is needed in order to investigate the reliability requirements of 12V system for the autonomous drive. To be able to analyze the power distribution system in the HEV, an electric system model is proposed.
Additionally, to complement the calculations, measurements are obtained from a real-test of 12V system and current battery. Based on the results of the power distribution system, a suitable Li-ion battery and its location in the vehicle is proposed.
Finally, the integration of the 12V battery is analyzed, including different Li-ion chemistries, battery shapes and location environments in the vehicle.

1.4 Scope

This work considers the 12V battery, the auxiliary electric distribution system, and the introduction of the autonomous drive for two types of hybrids vehicles - HEV and PHEV - with parallel driveline system structure. Since, the loads and 12V electric system are similar, the solution is valid for both, HEV and PHEV.

The main features of the current 12V Lead-acid battery and its performance in the auxiliary system are analyzed from provided data, documentation and testing on the vehicle. A market research of Li-ion battery is included, which shall fulfill the requirements for the low voltage system in HEV/PHEV.

Besides, the introduction of the autonomous drive is taken into consideration, including an analysis the 12V battery integration in the electric system. Test of the 12V system is carried out together with the battery, continuous and transient loads. To simplify the 12V distribution system, a DC/DC (400V/12V) converter is treated as a power source with a constant voltage, since it is a voltage controlled converter, the results are not affected.

The cable impedance is measured to analyze the current losses when the battery is placed in today's location of the vehicle. Other locations are proposed in order to decrease the cable losses.

A possible integration of the 12V system with the Energy Storage System (ESS) and High Voltage (HV)-battery pack are studied, including an analyze of different Li-ion chemistries, cell formats and battery locations. However, the powertrain components are not examined because they are not a part of 12V system.

2

Theory

This section describes the theoretical background and general concepts of batteries and chemistry technology. Additionally, hybrid vehicles as HEVs and PHEVs are presented. Besides, the result of a benchmarking explains of which battery technology is utilized in the hybrid vehicles today. Finally, autonomous drive technology is introduced.

2.1 Battery Principles

A battery is a device which stores electrochemical energy and is able to deliver into electrical energy. A basic battery contains three main components such as: cathode, anode and electrolyte. Cathode or negative electrode is able to collect electrons from the external circuit. Anode or positive electrode gives electrons to the external circuit. The electrolyte is a material where the ions are transferred from the anode to the cathode [10].
The main features must be taken into consideration when describing a battery such as: State of Charge (SOC), temperature range, cycling, rate of discharge when not in use, Deep of Discharge (DOD), $C - rate$, etc. [10], [11].

The SOC describes the charge content in the battery. It plays a key role for the battery management of the hybrids and electric vehicles in order to keep the health and safe operation of the battery. SOC can be defined as the ratio between the remaining capacity (C_r) and the nominal battery's capacity (C_n):

$$SOC = \frac{C_r}{C_n} \tag{2.1}$$

or

$$SOC(t) = SOC_{t0} - \frac{\int_{to}^{t} \eta I(\tau) d\tau}{C_n} \tag{2.2}$$

where SOC_{t_0} is the initial level of SOC, η is the efficiency of battery when charging/discharging and I is the current from/to the battery.

State of Health (SOH) can be defined as the ratio of the aged battery capacity (C_{aged}) and the nominal battery's capacity (C_n). It describes the degree of performance-degradation and can be used to estimate the battery remaining lifetime.

$$SOH = \frac{C_{aged}}{C_n} \tag{2.3}$$

2.1.1 Power & Energy Battery Content

Batteries can be designed with a specific requirement for power and energy content. The main impact of the optimization will be seen not only in the performance of the battery, but also in its physical components and electrochemestry. According to [12] the key design variables for a Li-ion battery are: electrode thickness, particle sizes, porosity and conductivity. Therefore, depending on the battery application, it can be power or energy optimized which has a direct impact in the final specifications and properties of the battery.

A power optimized battery focuses on giving a high current for a short period of time. This behaviour can also be obtained by a well-known passive element, a capacitor. New vehicle technologies are adding a supercapacitor in order to deliver high currents for transient loads. On the other hand, an energy optimized battery allows to feed a load with relatively low current for long-term periods. For instance, in a conventional vehicle application, the auxiliary battery of the car should fulfill the energy content that allows the vehicle to be parked at least for 21 days , this will be explained in detail in Chapter 3. However, a high current must be provided for a few seconds to crank the vehicle described in Chapter 6.

2.1.2 Battery Equivalent Circuit

The battery can have different electrical models depending on the study or involved application. A basic simple model of the battery is described in Figure 2.1, where the internal battery voltage V_{oc} (open circuit voltage) and the internal resistance R_i are a function of SOC. This means that V_{oc} and R_i are dependent on the SOC and change correspondingly to it. The difference of the voltage between V_{oc} and the terminal voltage V_t leads a current I_c to flow. The current I_c can be bi-directional if charging or discharging the battery [13].

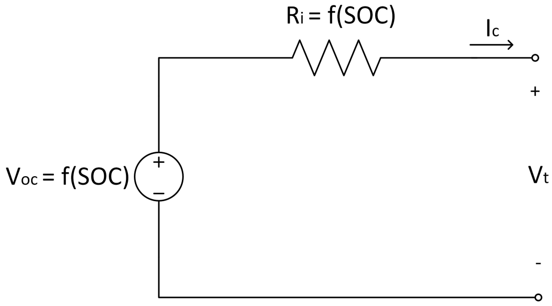


Figure 2.1: Basic simple battery model including the internal battery voltage V_{oc} and the internal resistance R_i which are a function of SOC [13].

The terminal voltage V_t can be calculated as:

$$V_t = V_{oc}(SOC) - R_i(SOC)I_c \tag{2.4}$$

2.2 Battery Technologies

There are different battery technologies that can be used for the 12V electric system in vehicles. The most common battery is the Lead-acid which has been under development the last century, even continuing today. Nowadays, the Li-ion battery technology is growing due to its advantages of energy content among others. A brief description of these battery technologies are given below.

2.2.1 Lead-Acid Battery

The Lead-acid battery is based on the metallic material *plumbum* (Pb) which means lead in Latin. This battery has the ability to provide a high inrush current, due to a low internal impedance, wherefore it is mostly used as power source for the ignition of a starter motor in automotive application. Also, due to its widely establishment and development the Lead-acid battery can be constructed to many forms and voltage levels. However, the metal itself is toxic and heavy which have impacts on the environment and complicates the battery construction. Due to the material's many features, the PbA battery is most convenient to use as an energy source for starting, lightning and ignition (SLI) functions in vehicles [14]. In this work, an investigation will be made to see if the 12V Lead-acid battery, as an energy storage of the electrical system, can be replaced by another type of battery in the HEV & PHEV.

The structure of the Lead-acid battery is a composition of two electrodes (or plates) where the anode is based on the lead dioxide and the cathode on the metal lead. These electrodes are separated from each other by sulfuric acid which is the electrolyte that stands for the production of electrons at chemical reactions. Normally, during discharging of the battery, sulphuric acid concentration in the electrolyte is low when lead absorbing the sulfur. When recharging, the concentration is high as the sulfur from the lead returns back to the electrolyte [14], [15]. When the PbA battery is fully charged, six cells produce a voltage. Each cell provides 2.0 V, in total it will be 12 V which is the nominal voltage of a 12V battery [16]. However, according to [17] the electrical 12V system in vehicle applications are normally 12.6 V at no load and with load approximately 14 V.

Depending on the battery application, a Lead-Acid battery can be designed in two different main types [18]:

- *Starting battery* (for SLI functions) - due to thinner plates and their material properties, the electrons are able to move faster in the battery to quickly generate a higher inrush current in order to start (cranking) an engine.
- *Deep cycle battery* - due to thicker plates they are fewer, which give the battery less inrush current, on other hand it can store energy during a longer period and handle many discharging cycles.

These types have several variations when it comes to PbA batteries, which are described in more detail in section 2.2.1.1.

2.2.1.1 Development of PbA Battery

Why Lead-Acid is still in used in batteries in conventional cars and in HEVs and PHEVs likewise depends on its history development. At the start, the PbA battery was implementing as a starting battery of the first developed electrical systems in vehicles for SLI functions. In the 1950s, the voltage level of the systems was selected to 12 V, ever since then there have been a lot of improvements of the battery [17]. The coming five decades the Lead-acid battery has developed, and still does, to many different versions accordingly to the requirements from the auto industry. The development has been going in two different directions, which have created two main groups of PbA-batteries, such as: *Flooded* and *Valve Regulated Lead-Acid* (VRLA), also known as Sealed Lead-Acid (SLA) [19]. The development of the Lead-acid battery is depicted in Figure 2.2.

The first batteries were Flooded (Wet cells) batteries which means that the electrolyte inside of the battery is in liquid form. Due to its open design, liquid and gas are leaked which is an environmental problem. This requires the electrolyte level is checked and water is added to the loss electrolyte solution regularly. Though, this kind of battery is still common on the market due to its high rate charge for a low price [20]. A similar battery to flooded batteries is Enhanced Flooded Battery (EFB) which has thicker plates which gain faster DOD and longer cycles [19].

Next, the VRLA battery was developed as sealed-constructed battery. Due to its design, liquid and gases in operation would not leak, hence the battery would be maintenance free. The VRLA battery can be divided into two categories - gel electrolyte battery (Gel cell) and Absorbed Glass Mat (AGM). The gel cell was designed

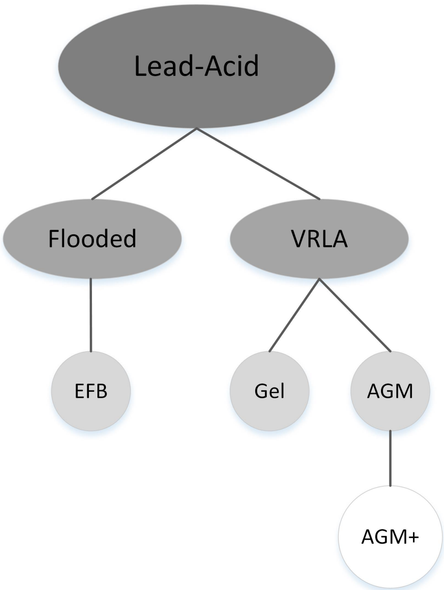


Figure 2.2: The development of the Lead-acid battery.

with a gelatinized electrolyte solution, which allows it to be in any position and be resistance against vibration. However, they have limited applications due to the many advantages of AGM. In AGM batteries the gelatin have been replaced by fiber glass. This allows the battery to directly absorbs the electrolyte. An extension of AGM is Advanced AGM (AGM+), which has compressed plates which allows a battery with small design size and high capacity [19], [21].
The VRLA was further developed when carbon was introduced, which becomes an advanced lead-carbon. In some cases, according to the U.S. Department of Energy, the Lead-carbon battery is equal or better than Li-ion and NiMH batteries in performance and are more economic to be utilized. The next coming generation of Lead-acid batteries are Advanced Lead-Acid Battery Consortium (ALABC), which will combine increased efficiency and low costs of HEV to meet the sustainable and economic demands.

The development of the battery has led to many types of PbA batteries, which consecutively contributed to its standardization as 12V battery. Now, it is the most common battery to use for the vehicle's electric system. Therefore, is an ordinary sight within the auto manufacturers [21].
In this work, the current 12V battery that is used in the electric low voltage system of the investigated HEV & PHEV is a VRLA battery that is based on AGM-technology. Therefore, this particularly battery will be study more deeply. Table 2.1 represents the specifications of that battery, or so called the battery capacity label.

Table 2.1: Lead Acid battery capacity label.

Feature	**HEV & PHEV**
Type	H6 (L3)
Nominal voltage (V)	12
Battery Capacity (Ah)	70 (20HR)
Rated Capacity (min)	120
CCA @ -18°C (A)	760
Charge Acceptance	$5I_{20}$
Weight (kg)	21.3
Dimensions (mm)	278 x 175 x 190

Where the geometrical dimensions of the battery are:

- Length = 278 mm
- Width = 175 mm
- Height = 190 mm

2.2.2 Li-Ion Battery

Lithium is the lightest metal, under normal conditions, among the chemicals elements. The electrochemical properties of the lithium-based battery gives the potential to achieve high power and energy densities. Currently, it is widely used in several electronic applications and electric vehicles. Lithium batteries can be modeled and customized according to specific requirements. Different combination of types, materials and structures for Li-ion batteries can be selected in order to have a suitable battery for electric cars. The energy density is increased with high open circuit voltage and low weight, the *SOC* where the battery can be cycled is wide. The main disadvantage of this technology is that in low temperatures (<10°C), the performance and life time of the battery can be reduced [14].
On the other hand, the temperature must be controlled in order to avoid capacity losses and thermal runaway. Therefore, Li-ion batteries must include a Battery Management System (*BMS*). Thus, a monitoring system has to be installed with the Li-ion battery in order to have an active measurement of some parameters of the battery such as:voltage, current, temperature, *SOC*, balancing, among others [14].

2.2.2.1 Lithium-Ion Battery and Chemistry Types

The Lithium-ion battery industry have been under development the last decades and several chemistries had appear into to the market. There are many applications that adopted this chemistry such as: electromobility, laptops, mobile phones, among others. The Li-ion chemistry still continues under development and the automotive industry is been adopting this technology. There are several Lithium-ion chemistries that are used in different applications. The main chemistries within automotive industry are described below [22], [23]:

- **Lithium Iron Phosphate (LiFePO4 or LFP)**
  This chemistry uses phosphate as a cathode material and is the most common technology used to replace the SLI lead-acid battery in vehicles. In order to get 12.8V from the this battery 4 cells in series are required. The main advantages to used this chemistry are: high current rating, long cycle life, good thermal stability, enhanced safety and tolerance. The typical temperature range is -20 °C to 70 °C. Besides, LFP is one of the safest chemistry in the Li-ion family, since it is highly stable during undesired conditions such as: short circuit, overcharge or overcurrent.

- **Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO2 or NMC)**
  The most common cathode material is nickel-manganese-cobalt, by combining these three elements the battery performance is achieved. Therefore, there are many combinations that can take the qualities of each element for different applications such as: electromobility, medical devices, industrial. The main features of this chemistry are: high capacity, specific power and popular in the market for many applications [22].

- **Lithium Nickel Cobalt Aluminum Oxide (LiNiCoAlO2 or NCA)**
  By adding aluminum to lithium-nickel-oxide, it is possible to develop a high stable chemistry. This one is so called NCA, its characteristics are similar to NMC, such as high specific energy, relative high specific power and long lifetime. Though, NCA comes with a high cost and due to a low thermal runaway this chemistry is less safety compare to other Li-ion chemistries [23].

- **Lithium Titanate (Li4Ti5O12 or LTO)**
  The best qualities of this chemistry are: long life, fast charge, wide temperature range. Besides, it is included in the safest Li-ion family due to its high thermal stability under high temperatures. On the other hand, it has a relatively high cost and low specific energy content. The common applications are: electric powertrain, lighting, UPS, etc. [23].

Current research continues developing Li-ion batteries for automotive industry in order to increase their performance and features, but also in aims of reducing the total cost.

2.3 Battery Comparison and Sustainability

Since the Li-ion and Lead-acid battery are based on two different chemistries, it is important two distinguish the advantages and disadvantages of each battery. This section describes the comparison of them and their impact on the environment.

Except for the low price, the PbA-battery can be recycled easily. Almost all components, like lead, sulfuric acid and plastics, in any kind of Lead-acid battery can be reused. Additionally, the manufacturing costs of new batteries are lower when utilizing reused material because less energy is required, which also means reduced pollution of CO_2 from the auto industry. Investigations by U.S. Department of Energy show the emissions of Lead-acid batteries are low during the production compared to other kind of batteries as shown in Figure 2.3 [21].

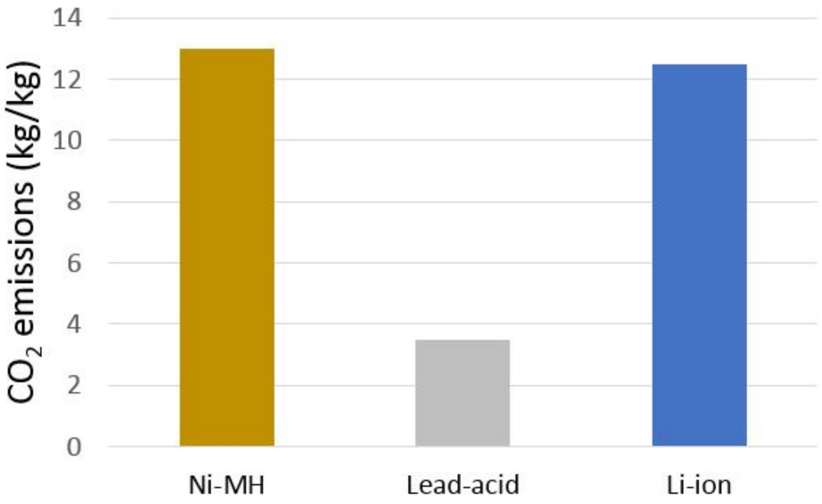


Figure 2.3: Average CO_2 emissions of different battery chemistries [21].

Besides, Lead-acid batteries comes in many variations (size, voltage level, etc.), they have a flexible design factor. Moreover, the internal impedance is low in the batteries which allow them to supply a high inrush current.
Despite the beneficial features of PbA, there are some drawbacks. According to the periodic table, the material has a density of 11.3 g/cm^3, which is much higher than it is for lithium, explaining why it is so heavy [24]. Hence, less specific energy and power which means reduced battery capacity. Even if the battery is recycled friendly, its acid is toxic and harmful for environment and people at leakages.

Lithium has a small density (0.534 g/cm^3), which means it can have a higher specific energy density (Wh per kilogram) [25]. This also involves reduced size and weight of a Li-ion battery. Figure 2.4 shows how the density of lithium is higher compare to other chemistries [26].

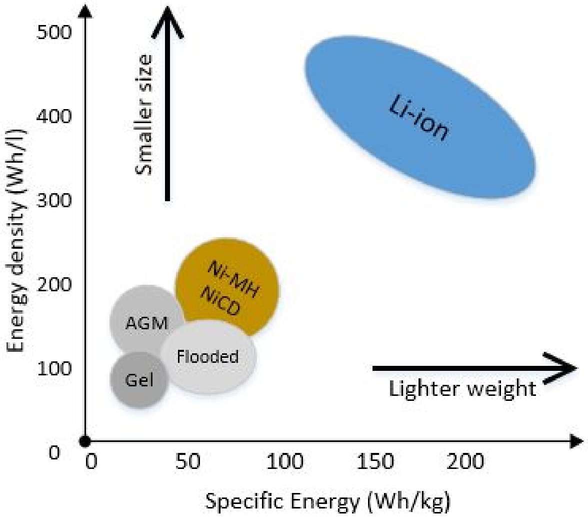


Figure 2.4: Battery density comparison. Nominal battery energy per unit volume vs. nominal battery energy per unit of mass [26].

Otherwise, the biggest issue for the Li-ion chemistry, at least for today, it is expensive and difficult to be recycled. However, according to [27], in 2018, scientists at Chalmers University of Technology have found a method of how lithium can be recycled. The method implies different applied chemistries that are separating the disassembled battery's metals. Though, this method is still expensive, the university and the battery company Northvolt are in collaboration in order to reduce the recycled cost.

As the use of electric vehicles is rising, the demand of lithium is increasing. Globally, within a decade, the manufacturing of lithium will grow dramatically. The battery manufactures are planning to establish new facilities which can give a total capacity growth from 28 GWh per year to 217 GWh per year [27].

Besides the manufacturing development, the mining of lithium will also increase. Although, this does not mean lithium as a raw material will end. There are large assets of lithium over the world and can be prospected in mines, dehydrated lakes and even from sea water, which can be considered as an infinitive source [28].

Table 2.2 shows the different battery chemistry properties between lead-acid and li-ion.

Table 2.2: PbA vs. Li-ion chemistry and general specifications [23], [26], [29], [30], [31].

	Lead Acid		**Lithium-ion**	
	Flooded	**AGM VRLA**	**LiFePO4 (LFP)**	**LiNiMnCoO2 (NMC)**
Specific Energy (Wh/kg)	30	40	90-120	150-220
Specific Power (W/kg)	100-200	100-200	500-8000	>500
Number of cycles to 80% SOH	200-1000	200-650	1000-4000	1000-4000
Temperature Range (°C)	-40 to +55	-15 to +50	-30 to +60	-20 to +60
Useful capacity	50	50	>80	>80
Self-discharge per month in %	3-4	3-4	2-3	<2*
Regular maintenance	Yes	No	No	No
Robust Over/Under Voltage	Yes	Yes	BMS required	BMS required
Average energy cost ($/kWh)	131	221	200-300	530

*Since NMC has the lowest self-discharge rate and LFP has a higher rate than other Li-ion chemistries, it is assumed that NMC has a self-discharge rate which is lower than 2 % per month [23].

2.4 Hybrid Vehicles

Any vehicle which is utilizing electric and combustion engines for the propulsion is classified as a hybrid vehicle. This kind of vehicle can be divided into four main groups which are: Hybrid Electric Vehicles, Plug-in Hybrid Electric Vehicles, Electric Vehicles (EVs) and Fuel Cell Electric Vehicles (FCEVs). These groups can, by consider the hybrid's powertrain form, reduce the reliance of the petroleum. Hence cut down CO_2 emissions and fuel costs. This project will be focused on HEV/PHEV.

2.4.1 Hybrid Electric Vehicles

HEVs have two different engines which can be operated simultaneously or separately. It has an Internal Combustion Engine (ICE) with a fuel tank, which is running on petroleum or diesel like a conventional vehicle, and an Electric Motor (EM) that is powered by the stored electric energy from a High Voltage (HV) battery-pack. The battery cannot be plugged-in and charged remotely from an electric outlet, only charged with regenerative braking or from the ICE when the vehicle is in movement. The combination of the two engines makes the ICE fuel efficient which reduce fuel costs and pollution [5], [32], [33].

2.4.2 Plug-in Hybrid Electric Vehicles

PHEVs are also known as Extended Range Electric Vehicles (EREVs). It consumes fossil fuels for an ICE and electric energy from a HV battery for an EM. This large battery can be charged from an electric power source in three ways. The battery can be charged by the PHEV is plugged-in to an external electric outlet, by regenerative braking and by the ICE. Due to the battery size and the different ways of recharging it is possible to drive only in electric mode. Besides, a longer driving distance is less dependent on fuel. Therefore, the impact on the environment and fuel costs are less than for HEV [32], [34].

2.4.3 Hybrid Powertrain Configurations

A powertrain (driveline or drivetrain) of a hybrid vehicle is the system of components which deliver power to the wheels. The powertrain can be categorized into three main classes: series hybrid, parallel hybrid and series-parallel hybrid. This section describes the configuration of each one of them [35]. For this work, parallel HEV & PHEV is studied.

- Series HEVs: This is the simplest configuration where the battery and the ICE are connected to the EM, which is subsequently, mechanical linked with the wheels through the driveline. A computer decides how much energy should be delivered to the EM, it can either gets its power from the battery, the ICE in generator-mode or both.

- Parallel HEVs: In this configuration, shown in Figure 2.5, the ICE and the EM have their own driveline which both are directly connected to the wheels through the transmission. Since the wheels are directly connected to the EM there is no conversion losses. The engines are operating separately or simultaneously. Regenerative braking allows a reduced size of the HV battery and when it needs to be recharged the ICE will work as an alternator (generator) to supply power. The 12V battery in the investigated HEV & PHEV is charged by a HV battery via a DC/DC converter.

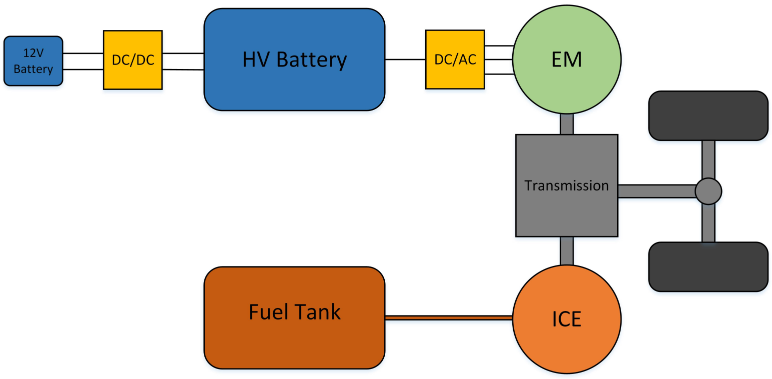


Figure 2.5: The parallel HEV configuration [36].

- Series-parallel HEVs: The configuration is a combination between the powertrains series and parallel. The ICE can either propels the wheels directly, or be disconnected and let the EM supply power to the wheels.

2.5 HV-Battery Pack

Today's platform consists of a HV battery that is special designed accordingly to the investigated hybrid vehicle. The battery in the PHEV is power optimized and has 24 cells more in series compare to the HEV. The PHEV has an energy optimized HV-battery with 8 connected modules where each module has 12 cells in series, i.e. 96 cells in series in total. The cell is designed with a prismatic form and has a chemistry of NMC 811. Each cell has a voltage of 3.6 V, which give a total voltage of 345.6 V. The battery pack is completed sealed under the rear seats in the vehicle. The total weight of the HV-battery pack is 146 kg, whereof 90 kg belongs to the modules and the rest to various plates, covers, pads, connectors, trays, sealers, systems and units. The specifications of the cell and the battery pack of the PHEV can be seen in Table 2.3 and Table 2.4 respectively.

Table 2.3: The specifications of the NCM 811 cell.

Feature	**Cell Data**
Cell chemistry	NCM 811
Cell type	Prismatic
Nominal Voltage (V)	3.6
Nominal cell capacity (Ah)	51

Table 2.4: The specifications of the HV-battery pack.

Feature	**Pack Data**
Number of cells series	96
Number of cells parallel	1
Number of modules	8
SOC_{max} (%)	95
SOC_{min} (%)	15
Pack capacity (Ah)	51
Nominal Pack voltage (V)	345.6
Total Energy (kWh)	17.63
Usable energy (kWh)	14.10
Power output (kW)	100
Weight (kg)	146
Operation range (°C)	-40 to +55

Each module is temperature measured by a Battery Management Unit (BMU) in the 12V system via the low voltage harness. The HV-battery pack can be cooled down due to the modules are connected with thermal pads which leads the heat from the pack. For maintenance of the HV-battery, it is crucial to disconnect the contactors from it to avoid personal damages. There are three ways to open the contactors, through HV-battery, a signal from 12V battery or 12V system.

2.6 Battery Utilization in Vehicles

The motor and the electric system of a vehicle are dependent on the 12V battery to run. However, the battery is used differently in an Internal Combustion Engine Vehicle (ICEV) compare to a hybrid vehicle, e.g. a HEV, regardless of powertrain design. This can be study by letting the motor of each vehicle be on and off. The section describes the differences between them [37].

ICEV - Motor On: The 12V battery is designed to produce a large current (inrush current) to start the vehicle (ignite the motor). For how long and how much power the battery will deliver counts on its RC and CCA ratings. As soon the motor is running, an alternator is providing power to the low voltage system including the 12V battery which can keep its voltage level.

HEV - Motor On: Less inrush current is needed to start the motor, because a DC/DC-converter is used instead of an alternator. Though, the motor requires sustain energy during a longer operation time from the battery. It must also handle low discharging levels and recharging regularly. No extra loads are added when the motor is on, i.e. same loads as before when the motor was turned off.

ICEV - Motor Off: Low 12V load, most of the components are not dependent on the battery when the vehicle is not running.

HEV - Motor Off: High 12V load, even if the motor is off the computer systems are still running to remain vehicle is ready to be turned on, the communications of charging and the BMS.

Since the battery in a HEV requires many cycles and less inruch currents, the requirements differs for the 12V system in HEV compared to ICEV. Starting batteries of PbA is suitable in an ICEV because, their high CCA rate, they can generate a high inrush current (discharge) and due to its low number of cycles it has a long lifetime, which is more economic over time. However, this kind of battery would not work properly in HEV that demands many repetitive cycles, which would damage the battery quickly. On the other hand, because a deep cycle battery of PbA has a high RC rate it would sustain many and deep discharges without destroying the battery [37], [38].
The 12V system in the hybrid vehicle demands a battery which is preferable smaller, lighter and can candle a large number of cycles (high RC). Additionally, a battery that has low losses of the capacity and degradation. The Li-ion battery have these features, which would be appropriate to adapt in the HEV & PHEV.

2.7 Benchmarking

This section presents vehicles where a 12V Li-ion battery has been already implemented, its battery specifications data and how the battery is integrated in the electric system.

In the investigated market analysis, of which cars are using a 12V Li-ion battery for the auxiliary system, it is shown that most automobile manufacturers have not adapting to the Li-ion technology yet.
According to John Voelcker, the first vehicle that uses a Li-ion battery is Toyota Vitz CVT 4, only available in Japan. This subcompact(B), conventional vehicle uses a 12Ah Li-ion battery with 4 cells, mainly to power up the electronic accessories and restart the ICE after idle stop [39].
Table 2.5 represents the type of battery that is used for each car model. All the HEVs from Toyota are represented as one vehicle model. In total there are 20 car models, whereof 16 having a Lead-acid battery and 4 (the gray rows in the table) are using a Li-ion battery. Tesla Roadster version 1.5 does not have a 12V battery whatsoever and using the HV battery as an energy source for the low voltage system [40]. For some of the Porsche HEV models, it is optional to change the 12V battery from Lead-acid to Li-ion technology [41]. The South Korean manufactures of the HEVs: Hyundai Ioniq Hybrid and Kia Niro, see them in Figure 2.6a and 2.6b respectively, have both decided to use 12V Li-ion battery which is integrated as a section of HV-battery pack. These models were developed from a common platform which is notable in their car features [42].

The focus will be on Hyundai Ioniq Hybrid and Kia Niro, due to they are the latest cars that are using 12V Li-ion battery on the market and the investigated HEV& PHEV has similar car features as them. In spite of the models from Porsche or Toyota Vitz CVT 4 are using Li-ion batteries, they will not be examined. Because, Porsche offers two different chemistries, while it was of interested to study a 12V Li-ion battery. The Toyota model has a Li-ion battery, however that car is consider to be too small, hence the battery requirements would be different and therefore the Toyota Vitz CVT 4 is not comparable with the HEV & PHEV.

(a) Hyundai Ioniq Hybrid [43]. **(b)** Kira Niro [44].

Figure 2.6: Two of the few car models that have adapting to the Li-ion technology for the 12V battery.

Hyundai Ioniq Hybrid is a HEV with a Permanent Magnet Synchronous Motor (PMSM) of a maximum power of 32 kW (43 hp) and 169 Nm in torque, which is supplied by a 240V Li-ion polymer battery with a capacity of 1.56 kWh. The EM can by itself reach 121 km/h (75mph) in vehicle velocity. In hybrid system mode, both engines can deliver a total output power of 104 kW (139 hp). The vehicle has a curb weight of 1359 kg [43]. In USA, the latest Hyundai Ioniq Hybrid model become one of the first manufactured car with a low voltage system that was powered by a 12V Li-ion battery. A section of the 240V HV-battery pack was left open which is the placement of the 12V starter battery. Both of these batteries are mounted together under the rear seats, though they are operating separately. Due to that reason, they are interconnected permanently. This allows the driver, if the 12V battery is discharged and hence not able to start the motor correctly, to use the 240V battery to recharge the 12V battery. This happens by pressing a reset button inside of the cab. Considering the weight of the 12V Li-ion battery that is 11.79 kg and its small size, 2 % of the cargo can be extended compare to the other two models in the same series - Ioniq Plug-in and Ioniq Electric, which both are using 12V Lead-acid battery that are located in different areas [45].

From the latest car model in the USA, a small 12V Li-ion battery, under the rear seats, has been integrated into a 240V constructed based Li-ion Polymer HV-battery pack of Kia Niro (HEV). This allows the driver to use the big battery's energy to recharge the small one by pressing a reset button. The HV battery, with its capacity of 6.5 Ah and 1.56 kWh. It also provides power to a PMSM that has power output

Table 2.5: Vehicle models that are using a Li-ion or PbA battery in the 12V electric system.

Brand	**Model**	**Vehicle Type**	**Battery**	**Location**
Hyundai [45]	Ioniq hybrid (modelyear 2017)	HEV	Li-ion	Under rear seat
Kia [42]	Niro (modelyear 2018)	HEV	Li-ion	Under rear seat
Toyota [39]	Vitz CVT 4	EV	Li-ion	-
Porsche [41], [46]	911 GT3, 911 GT3 RS, and Boxster Spyder	HEV	Li-ion	-
Tesla [40]	Roadster v1.5	EV	No 12V Battery	-
Hyundai [45]	Ioniq electric plus	PHEV	PbA	Rear cargo area
Hyundai [45]	Ioniq electric	EV	PbA	Rear cargo area
Kia	Niro (upto 2017)	HEV	PbA	-
Kia	Niro	PHEV	PbA	Under rear seat
Kia [47]	Optima SW	PHEV	PbA	Trunk wall
Mitsubishi [48]	Outlander	PHEV	PbA	Rear cargo area
Nissan [49]	Leaf	EV	PbA	Front hood
Smart ED [50], [51]	ED	EV	PbA	-
Tesla [52]	S	EV	PbA	-
Tesla [53], [54]	X	EV	PbA	-
Tesla [55]	Roadster 2.X	EV	PbA	-
Tesla [56]	Model 3	EV	PbA	-
Toyota	All hybrids	HEV/PHEV	PbA	-
Volkswagen [57]	Egolf	EV	PbA	Front hood
BMW [58]	i3	EV	PbA	Rear cargo area

of 32 kW (43 hp) and a torque of 169 Nm. In hybrid operation the vehicle can accomplish 104 kW (139 hp). The curb weight and the gross weight of the vehicle are 1409 kg and 1850 kg respectively. Depending on the vehicle's equipment, the vehicle is both a HEV and PHEV [42], [44].

The features of the 12V Li-ion battery and its auxiliary system in the Hyundai Ioniq Hybrid and Kia Niro (HEV) will be compared to the battery solution for the investigated HEV & PHEV.

2.7.1 Previous Technology of Battery Integration

In the platform of Hyundai Ioniq Hybrid and Kira Niro, an adaption of a lighter and smaller 12V battery has been made to reduce the fuel consumption and increase the performance of the vehicle. Also, in order to decrease the cable impedance of the electrical system, the low voltage battery must be close to the HV battery. Therefore, under the rear seats in theses vehicles, a 12V Li-ion battery is integrated with the HV battery together in one single box, which is known as the HV-battery pack, according to Figure 2.7.

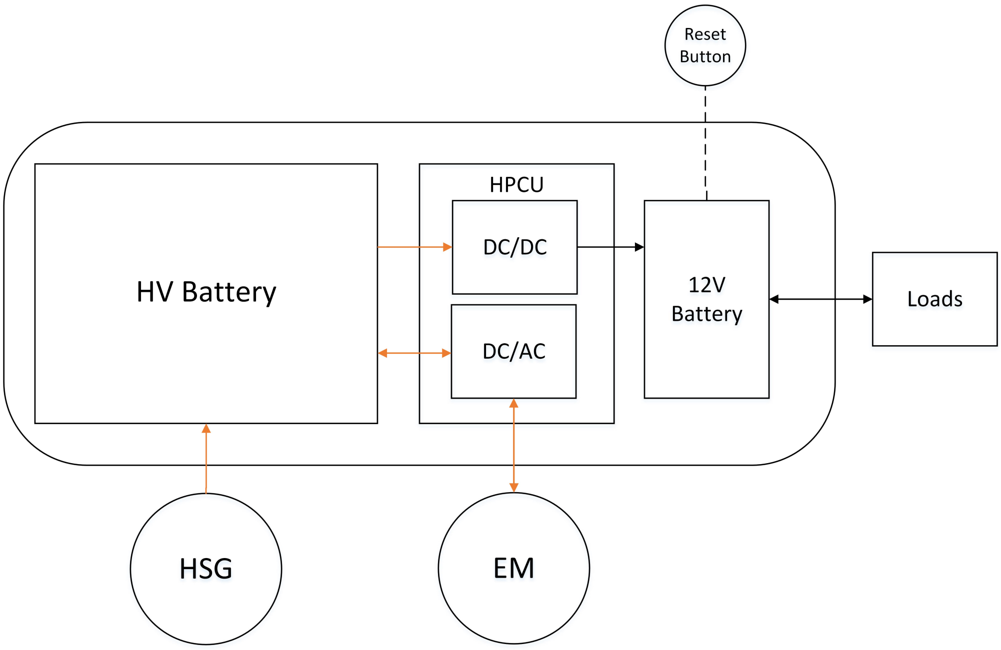


Figure 2.7: Integration of the 12V battery [59].

While the 12V battery powers the auxiliary loads of the low voltage system, the HV battery stores and supplies electric energy to the EM. The motor converts from electrical to mechanical energy for the traction of the vehicle. Between the batteries there is a unit called Hybrid Power Control Unit (HPCU) which controls the current supply from the HV battery. This unit is one common housing of one DC/DC converter, or Low Power DC/DC-Converter (LDC), and one DC/AC-Inverter. The converter transfers the power from high voltage to low voltage to supply the 12V battery and the auxiliary loads. The inverter transfers the power from DC to AC for supplying the EM. Also, inversion form AC to DC is done to charge the HV battery when the EM is operating as a generator (eg. at regenerative braking). The HV battery is also charged while driving at HEV-mode by a Hybrid Starter Generator (HSG). This generator can also restart the ICE. In a case of fully discharged 12V battery, a reset button is available in the driver's compartment which can be used to recharge the battery from the HV battery. The orange colorized lines shown in Figure 2.7 represents the high voltage cables according to SAE standards. These are cabling under the floor and connect HV-battery pack, HCPU and EM with other components in the front hood [59].

2.7.2 Previous Specifications

The two car models that are using a 12V Li-ion battery are described. The specifications for each one of them are presented before and after adapting to the Li-ion technology. Table 2.6 shows the battery capacity label of the 12V Lead-acid battery in the mentioned HEVs [60], [61].

Table 2.6: Lead-acid battery capacity label.

Feature	**Ioniq Hybrid**	**Niro (HEV)**	**Niro (PHEV)**
Battery name	AGM60L-DIN	AGM90L-DIN	CMF45L-DIN
Nominal voltage	12V	12V	12V
Nominal capacity	60Ah (20HR)	90Ah (20HR)	45Ah (20HR)
Nominal RC	100min	170min	80min
CCA by SAE*	640CCA	850CCA	410CCA
CCA by EN*	512A	680A	410A

Table 2.7 presents the battery specifications of the 12V Li-ion battery that is used in the latest Kia Niro HEV-model. It is assumed that similar specifications can be found in the Hyundai Ioniq Hybrid, since this vehicle and Kia Niro are built on the same platform.

Table 2.7: Li-ion battery capacity label in Kia Niro (HEV).

Feature	**Kia Niro (HEV)**
Model name of battery	Lithium ion Polymer Battery (LIPB)
Nominal voltage [V]	12.8 V
The nominal capacity [Ah]	30Ah (20HR)
Number of cells (EA)	8
Cell voltage Deviation [mV]	40mV or less
Operation Voltage [V]	10-14.8V

2.8 Autonomous Drive

Nowadays, most of the previous vehicle models have been implemented with different intelligent driver assist functions, which can help the driver to control the vehicle's speed and avoiding accidents. The technology within the industry is going to a driverless future. This has resulted to new auto-competitors like Uber and

Alphabet and electric vehicle maker like Tesla are testing autonomous driving functions. Traditional automotive makers, such as Volvo predicts the that no one will ever crash when driving one of their cars the year 2020 [62]. The same year, according to an announcement by Nissan, a self-driven car will be delivered by them [63].

A human has the ability to observe the surrounding environment, by scanning and collecting information from it, and an action can be made. A self-driven vehicle or a vehicle with autonomous drive is working according to the same principle [64]. The vehicle knows its surroundings with its moving objects in the traffic by several sensors or microchips such as lasers, cameras and GPS-units. Today, some of these sensors have the capability to let a self-driven vehicle in test to drive with or without a driver [63], [64]. Therefore, the grade of autonomous drive is usually described in six different autonomy levels, according to SAE International, as seen in Figure 2.8. The first level explains the vehicle control before entering into the autonomous-levels [62], [65].

Figure 2.8: The levels of autonomous drive [62], [65].

Level 0 - No Automation
The human driver has complete control of the vehicle, including accelerate/brake and steering, during the whole driving-cycle.

Level 1 - Drive Assistance
A driver assistance system supports the driver to either accelerate/brake or steering in certain traffic situations. Otherwise, the human is handle all driving conditions.

Level 2 - Partial Automation
Several driver assistance systems controls the acceleration/braking and steering of the vehicle. For instance, make sure the vehicle is on the route, brakes for obstacles and regulate the speed with an adaptive cruise control. Otherwise, the human driver is handling all driving conditions.

Level 3- Conditional Automation
The vehicle is driving by itself in certain traffic conditions, e.g. on highways and in traffic jams. Otherwise, it is expected that the human driver will act and intervene when the autonomous driving-function encounters problems.

Level 4 - High Automation
The vehicle is driving itself in most traffic conditions. The autonomous system can handle and solve almost any kind of traffic situation. For example, when the vehicle is leaving areas or roads where autonomous drive is activated, the system requests

the driver to take over the vehicle. If the driver does not take the vehicle's control, the autonomous drive will handle the situation by itself.

Level 5 - Full Automation
The vehicle can handle any kind of traffic situation and the human driver does not have to act nor intervene. The vehicle is driven by itself, i.e. the vehicle is performing a completely autonomous drive.

3

12V Electric System & Battery Specifications

This chapter describes the 12V electric system in a hybrid vehicle, which has three main components: 12V battery, loads (continuous and transients) and DC/DC converter. The low voltage system has the same characteristics for both HEV & PHEV which are based on the same vehicle's platform. Therefore, they will be referred as one hybrid vehicle called HEV/PHEV.

3.1 Electric System Overview in a Hybrid Vehicle

The electrification of the vehicle has been increasing the last years. Thus, more electric loads demands more electricity and increasing the reliability of the system. Usually, the HEV/PHEV has the electric system running at two different voltages, 12V and 400V. There are some cars that are migrating from 12 V to 48 V for the low voltage system, though it is not of interest in this project.

The so called High Voltage (HV) electric system, manages a voltage level around 400 V (it may differ from different vehicle's manufactures that can use voltage levels up to 600 V). Generally, this system consists of a HV-battery pack mainly used for the vehicle's propulsion, HV cables, a power inverter and a DC/DC converter. On the other hand, the 12 V electric system manages the operation of all the auxiliary loads, Electronic Control Units (ECUs) & devices to control and protect the HV system.

The correct operation of the vehicle including the HV electric system depends on the reliability of 12 V system, thus its importance. The low voltage system consists of electric loads, a DC/DC converter (400 V to 12 V) and a 12V battery, conventionally based on Lead-acid technology. This project focuses on the study of the 12 V power distribution system including the battery for the auxiliary system. The low voltage loads are described by using HEV/PHEV model on the market. The low voltage electric system is shown in Figure 3.1.

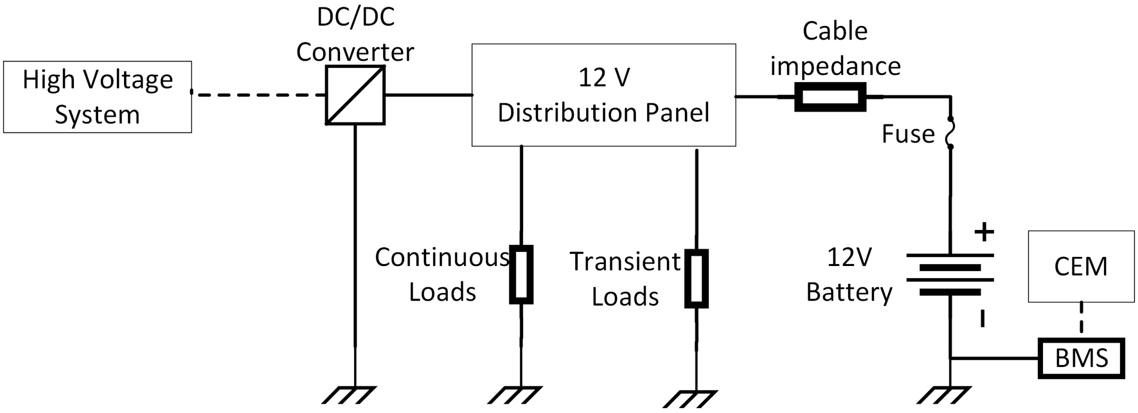


Figure 3.1: Low voltage electric power distribution system of common HEV/PHEV.

The DC/DC converter decreases the voltage level from 400 V to 12 V to feed power to the low voltage circuit. The converter is a voltage controlled device, which means the voltage will be stable on its operating current range. The battery used for the investigated HEV/PHEV is a Lead-acid AGM H6 70 Ah (full specifications mentioned in section 2.2.1.1). The loads can be supplied by two power sources, the converter will provide power to the low voltage loads when the vehicle is turned on (running mode). The 12V battery provides power to the loads when the car is standstill, for starting the computers and controllers of the car before the ignition. It is important to describe that the main difference of the conventional cars compared with the HEV/PHEV is that the start/stop function energy requirements is provided by the HV electric system.

3.1.1 Load Description

In a conventional hybrid vehicle the electric loads represent hundreds of different devices with a wide range of applications and functionalities. The 12V electric loads are divided in several subsystems such as: active safety, ambient light, body, climate, exterior lights, heater, infotainment, interior lights, power train, restraints and power outlets. The loads can be categorized into two different characteristics - continuous loads and transient loads.

Continuous loads
The continuous loads are consuming a constant current over a long period of time. An example of continuous loads are ECUs which are small electronic computers in the 12V electric system.

Transient loads
The transient loads are consuming high power over a short period of time. Braking and steering systems are the most power consuming in the 12V electric system.

- *Electric Power Assisted Steering (EPAS)* is an electric power unit in the vehicle's system which supports the steering function of the vehicle [66].

- *Vehicle Dynamics Domain Master (VDDM)* is a module in the braking system which can avoid the wheels from slipping [67].
- *Brake Boost Module (BBM)* is an electric pump in the braking system that gives a certain pressure based on the position of the break pedal [68].

The 12V loads are analysed and prioritized according its importance focusing on the safety and reliability of the electric system.

3.1.2 Prioritizing 12V Loads

There are electric loads that are significantly more important than others to make the basic operation possible and enable the primary functions of the vehicle. The electric loads in the low voltage system were prioritized by taking into consideration the following aspects:

- Vehicle's safety operation.
- Continuous operation loads to run the vehicle's computer (controllers).
- Transient loads e.g. steering, braking.
- Vehicle's performance.

Therefore, the most relevant loads to be considered are: EPAS, VDDM and BBM.

3.2 12V-System Requirements and Electrical Performance

In order to describe the specifications of the 12V battery for HEV/PHEV based on the vehicle platform, the requirements of the electric system are analyzed including the behaviour of continuous and transient loads, the DC/DC converter, the electric system performance and test data.

The 12V system shall always provide electric power and therefore ensure functionality, security and reliability of the system's driving mode and battery lifetime. The vehicle shall be safely drive regardless of the 12 V supply source. The system has a nominal voltage range between 12.5 V and 15.5 V. In normal case, the electrical distribution system has a total maximum voltage drop which is less than 1.5 V.

The 12V electric system considers not only the specifications of the current architecture but also different load conditions. The following requirements and performance are consider for: loads, DC/DC converter and 12V battery.

3.2.1 Loads

The loads which require a constant power supply should be fed accordingly with its demand in order to fulfill operative conditions. When the vehicle is parked, the total sum of all currents to support the driver's activity functions (radio, alarm, locker, emergency lights etc.) shall be less than 0.5 A. If the functions are not used by the driver, then the parking condition is valid.

Functions that are not used by the driver shall be set in low consumption mode (sleep mode) or turned off, e.g. ECUs in sleep mode are expected not to consume more than 0.1 mA.

Electric climatic loads such as heated seats, windows and mirrors should only consume current when the vehicle is turned on with the DC/DC converter.

Overloading should not cause any component damage, including fuses or other protection devices, of the electrical system.

The minimum voltage for EPAS should not be lower than 10.5 V.

3.2.2 DC/DC Converter

In contrast to a conventional vehicle, the alternator has been replaced by a DC/DC converter in HEV/PHEV. The DC/DC converter shall supply current to all loads and recharge the 12V battery. The converter is consider as a constant power source with a regulated voltage, which shall be controlled to supply power to all loads. However, large transient currents may appear, e.g. EPAS and BBM together, where power is supplied from the 12V battery as well. The current from the converter is always higher than zero (positive), since it delivers power to the loads in one direction or unidirectional power flow.

Table 3.1 shows the specifications of the DC/DC converter. The converter has 400 V input voltage and a maximum current of 170 A at 14.5 V. The nominal voltage range is within 10.6 V and 15.5 V. This condition is also valid for the power conversion between the high voltage to the low voltage.

Table 3.1: The specifications of the DC/DC converter.

Feature	**Specification**
Input voltage	400 V
Nominal output voltage	10.6 V – 15.5 V
Max. output current (t>0)	170 A @ 14.5 V
Max output current	250 A/5 s, every 1 min
Max efficiency	93.5% @ 20 °C
Max output Power	170 A×14.5V

3.2.3 12V Battery

The battery shall have a high durability and reliability. A high number of charging/discharging events shall be possible. A battery with big SOC window (relationship between SOC and open circuit voltage) may decrease the number of cycles.
The temperature of the battery is between -20 °C to 40 °C shall decrease the battery capacity no more than 30 %.
Since 12V battery does not ignite the ICE, a cranking current is not needed. Though, a 50% discharged battery shall be able to start the ECUs at -20 °C. Also, a fully charged battery shall have sufficient electrical energy in order to start the ECUs in the vehicle after being parked for 21 days in any temperature between -20 °C and 40 °C. The total average current consumption from the battery shall therefore be under some limits and is defined as:

$$I_{quiescent} < 0.15\frac{C_{20}}{504} \tag{3.1}$$

where the 504 represents the numbers of hours for 21 days. This condition is valid when the vehicle is locked and alarmed, some functions are activated by the driver.
To start the vehicle, the battery minimum voltage shall be 1.5 V higher than the voltage specified in the standard ISO 16750-2:2012 clause 4.6.3.2. Table 3 Level II.
In normal condition, the BMS shall recharge the battery when needed, i.e. it shall recharge the battery before a certain SOC-level where driving mode or starting the engine is no longer possible. However, the driver may see a warning of the SOC-level of the battery is low.
During idling at battery SOC < target value, a power management function makes sure that the battery is not allowed to be discharged more than:

$$I_{idling} < 0.07\frac{nominalcapacity}{hour} \tag{3.2}$$

A charge balance cycle shall be performed by the BMS in the battery to maximize its capacity and performance in temperatures between -20 °C and 40 °C.
In driving mode, the charge balance cycle should reach the target value of SOC and then be in regenerative charging mode.
The target value for battery SOC shall be optimized in order to save fuel.
The battery SOC is measured by the battery monitoring which has an accuracy of ±5 %.
The electrical system must be designed in order to enable a battery lifetime of at least 4 years or 96000 km. The battery shall be located close to the main loads, thus the losses in the cables can be reduced including less total weight of the vehicle.
Finally, there should be clear and visible terminal points where cables can be connected for jump start. When jump starting, the essential loads shall activate the ECUs of the HV-battery pack and DC/DC converter, not to start the engine. Once the main power source (converter) is activated, the 12V battery is reconnected since it will be recharged by the converter. However, the terminal points may not be possible due to a sealed battery integration. The positive and negative poles shall be well separated to prevent short-circuit.

3.3 12V Battery Usage and Testing in a PHEV

The conventional Lead-acid battery is tested in a PHEV under different conditions, where measurements of voltage and current are taken in the 12V battery terminals. The battery has to work properly in different operation scenarios of the vehicle, regardless its chemistry. Therefore, the results in this section show the current that the battery must supply to the loads in different cases. Besides, the voltage profile in the battery terminals is also measured and analyzed. Two standstill cases and three driving cases are defined to study the electric system behaviour. Based on the vehicle test data and own test, the following cases are consider: starting, parking, normal, maximum and emergency.

3.3.1 Starting Case

The initial condition of the vehicle is standstill and turned off. In this state, a few loads such as sensors and ECUs are running, similar to the parking case that will be treated later. The only power source is the low voltage battery feeding the loads. The driver press the "start button" to achieve the following states:

- "Start button" pressed for 1 second. The *convenience mode* is activated, the driver can use the infotainment system and various ECUs are running. The engine is off and the 12V battery feeds the loads.

- "Start button" pressed for 7 seconds. The *active mode* is set where the driver can turn on the lights, wipers, windows, infotainment system and various ECUs are running. The engine is off, but ready to start the ICE or the EM. Since the DC/DC converter is not turned ON, the 12V battery still feeds the loads.
- Brake pedal and "start button" pressed once. The *running mode* is achieved and can be seen in the driver's display. The ICE or the EM turns ON, the vehicle is ready to drive. The DC/DC is activated, feeding the loads and recharging the 12V battery.

The starting case process can be seen in Figure 3.2 and Figure 3.3 where the battery voltage and current are measured dynamically from parking mode to running mode.

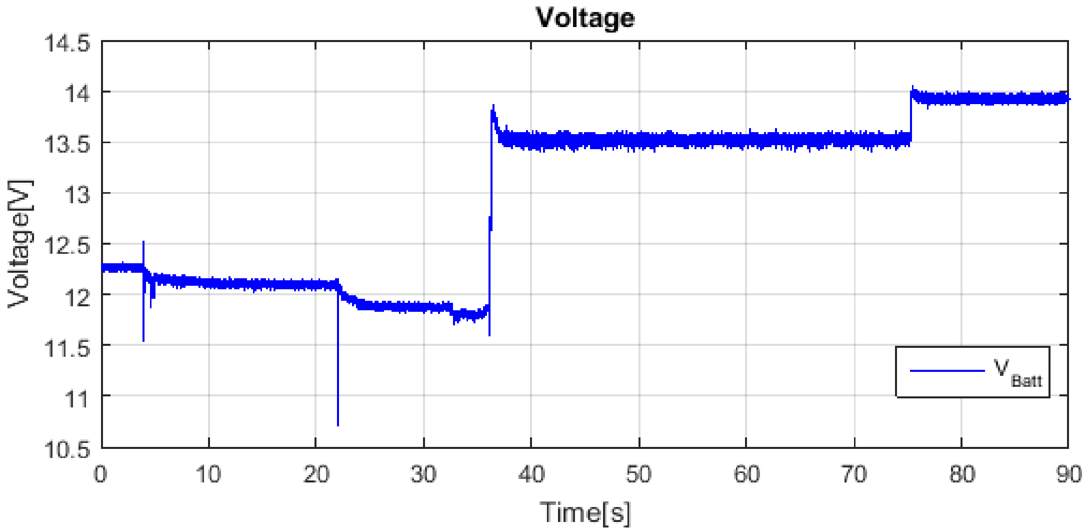


Figure 3.2: Voltage measurement in the 12V battery terminals for the starting case in a PHEV.

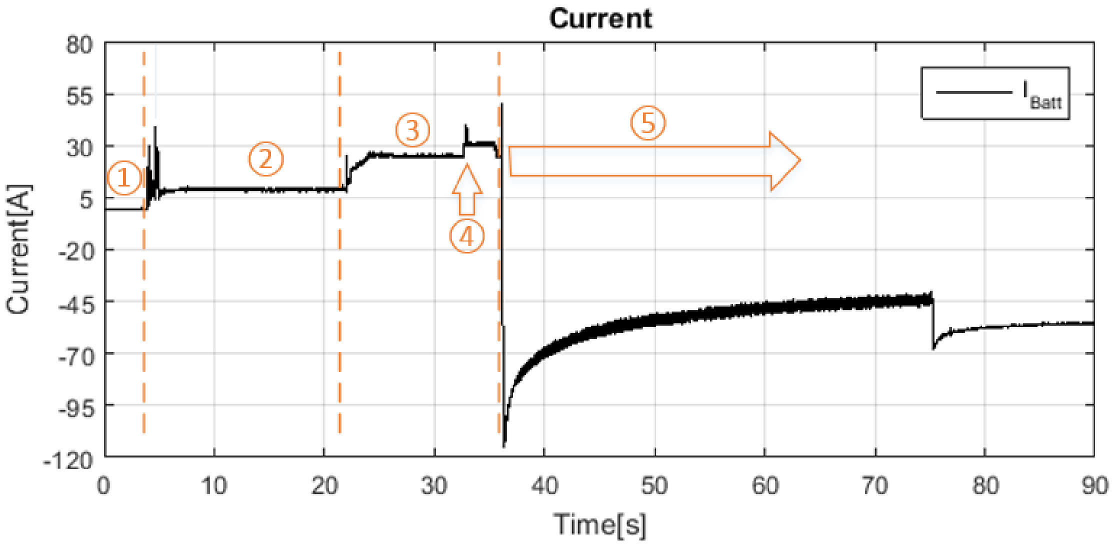


Figure 3.3: Current measurement in the 12V battery terminals for the starting case in a PHEV, where: ① *Parking mode*, ② *Convenience mode*, ③ *Active mode*, ④ *Manual press of the Brake pedal*, ⑤ *Running mode.*

3.3.2 Parking Case

The vehicle shall withstand for 21 days in parking mode according to its requirements. Several functions in the vehicle are deactivated and ECUs go to sleep mode. Therefore, the current consumption is decreased. After some minutes the quiescent current is measured. In this case the loads are disconnected progressively from running to parking mode, as described below:

- The car is stopped in running mode, then the engine is turned off by pressing the "Start button" and "Lock button".
- When the engine is off, the high voltage system in the vehicle is still running and the DC/DC converter is ON. It takes 120 seconds until the HV-breakers or contactors disconnect the HV system.
- Vehicle's functions are deactivated, e.g. breaking, steering. ECUs go to sleep mode.

Test result
Figure 3.4 and Figure 3.5 show the voltage and current measured in the 12V battery terminals respectively. The test starts with the car set in running mode, after 10 seconds the engine is turned off. A negative current is measured, thus the battery is recharged. The HV breakers disconnect the HV-system after 120 seconds. When the HV-breakers are opened the battery starts to provide current to the loads as seen in Figure 3.4, a process called loads disconnection. The 12V battery feeds current for 320 seconds to disconnect the loads. Finally, the current decreases to

a few milli-amperes where the quiescent current is started to be measured for one hour.

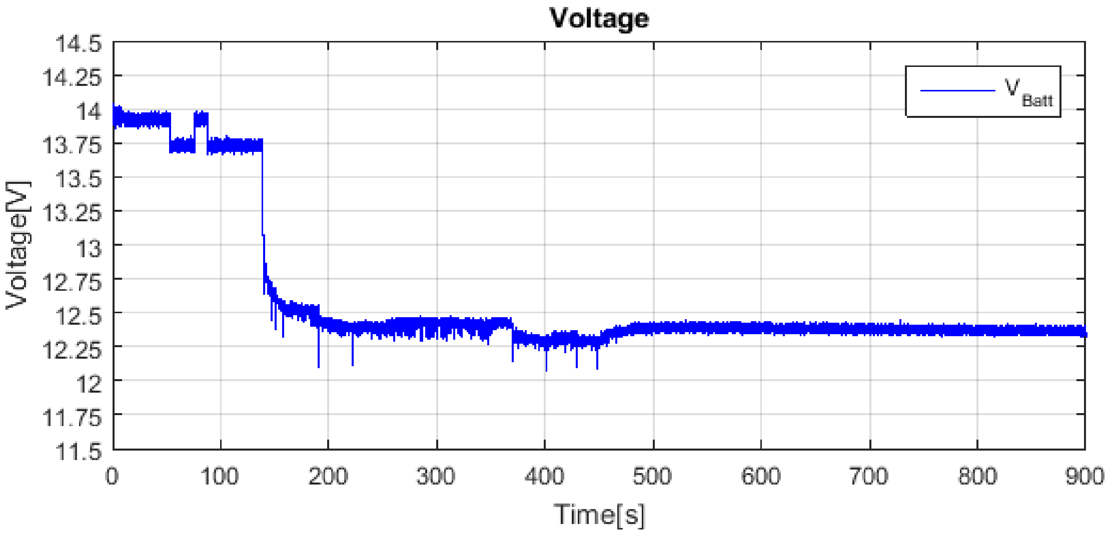


Figure 3.4: Voltage measurement in the 12V battery terminals for parking case in a PHEV.

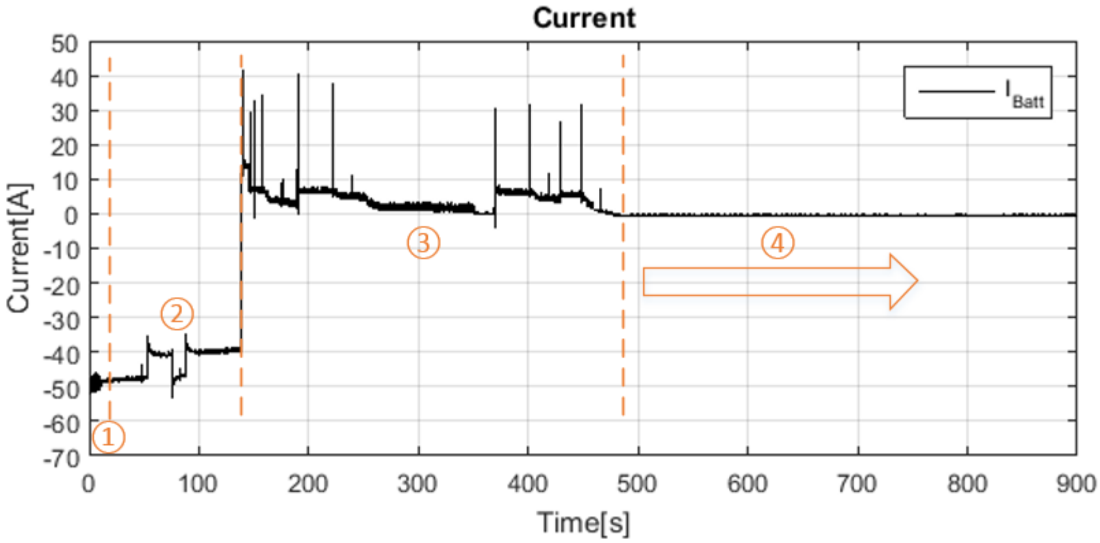


Figure 3.5: Current measurement in the 12V battery terminals for parking case in a PHEV, where: ① *Running mode*, ② *Turn off, HV connected*, ③ *HV contactors opened and loads disconnection*, ④ *Quiescent current.*

3.3.2.1 Quiescent Current Result

The vehicle is in parking mode, the quiescent current is measured with a mili-amperemeter. Every 5 minutes a current sample is taken during one hour, the result is shown in Table 3.2. The average quiescent current is 57.3 mA.

Table 3.2: Quiescent current result.

Time [min]	0	5	10	15	20	25	30
Current [mA]	55.6	54.8	56.7	64.1	56.6	66.6	55.6
Time [min]	35	40	45	50	60	**Average**	
Current [mA]	56.2	56.54	57.99	55.56	51.31	**57.3**	

Nevertheless, from the battery requirements perspective and according to the equation 3.1, for a 70Ah PbA conventional battery, the quiescent current should be lower than 20mA. According the company experts, in a healthy vehicle, the quiescent current could be between 10mA to 15mA. For this project, a value of 15mA is selected, assuming a healthy and fully developed vehicle.

3.3.3 Normal Case

The low voltage electric system is working under normal conditions, where the main components are fully operative, such as: DC/DC converter, 12V battery (SOC>95%) and ECUs. The DC/DC converter is feeding to the continuous and transient loads, the battery is not feeding any current to the electrical system, instead it is recharged.

Test result
An evasive maneuver action is tested while a constant load of 25 A is applied. The steering wheel angle (SWA) is done by a computerized system that simulates an evasive maneuver action. The transient loads take action for approximately 4 seconds. In the normal case, the battery voltage remains constant, even when a transient load is applied. The reason is that the DC/DC converter is the main source feeding to the loads and the maximum current limit of 250 A is not achieved. The positive current represents a charging current. Therefore, during a transient in the normal case the battery is recharged due to a rise in the DC/DC voltage.

3.3.4 Maximum Case

All the main components mentioned in the normal case are working correctly. The electric loads in the 12V system are set to a maximum value of 170 A. The maximum current represents the continuous loads that are running in the vehicle.

Test result
At 4.7 seconds and evasive maneuver action is performed while a continues load is consuming 170 A. Besides, the maximum current consumption is set to the maximum DC/DC constant current. As mention in Table 3.1 the DC/DC can provide a

maximum current of 255 A for 5 seconds. Therefore, in this case the 12V battery provides transient support from 4.7 s to 4.85 s. For the maximum case, both power sources, the DC/DC converter (at 255 A) and the 12V battery (at 75 A peak) provide current to support the transient load. After the event, when the load current decreases, the battery is recharged by the converter.

3.3.5 Emergency Case

For the emergency case, it is assumed that the DC/DC converter is disconnected or failed. The function of the battery is to provide back up power to the loads and avoid a black out of the electric system. Therefore, the 12V battery shall withstand an evasive maneuver action. The most relevant loads for a certain period of time are fed by the 12V battery until the vehicle can be parked out of the road.

Test result
A consumption of 25 A is required from continuous loads that are fed by the battery. At 5.6 seconds evasive braking and steering are applied. The transient load last for approximately 4 seconds.

3.4 12V Li-Ion Battery Solution

The advantages of Lithium batteries are high energy density, high operation voltage, long cycle life, no pollution, low self-discharge rate, light weight and small size. Due to the beneficial qualities with Lithium batteries, a 12V Li-ion battery is selected which is suitable in a vehicle platform that requires a small and light power source with high reliability and durability. Also, the HV battery in the platform has the same technology, which can be utilized for future applications such as battery integration.

3.4.1 Battery Li-Ion Specifications

The battery specifications can be estimated by making general assumptions and calculations based on a specific chemistry. Since Li-ion phosphate (LiFePO4) is the most common chemistry on the market for plug-and-play 12V Li-ion batteries, it is investigated as a potential chemistry for the 12V Li-ion battery solution. Additionally, except LFP, other Li-ion chemistries such as NMC, NCA and LTO are also analyzed for the 12V Li-ion section solution in the HEV/PHEV.
When rating the specifications of the battery, a number of factors need to be consider. For example, the calculation of the nominal battery capacity is based on a certain discharge conditions including the factors C-rate, temperature, minimum

voltage etc. which are compared with manufacturer specifications. The factors which may affect the decision of selecting a battery are [69], [70]:

- **Starting current**
  When starting the vehicle, the internal battery impedance will have less impact on the battery performance, since a high cranking current is not needed. Starting current for the hybrid vehicle is around 10-30 A to start the ECUs and other functions.

- **SOC-levels**
  A battery with a long life time is desired and high number of cycles. A typical Li-ion battery SOC level of 25-85 % is selected [71].

- **C-rate**
  An energy optimized Li-ion cell can be discharged at C-rates at 1C and 2C. A power optimized Li-ion phosphate cell can be discharged from 1C to 10C (sometimes up to 25C depending on the cell). A LiFePO4 cell has a charging-rate of 1C at charging at 3.65 V [23], [72], [73].

- **Self-discharge**
  The self-discharge rate for lithium in general is estimated approximately to 5 % during 24h, and thereafter 1-2 %/month and additionally 3%/month more by consider the protection circuit of the BMS [74]. For Lithium iron phosphate, the self-discharge rate is lower than 3 %/month [75]. Other Li-ion chemistry types have usually a lower self-discharge rate than LFP [23].

- **Typically 12V Li-ion battery voltage range**
  The voltage range of a 12V Li-ion battery is typically between 8 V and 14.6 V [75], [76].

- **Cell-voltage**
  A Li-ion cell has a voltage range between 3.6 V and 3.8 V, where 3.7 V is the nominal voltage [77]. At fully discharged and fully charged, the minimum and maximum cell voltage is 2.8 V and 4.2 V respectively. When applying a transient load the minimum voltage can be decreased even to 2.7 V at discharged [16], [78].
  Li-ion phosphate cell has a nominal voltage between 3.2 Vto 3.3 V [16], [79]. At complete discharged and complete charged, the minimum and maximum voltage is 2.7 V and 3.65 V each. Minimum voltage 2.45 V is possible to reach with BMS [78], [80].

- **Form Factor**
  Since the nominal voltage is 3.7 V of a Li-ion cell, the cell type is considered to be a *14500 cell* with the following dimensions: diameter = 14 mm, height = 50 mm and weight = 20 g. Its maximum voltage is 4.2 V and the discharge cut-off voltage is 2.75V/cell [77], [81], [79]. Li-ion phosphate is commonly used in a *32650 cell*, which has the typical dimensions: diameter = 32 mm, height

= 65 mm and weight = 136 g. [79], [82].

- **Cost**
  Based on certain applications of Lead-Acid cells, Li-ion phosphate cells cost 20-50 % more [83]. On the other hand, Li-ion phosphate is in the same price range as other Li-ion chemistries [23].

- **Power content vs. Energy content**
  A Li-ion phosphate cell provides specific energy between 90 and 120 Wh/kg, which is low compare to other Li-ion cell chemistries. The specific power for Li-ion phosphate is between 500 and 8000 W/kg [23], [26], [29], [30].

- **Weight & Volume**
  In general, the weight of a Li-ion battery is estimated to be one-third of the weight and half of the volume of a Lead-acid battery [84].

- **Temperature**
  The charge temperature range is usually between 0 °C to 45 °C, and above 5 °C the C-rate is starting to increase. Charging a Li-ion battery at temperatures below 0 °C gives a low C-rate, as a result the charging time would be longer and the charging current lower. Typical discharging temperatures are between -20 °C and 60 °C, the lowest temperature can be reached down even to -40 °C [85], [86].
  The temperature in Li-ion batteries should stay in the range as much as possible in order to mitigate the impact on the battery capacity. Preferably a Li-ion battery should not drop to temperatures below 0 °C, because the battery capacity will be reduced. However, some battery manufactures allows for charging at -10 °C and even lower. For example, batteries from Smart Battery have low temperatures around between -20 °C and -22 °C, these can be considered to be lowest temperatures for Li-ion batteries in general [75]. Though, charging at low temperatures is possible at a low charge current [87].

- **Safety**
  Due to a relative small battery size and phosphate is used as a material to the cathode, temperatures between -20 °C and 70 °C can be reached. Therefore, a Li-ion phosphate battery is considered to be safe from fire and explosions [22].

- **Cycle life**
  The battery capacity is reduced to 80% when the cycle life of the battery is between 1000 and 4000 charging/discharging cycles [26]. Consider the DOD and the temperature, li-ion phosphate has a cycle life of 1000-2000 [23].

3.4.2 Battery Calculations

The most relevant battery specifications are calculated in this section, subsequently to search for a battery supplier in the market.

Battery capacity calculation
The capacity of the battery shall withstand the worst condition cases which are parking, starting and emergency. The parking case requires a significant quantity of energy, after 21 days the car should be able to start, including an emergency case event where an evasive maneuver action is performed. The battery capacity calculation starts by integrating the current over the time for different driving cases. The total electric current flow per second is defined as:

$$Q_{flow} = \int_{t_1}^{t_2} i_{batt} dt \tag{3.3}$$

where i_{batt} is the battery current.
Table 3.3 uses the results showed in section 3.3 to calculate the current flow per second when parking, starting and emergency.

Table 3.3: Current flow integration for different cases.

Cases	**t1**[s]	**t2**[s]	**Current** [A]	**Qflow**[**Ah**]
Parking (Transient)	139.1	490	41.23 Peak	0.337
Parking 21 days (Continuous)	0	1814400	0.015 Average	7.56
Start (Transient)	3.83	36.16	50.5 Peak	0.141
Emergency (Transient)	5.6	9.4	200 Peak	0.055
			Total	8.09

The continuous parking current for a healthy car is 15 mA within a continuous period of 21 days (504 hours). These can also be presented in Ah as:

$$Q_{cont} = 15mA \times 504h = 7.56Ah \tag{3.4}$$

The total current per hour for transient cases is:

$$Q_{trans} = 0.533Ah \tag{3.5}$$

The initial capacity of the Li-ion battery is:

$$Q_{initial} = Q_{trans} + Q_{cont} = 8.09Ah \tag{3.6}$$

However, impacts of SOC-levels, cycle-life, self-discharging and temperature will affect the battery capacity. Therefore, correction factors for these impacts are added to the calculation.

Based on the assumed SOC-levels, not more than 60 % of the battery's initial capacity is utilized, since the maximum and minimum SOC levels are considered to be 85% and 25%, respectively. The capacity is calculated as follows:

$$Q_{nominal'} = \frac{8.09Ah}{0.6} = 13.483Ah \tag{3.7}$$

Due to aging the Li-ion battery capacity will be reduced. A SOH-factor of 20 % is multiplied with the battery capacity in order to compensate the initial capacity.

$$Q_{nominal''} = 13.49Ah \times 1.20 = 16.19Ah \tag{3.8}$$

At low temperatures Li-ion battery capacity is reduced. Some manufactures advertise that at -20 °C the corresponding battery capacity is reduced to 70 %. This capacity is taken into account by a temperature-factor of 30 %.

$$Q_{nominal'''} = 16.19Ah \times 1.30 = 21.04Ah \tag{3.9}$$

By consider the self-discharge for Lithium phosphate is 3 % per month plus 3% per month due to the safety circuit, the total discharge is 6 % per month for the battery. Therefore, a self-discharge-factor is added to the capacity.

$$Q_{nominal} = 21.04Ah \times 1.06 = 22.30Ah \tag{3.10}$$

Among others, the Peukart effect is neglected in this project for the Li-ion battery solution [88], since the small impact in the capacity compared with lead acid chemistry. This effect relates the high current consumption in short time periods, e.g. transient currents.

The calculated nominal capacity of the battery is 22.3 Ah according to the result in the equation 3.10. However, in the market there are specific capacity rates that can fulfill this requirement, the most approximate value is 25 Ah shown in Table 3.5.

Number of cells

The Li-ion phosphate nominal cell voltage is around 3.20-3.30 V, and is selected as mid-voltage of 3.25 V. The nominal voltage of the battery is 12.8 V, the number of cells in series are estimated as:

$$\frac{12.8V}{3.25V/cell} \approx 4cells \tag{3.11}$$

More cells can be added in parallel in order to fulfill the total battery capacity.

Vmax and Vmin

A battery that is discharging below the minimum voltage has a risk to be damaged or its capacity can be decreased. Therefore, it is important to estimate the lowest allowed voltage. The maximum charging voltage is usually given by the manufacturer. However, the voltage limits can be calculated based on typical voltages for

Li-ion phosphate such as: 2.7 V minimum cell voltage and 3.65 V maximum cell voltage. The battery voltage limits are calculated as follows:

$$V_{min} = 4cells \times 2.7V/cell = 10.8V \tag{3.12}$$

$$V_{max} = 4cells \times 3.65V/cell = 14.6V \tag{3.13}$$

The voltage V_{min} is higher than 10.5 V which is normally the lowest voltage at discharging for 12V battery, while V_{max} is within the range of 12.5 V and 15.5 V at charging according to the electric system requirements for HEV/PHEV.

Reserve capacity
The reserve capacity calculates the minutes that a fully charged battery can provide 25 A to the load. The nominal capacity of the battery can be used and transformed from Ah to As (Coulomb), in order to determine the reserve capacity.

$$RC = \frac{22.3 \times 3600As}{25A} = \frac{80280As}{25A} = 3211.2s \tag{3.14}$$

where the time 3211.2 s can be divided by the number of seconds in one minute to get RC:

$$RC = \frac{3211.2s}{60s/min} \approx 54min \tag{3.15}$$

Summary
The assumptions with the calculations give the final specifications of that seeking 12V battery according to Table 3.4.

Table 3.4: 12V Li-ion battery specifications.

Feature	**HEV/PHEV**
Chemistry type	Lithium-ion
Nominal voltage [V]	12.8
Nominal capacity [Ah]	22.3
Number of cells-in-series	4
Vmax [V]	14.6
Vmin [V]	10.8
RC [min]	>54
Imax transient [A]	200
CCA	not required
Temperature range [°C]	-20 to 40
Cycle number	>1000

3.4.3 Battery Selection and Cost

Table 3.5 shows the found battery in the market that fulfills the battery specifications. The common chemistry offered by different manufactures is Li-ion phosphate

(LiFePO4). The specifications, including weight, size and costs, of these batteries are presented in the following table [89], [90].

Table 3.5: Market analysis of Li-ion batteries.

Feature	**H6 (L3) Battery**	**Smartbattery Battery**
Chemistry Type	PbA	LiFePO4
Nominal voltage [V]	12	12.8
Nominal capacity [Ah]	70	25
Imax transient [A]	200	250
CCA [A]	760	250
Temperature range [C]	-40 to 60*	-20 to 80
Cycle number	200-650*	2000@80% capacity
Weight [kg]	21.3	4.1
Dimensions [mm]	278 x 175 x 190	175 x 104 x 165
Reduced weight [%]	Basis	80.8
Reduced volume [%]	Basis	67.5
BMS	No	Integrated
Initial cost [per unit]	1	2
Cost per cycle [per unit]	2	1

*According to the general specifications in Table 2.2.

The packaging space can be improved when the Li-ion battery solution is introduced. As shown in Table 3.5, the capacity of the battery is reduced from 70 Ah to 25 Ah. Furthermore, both size and mass of the 12V battery are decreased considerably. The volume of the Li-ion solution is 80.8 % smaller and the weight is 67.5 % lighter compared with the conventional Lead-acid battery. Figure 3.6 illustrates the the real size comparison between the H6 Lead-acid battery and the 12V Li-ion phosphate battery.

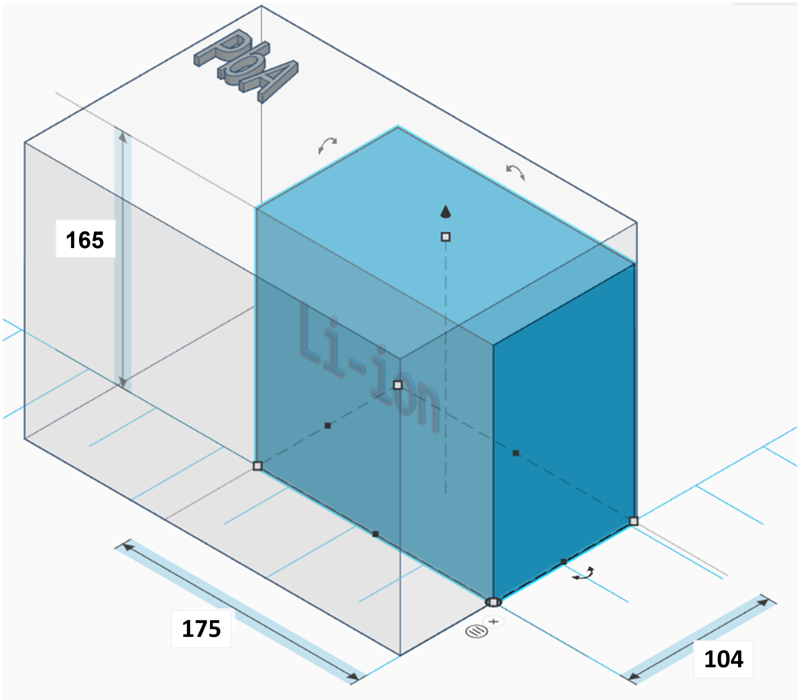


Figure 3.6: Battery size comparison, PbA vs. Li-ion. Dimensions presented in millimeters.

Cost analysis

The cycle number of the Li-ion phosphate 25Ah, is 2000 compared with only 750 cycles in average for the PbA-H6 battery, as shown in the Figure 3.7. In contrast, the initial cost of the Li-ion phosphate battery selected is double that of the Lead-acid H6 AGM battery, according the current market research. The mass production of both batteries, PbA and LiFePO4, can result in a reduction of the selling cost to the automaker in approximately 1/3 of the price for single costumers. The initial cost assuming mass production of the Lead-acid battery H6 70Ah and the LiFePO4 25Ah is shown in Figure 3.8.

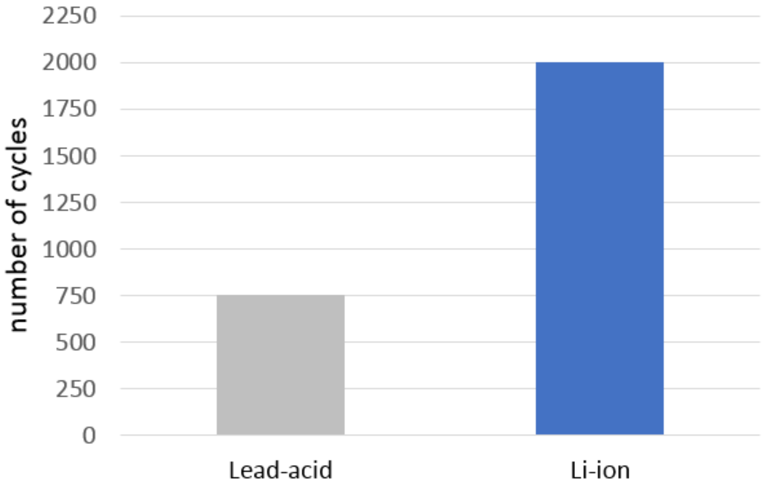


Figure 3.7: Average life-cycle of PbA-H6 AGM and Li-ion Phosphate-25Ah.

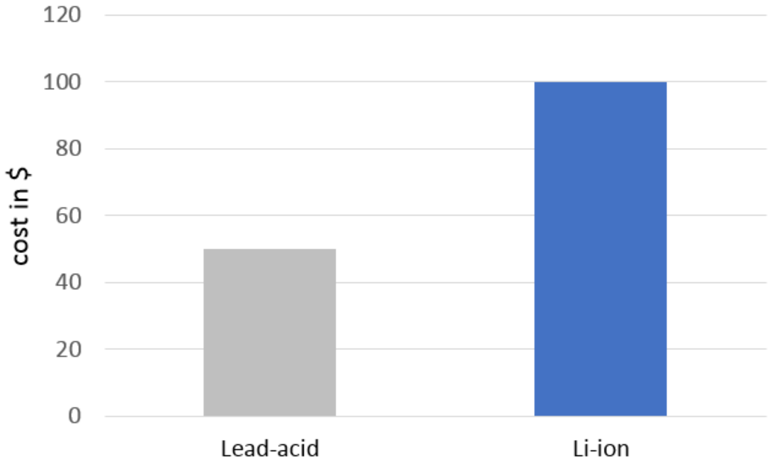


Figure 3.8: Average initial cost of Lead-Acid H6 AGM 70Ah and Li-ion Phosphate-25Ah.

The impact of the cycling number in the cost is shown in the cost per 2000 cycles, see Figure 3.9. The Li-ion is a cheaper solution in long term, since after its lifetime (based on the cycle number), the initial cost is recovered. The Lead-acid battery has a higher cost after 2000 cycles, it shall be needed to change 2-3 times the 12V PbA battery in order to achieve the same number of cycles of a single Li-ion battery. Furthermore, the service of replacing the PbA is not included in the average cost per 2000 cycles, thus the cost is increased even more.

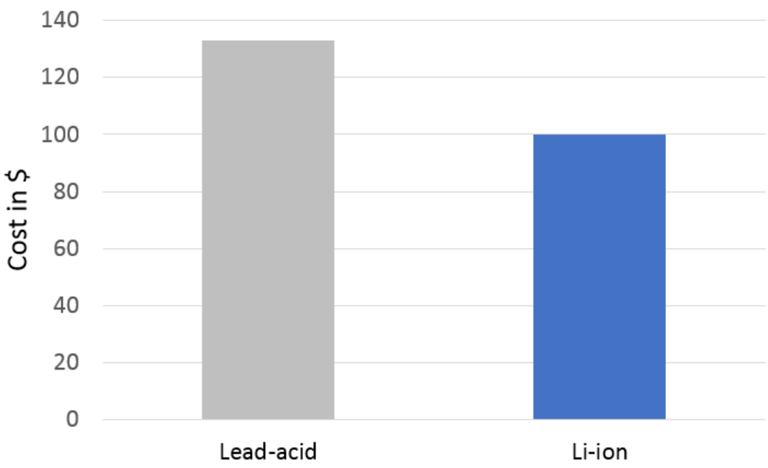


Figure 3.9: Average cost per 2000 cycles of Lead-Acid H6 AGM 70Ah and Li-ion Phosphate-25Ah.

Besides, a lighter 12V battery reduces the total vehicle's weight in approximately 17.2 Kg, improving its performance and energy consumption. The total vehicle weight is 1810 kg, which is reduced by approximately 1 %, as a result the total fuel consumption is reduced by 0.4 %.

3.4.4 BMS for the 12V Li-Ion Battery

The Li-ion battery requires a BMS in order to operate correctly, avoid thermal runaway, cell balancing, among others. The most important parameters for the battery to be measured and monitored are voltage, current and temperature. The SOC level is calculated continuously using the measurements in order to estimate in real time the current state of charge. The performance and the life time of the Li-ion battery can be degraded rapidly when the battery works under different conditions presented in section 3.4.1 and manufacturer specifications. According to the market analysis, the selected 12V Li-ion battery is integrated with a BMS and PCB, for the same price. However, other manufacturers do not include the price of the BMS in the cost of the li-ion battery. The selected 12V Li-ion battery has an automatic battery protection system which is built-in the battery. It is designed to prevent the damage to the cell from external and unwanted conditions. The selected 25Ah battery will be protected according to the following limits:

- Low voltage disconnection: 8V
- Over voltage disconnection: 15.8V
- Short circuit protection: Instantaneous
- Cell balancing: Automatic

The DC/DC converter shall control the charging current and voltage of the battery according the different SOC levels. From the safety perspective, the DC/DC shall disconnect the output to the battery in the case that the monitoring system of the battery fails in order to avoid over charging the battery. The DC/DC can add battery protection requirements for a future platform. Therefore, the Li-ion battery can be protected from the converter and through the in-built BMS and a protection circuit board (PCB).

4

Integration of the 12V Li-ion Battery & Autonomous Drive

This section treats the extra load added to the 12V power supplies when the autonomous drive is implemented. On the other hand, it is analyzed the feasibility of integrating the 12V battery in 3 locations such as: front hood, front seat and HV-battery pack. Finally, the design and packaging space for the 12V battery are determined.

4.1 Electrical System of Autonomous Drive

One important requirement to allow the autonomous drive-function in a vehicle up to level 4 of autonomous drive, is that the driver can always intervene and control the steering and braking if the Advanced Driver-Assistance Systems (ADAS) fails. Therefore, the auto industry guarantees that the vehicle can be controlled in three ways independently:
Firstly, the autonomous drive system controls the vehicle entirely. Secondly, the power steering (electrical/hydraulic) and the brake servo (hydraulic) are connected to the driver in normal conditions, without ADAS. Thirdly, the steering is always mechanically connected to the driver when the power steering fails, while the braking is still hydraulically connected due to a twin hydraulic system [91].

Although, there are several ways of controlling the vehicle, the requirements on the autonomous drive system almost guarantee not to fail from an electrical point of view. Since it is built on two separated electrical 12V systems, a main system (12V system I) and a backup system (12V system II), which are mechanically connected together, redundancy is possible to achieve. The electrical systems have their own power supplies which are supplying power to ECUs, they control the steering and braking units, which include small electric motors, that consequently are controlling a steering-wheel and a braking-paddle. A general illustration of these systems is shown in Figure 4.1.

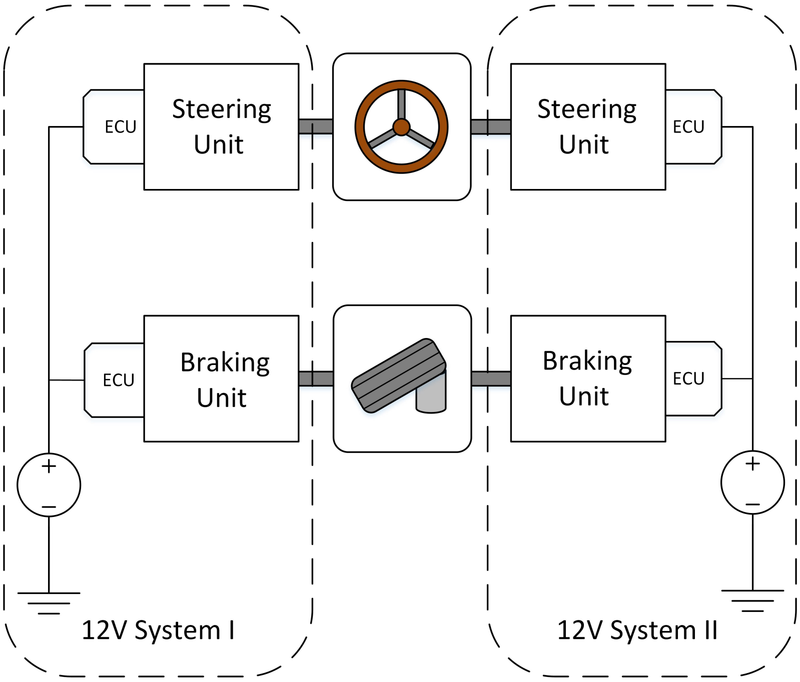


Figure 4.1: The autonomous drive system in general.

Figure 4.2 shows a simplified concept solution of the 12V system for a future platform HEV/PHEV, from a system perspective. This one includes the power sources (in yellow) and loads. Both systems are linked together through two busbars, one busbar for the auxiliary (AUX) loads and another for ADAS loads. On the main system side, the HV battery and the ISG (Integrated Starter Generator) are supplying power through a CIDD (Combine Inverter DC/DC), where an inverter and a DC/DC converter with a dual output which are separated internally, to AUX loads and the ADAS loads. The dual output of the converter could also be replaced by another connected DC/DC converter. The system will mainly use power from the ISG which is working as a starter motor and an alternator in a normal case [92].
On the backup side, the AUX loads have the 12V battery as a backup power source, while the ADAS loads have a separated small 12V battery (H4). Although, this battery will provide power occasionally even when the main system is running properly, similar to the 12V battery function to support transients. The two busbars are connected together in order to give additionally redundancy for both loads.

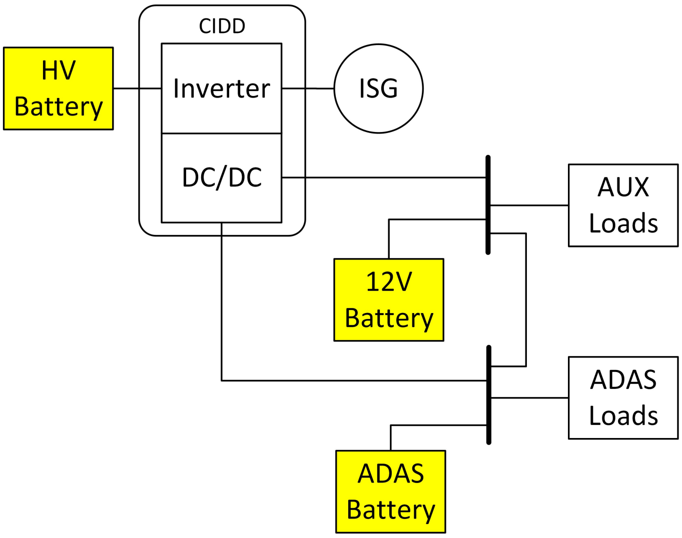


Figure 4.2: A concept of the autonomous drive system in the hybrid vehicle.

In this project, from a safety perspective, the steering and braking units are considered to be the most critical loads. Therefore these will be studied in the emergency case. Also, the backup system should sustain a current that is at least 5 minutes. The ECUs in ADAS are considered to be continuous loads which are consuming a power of 500 W.

4.1.1 Electrical System Solution

Based on the mentioned concept in the previous section, the 12V electrical system can be further developed in the hybrid vehicle as Figure 4.3 depicts. The suggestion is that the HV battery and the ISG are connected to a CIDD which contains two DC/DC converters with a dual output each. These allow the converters to deliver power to the AUX loads and the ADAS loads, and recharging the 12V battery simultaneously. The main advantage of the dual outputs is that the 12V battery can still be recharged if one of the converters fails. However, by using two DC/DC converters, size and weight of CIDD would increase. By the capacity of the 12V battery is increasing sufficiently enough, it can handle auxiliary loads and the continuous power consumption from ADAS loads. Hence, the ADAS battery can be removed from the electrical system which would save space and weight in the vehicle. Though, despite a removed ADAS battery, both HV battery and 12V battery need a higher capacity in order to give more power to the loads. Besides an increased capacity, the batteries would be heavier and larger.

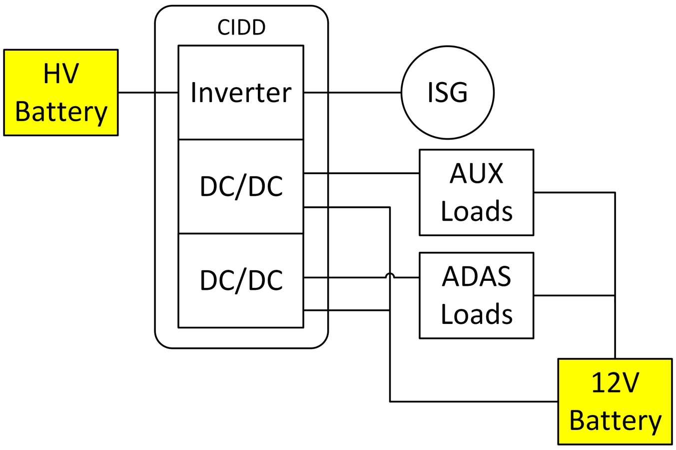


Figure 4.3: A proposal of the autonomous drive system in the hybrid vehicle.

4.1.2 Consumption Estimation with Autonomous Drive

The sensors in an autonomous drive vehicle make the self-driven function possible, though it requires a high amount of power. This is highly needed in order to compute the largest amount of vehicle's environment data. According to Ny Teknik, the car prototypes of autonomous drive are consuming a power of 2.5 kW. This amount of power would imply a vast increase of fuel consumption in an ICEV, which is not an appropriate application of ADAS. It is more useful for EVs and HEVs/PHEVs, though the driving distance would be shortened. In the prototype cars, the autonomous drive system is taking the whole space in the rear, which is a temporary solution to store all the data, which will not be in the final version of the car [93]. The microchips makers know about the consumption issue and they are working on it, in aims of improving the efficiency. For example, Xavier chip from Nvidia, with a CPU (central processing unit) of 8 cores and a GPU (graphics processing unit) of 512 cores, can do 30 billions/second calculations and consuming 30 W. However, for a self-driving vehicle at level 5, Nvidia is suggesting two Xavier chips and together with two GPUs are necessary to cover 500 W consumption. According to [93] Tesla and Intel are developing low power chips like Xavier.

The ADAS system has two main power consumers - ECUs and sensors. According to University of Michigan, the allocation in percent between these consumers can be presented as shown in Figure 4.4 [94].

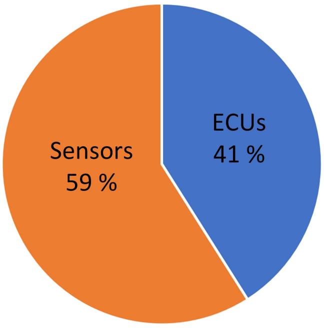


Figure 4.4: Power consumption in an autonomous system [94].

All active ECUs and sensors in the ADAS system are represented by a continuous base load of ADAS, so called ADAS loads. Due to incomplete system design, this base load is consuming current intermittently less than 50 A. Therefore, the ADAS loads are expected to consume current between 30 A and 50 A. According to earlier consideration, the consumption current can be found within this range:

$$i_{ADAS} = \frac{P_{ECUs}}{V_{system}} = \frac{500W}{12V} \approx 42A \tag{4.1}$$

The ADAS consumption can be considered as an "extra load" which will be added together with the AUX loads, when introducing autonomous drive to a future platform.

Since safety is prioritized, a study at the emergency case is taken into account. To start with, as ADAS loads have a constant base current it is added as a continuous load at its highest limit to the continuous loads of the auxiliary 12V system. The total current consumption for continuous loads is estimated as follows:

$$i_{ADAS} = 50A \tag{4.2}$$

$$i_{totcont} = i_{ADAS} + i_{cont} = 50A + 25A = 75A \tag{4.3}$$

This estimated current consumption will increase the battery current, hence give a higher battery capacity according to equation 3.3.

Many automakers have the ability to reach level 2 of autonomous drive today [65]. Therefore, it is expected that the main 12V system in the current platform and the next one will have ADAS loads, which are consuming 50 A and which are adapted to level 3 or 4 of the autonomy levels, within a few years.

Battery capacity calculation with ADAS

The total battery capacity is increased due to the introduction of ADAS loads to the electric system. According to the proposed solution showed in Figure 4.3, the 12V Li-ion battery will supply current for both loads, auxiliary and ADAS. The extra current due to ADAS loads is estimated to be 50 A continuous. Since the main power is provided for the DC/DC converter when the vehicle is in *running mode*,

the 12V battery shall provide a backup power for 5 minutes (0.08h). The estimated time of 5 minutes has the objective that the vehicle has enough energy to be parked in a safe place out of the road, when the DC/DC converter fails.
In Chapter 3, the battery capacity for the current loads is calculated. The following calculations are based on the same method as seen in the section 3.4.2.
The initial capacity of the Li-ion battery is:

$$Q_{ADAS'} = 0.08h \times 50A = 4.17Ah \tag{4.4}$$

Considering the correction factors in the section 3.4.2, the extra capacity due to ADAS loads is:

$$Q_{ADAS} = 11.48Ah \approx 12Ah \tag{4.5}$$

The total capacity is calculated as follows,

$$Q_{total} = Q_{ADAS} + Q_{AUX} = 12Ah + 25Ah \tag{4.6}$$

where Q_{AUX} is the capacity calculated in Chapter 3.

$$Q_{total} = 37Ah \tag{4.7}$$

4.2 Battery Location Study and Losses in the Cable

The 12V battery dimensions and weight are key factors to determine a suitable battery location in the vehicle. Besides, the 12V battery may take into consideration to be located as close to the main loads as possible, that is in front of the vehicle. However, packaging space is becoming an issue since more electric components and systems have been added to the vehicle. In the vehicle under research, the 12V battery-H6 is located in the trunk. The 12V battery location can be seen in Figure 4.5.

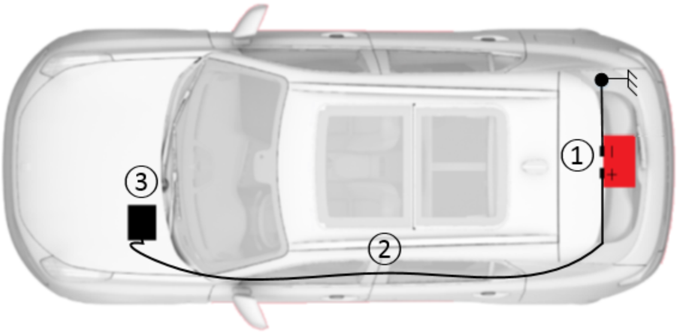


Figure 4.5: 12V Battery location and cable connection to the distribution box, where: ① *12V battery*, ② *Wire*, ③ *Distribution box (CIDD).*

This battery location implies several issues related to wire length and reduced packaging space. The main loads are located in the front or engine bay of the vehicle, thus the length of the wire is considerable long. Nowadays, the 12V battery is located in the furthest part of the vehicle to the distribution box (CIDD). Therefore, the impedance of the wire is considerably higher than if the battery were located closer to the distribution box, thus higher power losses in the wire. In the current vehicle under research, the battery is located in the trunk, removing space for a spare wheel or packaging for the customer. When Li-ion battery solution is introduced, the total volume and weight of the battery is decreased significantly as shown in Chapter 3. In order to investigate a possible 12V integration, the location of the Li-ion battery is studied.

4.2.1 Impact of Cable Impedance Results for Current PHEV

Figure 4.6 shows the voltage drop in the wire when the starting case test is conducted in the vehicle. The blue curve is the voltage measured in the connection terminals of the distribution box, while the black curve is the voltage in the battery terminals. When a transient or high current flows through the wire the voltage drop is increased as can be seen in Figure 4.7.

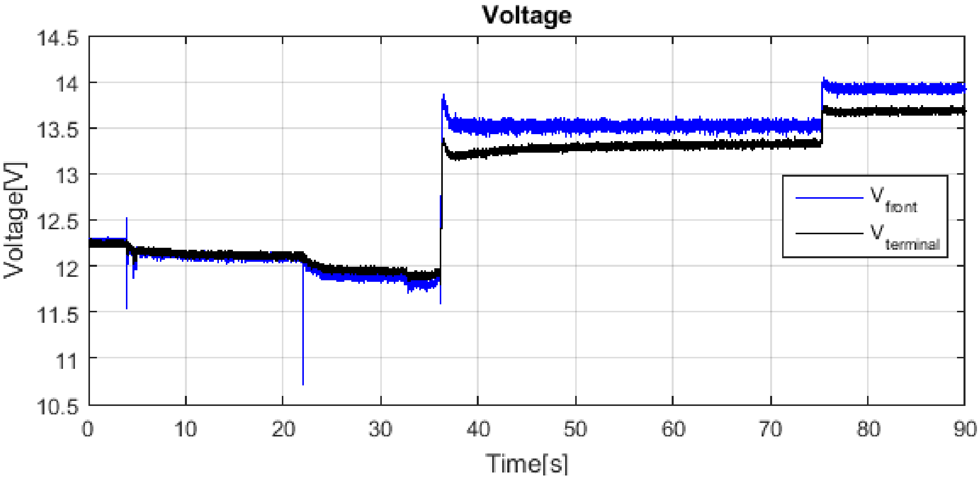


Figure 4.6: Voltage measurement in battery terminals and distribution box.

For the starting case, the voltage drop is 5.42% when the maximum current is reached. Therefore, the voltage drop in the wire due to the location of the 12V battery represents a negative impact in the performance of the 12V system.

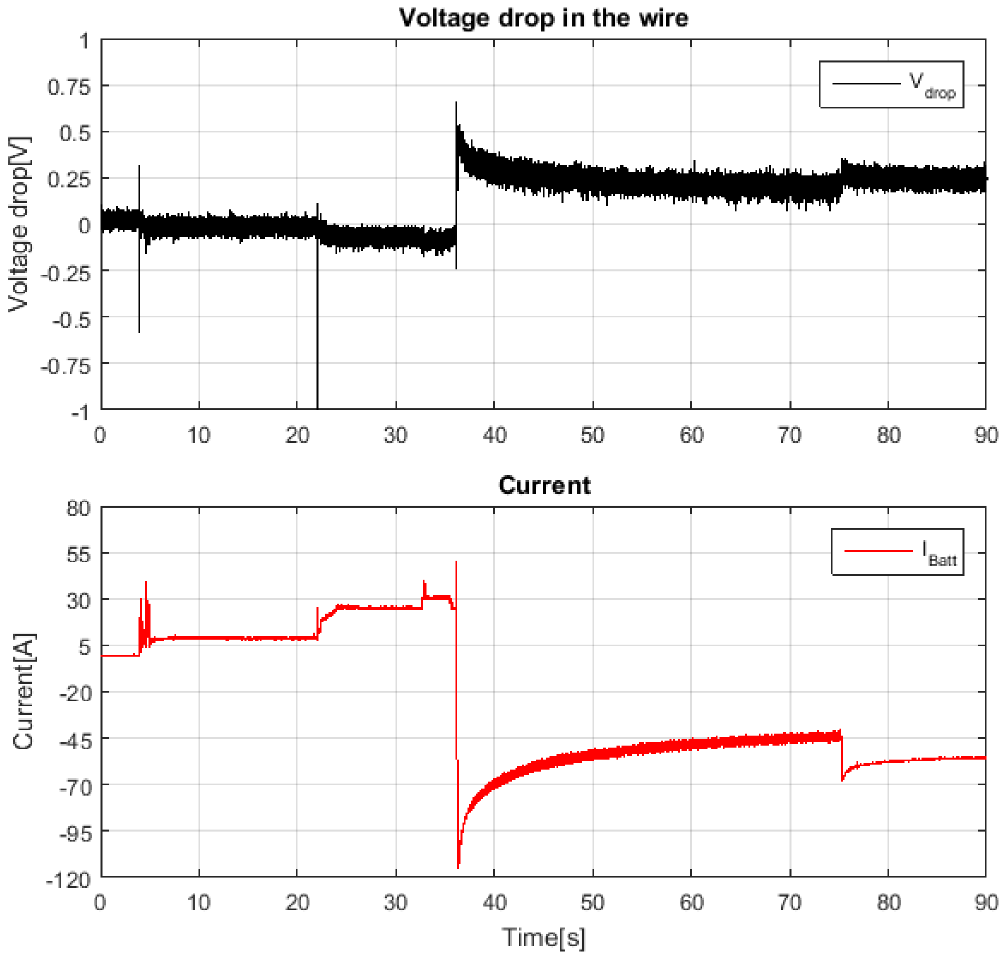


Figure 4.7: Voltage drop in the wire between the 12V battery terminals and the distribution box.

The wire length is 3124.79 mm and the diameter of the copper wire is 1.07 cm. According to [95] the wire self inductance can be obtained as follows:

$$L_{wire} = 2l \left\{ ln \left[\left(\frac{2L}{D}\right) \left(1+\sqrt{1+\left(\frac{D}{2L}\right)^2}\right) \right] - \sqrt{1+\left(\frac{D}{2L}\right)^2} + \frac{\mu}{4} + \left(\frac{D}{2L}\right) \right\} \tag{4.8}$$

where: L_{wire} is the wire inductance, D its diameter, L is its the total length, and μ the wire permeability. The value of the current cable is:

$$L_{wire} = 4\mu H \tag{4.9}$$

The resistance is calculated by measuring the current and voltage at both ends of the wire. Using Ohms Law the resistance is obtained as follows:

$$R_{wire} = \frac{\Delta V}{I} = 4.2m\Omega \tag{4.10}$$

The test results presented in section 3 show transient currents e.g. in an emergency condition that will impact in a voltage drop in the wire due to fast current variations. The voltage drop due to the inductance is defined as $V_L = L\frac{di}{dt}$. The copper losses are well known and calculated as $I^2 \times R$. Therefore, a solution to decrease the losses in the cable is locating the battery closer to the distribution box, other factors must be taken into consideration. The location of the battery solution is further studied in the following subsection.

4.3 12V Li-Ion Section Solution

Lithium allows to create a 12V section in locations of a vehicle where it was impossible before. Consequently, a suitable architecture of a 12V battery pack, which is beneficial for the vehicle's space and weight, is to be defined for this 12V section. However, when designing a battery pack, many factors are important to consider. Because the battery architecture changes entirely if one factor is changing. For instance, the type of cell is vital for the height of the pack which would affect the space in the vehicle, while the choice of chemistry and location affect the performance, temperature and lifetime of the battery. Therefore, location environment, chemistry and cell format of the battery are taken into account when the battery pack or section is designed in this chapter.

4.3.1 Cell Chemistry

Four different chemistry types of Lithium are treated - LFP, NMC, NCA, and LTO (see more in 2.2.2.1). The analyze of these chemistries is based on six characteristics which are: safety, cost, performance, specific energy, specific power and lifetime.
According to [23], the characteristics for each Li-ion chemistry are scaled and compiled in Table 4.1. The scale is between 1 and 4, where a low number means worse and a high number means better characteristic (note: it is the opposite for the cost-characteristic).
In this project, the first three characteristics are prioritized when it comes to the selection of the Li-ion chemistry. They are prioritized in the following order: safety, cost, and performance.

Table 4.1: The characteristics of four different Li-ion chemistries [23].

Characteristic	LFP	NMC	NCA	LTO
Safety	4	3	2	4
Cost	3	3	2	1
Performance	3	3	3	4
Specific energy	2	4	4	2
Specific power	4	3	3	3
Lifetime	4	3	3	4

LTO has the best performance compared to the other three Li-ion types. On the other hand, LTO comes with the highest cost while LFP and NMC are the cheapest ones. Due to high stability, LFP and LTO are the most safety Li-ion chemistries. Since safety, cost and performance are prioritized, the LFP chemistry is selected.

4.3.2 Cell Shape

A battery cell's performance to deliver and store energy is not determined just by its chemistry, it is also determined by the cell's shape. The Li-ion cells are coming in a wide range of different cell formats - cylindrical cell, prismatic cell, pouch cell and button cell [96], [97]. The first three cell shapes are examined in this project, since they are used in electric powertrain applications. Because volume was one of the most important aspects for the battery solution, a flexible form factor is prioritized. The most appropriated cell shape is utilized for the designing of the 12V battery section solution.

To find that cell shape, the features of cylindrical cell, prismatic cell, and pouch cell have been analyzed including the battery section solution. The advantages and disadvantages of each cell for this solution are listed below.

Cylindrical cell

+ Its cylindrical shape creates space between the cells that reduce the effective use of space. Although, this can be utilized for cooling, which is required for a battery in the engine bay or in the HV-battery pack.

+ LFP gives a high specific power which the cell is constructed to handle.

+ The cell offers a long lifetime for a low cost and effective cycle performance. These are highly needed since the battery lifetime shall be at least 4 years and not be fully discharged after 21 days of parking.

+ Some cells provide safety vents against internal overheating and overpressure to prevent fire and electrical disconnection caused by the cell breaks. This is required for a sealed integrated battery solution to remove maintenance and extra costs.

- \+ The cell has a high mechanical strength and does not deform at high internal pressure.
- \- Since it has lower form factor compared to other shapes, it makes the battery integration more complex.

Prismatic cell

- \+ The case, made of aluminum or steel, gives the cell strength, stability, and water protection. This allows the cells to be packed around heavy and non-sealed areas in the hybrid vehicle.
- \+ Vents allow pressure can be relieved to avoid internal overpressure and reduce the risk for an uncontrolled cell. This is needed to avoid maintenance and prevent capacity is abused in the solution. This is not possible for pouch cells.
- \+ The cell has thermal management problem to prevent fire or overheating. However, LFP is safe against high temperatures.
- \+ More flexible for packaging than cylindrical cells due to its high form factor, which can be utilized to pack the cells together in various locations in the vehicle.
- \- Gas formation can expand the cell with 3 mm, this would increase the space in the battery section.
- \- It is more expensive and has a less effective performance than cylindrical cells which would reduce the overall battery performance.

Pouch cell

- \+ The cell has a laminated structure in a pouch, which minimized the cell packaging. This results in higher stored energy that can take care of long continuous or high transient power consumption.
- \+ The highest form factor of all kind of cell shapes, this allows the cell packaging can be done almost anywhere in the vehicle.
- \+ None metallic case gives low weight and low cost, light weighted is desired for the battery solution.
- \- LFP might not be suitable since Li-ion polymer is the most common and adapted chemistry for this cell.
- \- For some cells, deformations can occur due to there are no vents to relieve the gases, this would make the integration complicated.
- \- Complex to form the pack structure for the cells complicates the integration even more.

- The cell is sensitive to humidity and high temperatures, which can reduce its lifetime. This means an integration is required, though an integration in HV-battery pack or engine bay might cause overheating. However, the large surface of the cell can be used for thermal management.

Even though the pouch cell has the highest form factor, the prismatic cell is chosen for the 12V battery section design. Mainly because of the many downsides of the pouch cell, such as risk for cell deformation, difficulties to form the pack structure, high temperature, and humidity sensitive and the cell is not manufactured to carry Li-ion phosphate. Also, because of the beneficial properties of the prismatic cell; high strength and stability, sustain humidity and prevent deformation. The cylindrical cell comes also with several advantages like low cost, no deformation, high power and performance and could, therefore, be used for the integrated application. However, due to its low form factor and even if it is less costly compared to the prismatic cell, the cylindrical cell is not a suitable format to use in the battery section integration.

4.3.3 Battery Pack Design

Prismatic cells are coming in a various range of formats. Also, in different sizes, as smaller cells in mobile phones, tablets, and laptops or as larger cells in electric powertrains of hybrid vehicles [97].
In this project, small prismatic cells are considered for the battery section solution, despite smaller prismatic cells are not in use in hybrid vehicle applications. Because smaller cells allow the packaging to be more flexible and if one cell fails it would not reduce the capacity as much as a failed larger cell. Besides, the risk for the whole battery fails or explodes is greater with an overheated large cell than it is with an overheated small cell.
By consider the battery capacity of 37 Ah which is required for the loads, including ADAS loads, the battery pack's desired energy is estimated as [15]:

$$E_{pack} = 37Ah \times 12.8V = 473.6Wh \tag{4.11}$$

Since Li-ion phosphate is applied and the battery pack voltage shall be 12.8 V, the number of cells is 4, as in Chapter 3. These cells are connected in series which create the voltage 12.8 V over the battery pack. However, to obtain 473.6 Wh battery pack energy, it is required 4 cells in series that can deliver 37 Ah each. A capacity of this size is considered to be a large prismatic cell due to most larger cells have their capacity between 20 Ah and 50 Ah [97].
To obtain the same battery pack energy of 473.6 Wh with smaller prismatic cells, they also have to be connected in parallel. The cell capacity is within a range of 0.8 Ah and 4 Ah. The capacity of small prismatic cells differs from each manufacturer because there is no standard format [97]. Therefore, a midpoint value of 2.4 Ah per cell is selected within this range. The cell energy is obtained by the cell voltage and the cell capacity are multiplied:

$$E_{cell} = 3.25V/cell \times 2.4Ah/cell = 7.8Wh/cell \tag{4.12}$$

Now, by using the battery pack's desired energy over the energy per cell, the number of cells in the battery pack is calculated:

$$N_{pack} = \frac{473.6Wh}{7.8Wh/cell} \approx 62cells \tag{4.13}$$

Observe, the answer of this calculation is rounded up to 62 cells in order to achieve the desired capacity. Also, by rounding to an even number, the cell packaging can be divided equally into one or several modules.

The known number of cells in the battery package allows for estimation of the total battery pack volume. First, the dimensions of a small prismatic cell are defined. Most small prismatic cells have dimensions in the following ranges [98]:

- Length: 40 to 60 mm
- Width: 4 to 10 mm
- Height: 30 to 40 mm

The dimensions of the prismatic cell for the battery pack design are selected as midpoints within these ranges, i.e. 50 x 7 x 35 mm. These dimensions are reasonable because the prismatic cell PICPAL2138 has similar measures for the same capacity [99]. Although, since the cell might expand caused by gas formation, a gas growth allowance of 3 mm is added to the dimensions: 53 x 10 x 38 mm.

The battery pack design is based on the calculations stated in [100]. When forming the cell pack, the assembling process of the cells, e.g. welding and cabling will increase the space in the package. Therefore, it is assumed that the length, the width and the height of each cell will increase by 4 %, 9 %, and 26 % respectively. Hence, the size of the cell would be 55 x 11 x 48 mm.

In this case, the 62 cells are assembled together into one module in the cell pack, where the cells are arranged in a series/parallel configuration which is depicted in Figure 4.8. Though, theoretically, 62 cells give 4 connected cells in series and 15.5 connected cells in parallel. The number of parallel cells can be rounded up to 16 cells. Hence, in order to use 4 cells in series and 16 cells in parallel, 64 cells in total are utilized instead.

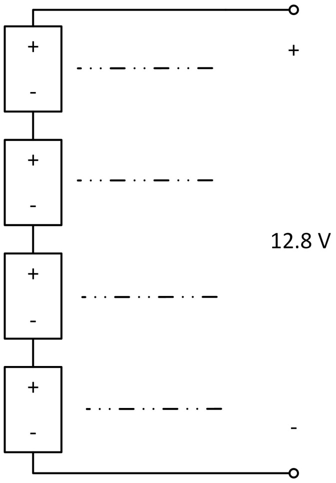


Figure 4.8: Series/parallel cell configuration [101].

This arrangement, plus 10 % increase in height, due to additional cabling and welding of battery terminals, are completing the cell pack size. The length is calculated by $55mm \times 4cells = 220mm$, the weight is given by $11mm \times 16cells = 176mm$ and the height is obtained by $48mm \times 1.1 = 53mm$.

The implementation of a BMS is normally on the top of the cell pack. Then, the total height includes the height of the cell pack 53 mm and the heat isolation material between the BMS and the pack which is around 3 mm. Also, the thickness of the BMS is 12 mm which is a common measure for BMS types S12 and S16. By taking these into consideration, 15 mm is added to the total height. Thus, the following dimensions are estimated: 220 x 176 x 68 mm.

To build the battery pack, a case of metal is assembled on the cell pack with the BMS. A layer of foam is installed between the case and the cell pack to protect the pack against vibrations. This will increase the size of the battery pack in all dimensions with 9 mm, whereof the thickness of the metal case and the foam is 4 mm and 5 mm each. Hence, the final dimensions are defined as 229 x 185 x 77 mm and the total battery pack volume is calculated to:

$$V_{pack} = 229 \times 185 \times 77mm = 3262cm^3 \tag{4.14}$$

4.3.4 Packaging and Location

As it was stated before, an even number of cells allows the cells to be packed in one or several modules. However, by using several modules, they would fit in certain areas of the battery pack and leave some space unused. Therefore, to utilize more space of the pack, one single module can be applied. The cell packaging of this module could be adapted to a specific location in the HEV/PHEV.

Figure 4.9 presents four possible locations where the battery pack can be integrated with the hybrid vehicle. In order to reduce the cable losses, the battery has to be located close to the distribution box and the loads. Therefore, front locations, such as the front hood, the front seat, HV-battery pack have been examined as possible battery locations for a future platform.

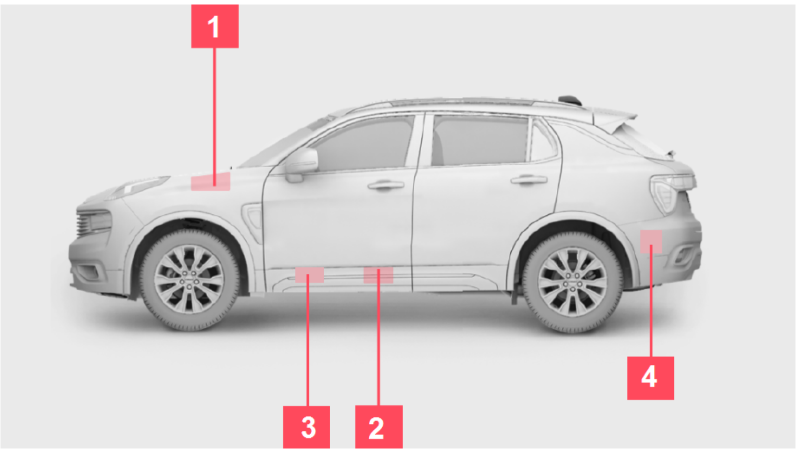
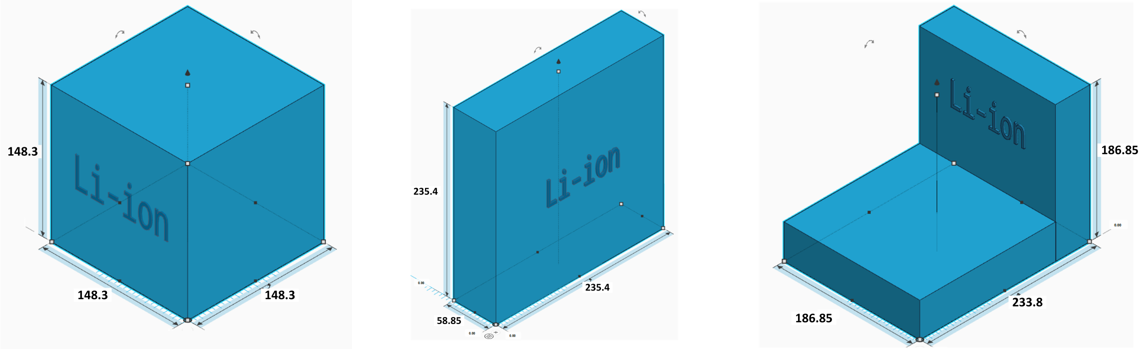


Figure 4.9: The possible locations for the 12V battery section in the HEV/PHEV vehicle: ① *Front hood*, ② *Front seat*, ③ *HV-battery pack*, ④ *Trunk*.

Since the battery pack can be designed in a various range of shapes, three different illustration concepts of the battery have been developed as shown in Figure 4.10a, 4.10b and 4.10c.



(a) Cube-concept.

(b) Rectangle-concept.

(c) Mix-concept.

Figure 4.10: Three different shape concepts of the 12V li-ion battery section.

Based on the total battery pack volume, each side length of the shapes could be derived. The cube-concept (a) gives identical side lengths. Since the rectangle-concept (b) has different side lengths, a side-rate was included, i.e. the short side is 1/4 of the long side. The mix-concept (c) is split into two equivalent parts, hence the side lengths are estimated at half of the total volume of the pack, where the same side-rate was applied.
The locations in the vehicle for the battery pack are analyzed. This analyze is based on different factors. Table 4.2 summarizes the benefits and drawbacks of each factor for each location.

Table 4.2: Analysis of different locations in the vehicle.

Factors	Front hood	Front seats	HV-battery pack	Trunk
Cooling	+	-	+	-
Maintenance	+	-	-	+
Replacement	+	-	-	+
Close to loads	+	+	+	-
Close to CIDD	+	+	+	-
Battery space	-	+	+	+
Cable losses	+	+	+	-
Magnetic fields	+	-	+	+
Noises	+	-	+	+
Crash safety	-	-	-	-

Front hood

In the front hood, there is a lack of space due to the high number of components and units that are already located there. However, since the Li-ion battery is flexible to pack and it is smaller in space and weight, a packaging in the engine bay would not be an issue. An integration of the battery pack in front hood, as depicted in Figure 4.11, comes also with other advantages. As the cooling system for components, such as inverter and ISG, is located there, the same system can be utilized for the 12V battery. Besides, the battery would be external integrated in the front which would make it possible for maintenance and replacement of the battery. Moreover, a front hood location implies in shorter distances between the battery and loads and CIDD, thereby reduced power losses in the cables. Distribution from electromagnetic compatibility (EMC) and noises caused by the battery are not an issue because they would not have an impact on driver either passengers.

Vehicle crashes are inevitable, regardless of where the crash impact occurs the battery pack would most likely get damaged. Although, protective plates can reduce the damage of the cells in the battery pack during vehicle crashes.

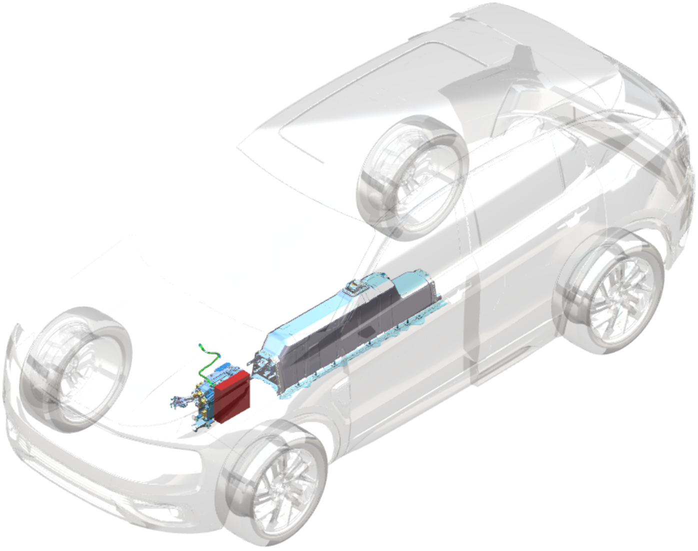


Figure 4.11: Front hood integration of the 12V battery pack (the red rectangle).

Front seat

If there is sufficient space in the next platform, it might be plausible to assemble a battery pack under the front seat, according to Figure 4.12. Since, this solution would be integrated under the front seat, more specifically under the vehicle floor, it would not be possible to repair or replace it. Though, in this location, the battery is close to loads and CIDD, which would give less cable losses as in the front hood location. An issue is the electromagnetic fields from the battery cables which are exposed directly to the driver. The fields are especially high under the front seat and could affect the driver. However, this could be solved by protective covers or by locating the battery cables with a certain distance from each other in order to cancel out EMCs.

Besides, the electromagnetic fields are also disturbing the ECUs. Despite the location, this problem is not avoidable due to the vast expansion of electronics in modern vehicles. Noises are also a problem created by a relay (if installed in the PCB), which is disturbing for passengers.

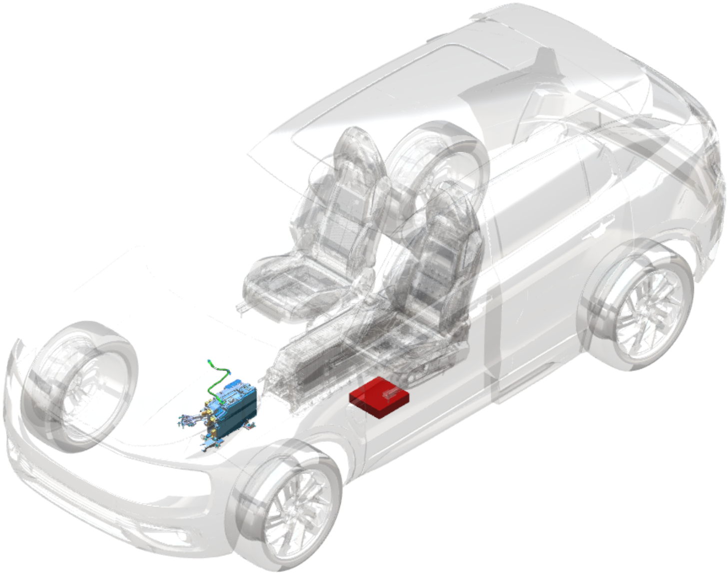


Figure 4.12: Front seat integration of the 12V battery pack (the red rectangle).

HV-battery pack

Another idea is to integrate the battery as a small section of the HV-battery pack, shown in Figure 4.13, since the specifications of a new HV-pack is under development. The cooling system of the HV-battery pack can contribute to the cooling of the 12V battery. This integration of the battery is sealed which would remove some features, like in the previous location-case, battery maintenance and replacement. Reduced power losses in the cables due to loads and CIDD are near the battery. EMCs and noises from the battery have less impact to driver and passengers due to the battery is covered by the HV-battery pack.

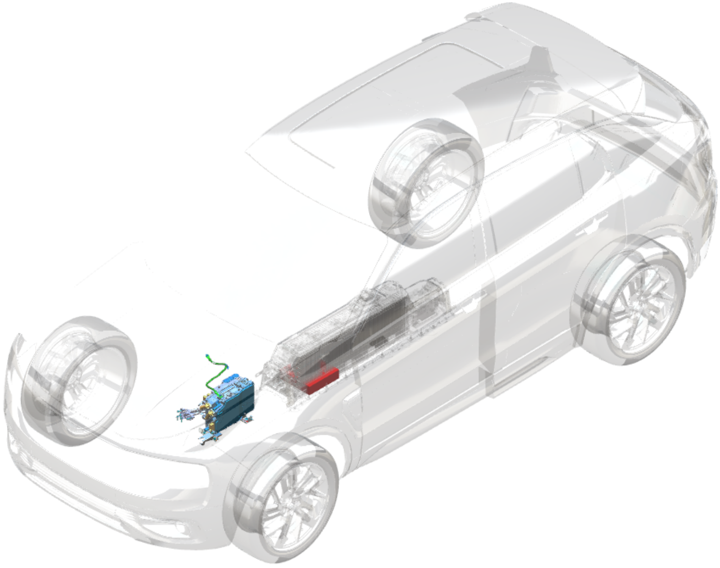


Figure 4.13: HV-battery pack integration of the 12V battery pack (the red rectangle).

Trunk
The current location of the 12V battery is in the trunk, where the battery space is not a problem in the vehicle. Though, the space of cables is a problem, since this location requires many, thick and long cables between the battery and the distribution box. Thereby, higher cable losses, increased weight and reduced spaces are expected when using the trunk-location. Also, heat might be a problem since the battery does not have access to a cooling system. Though, it is possible to change and repair the battery. In this location, EMCs and noises are not an issue for driver and passengers.

4.4 Complete System including 12V Li-Ion Battery and Autonomous Drive

The following sketch in Figure 4.14 presents the complete 12V electrical system including the autonomous drive in the HEV/PHEV. Moreover, the system contains the following components: an HV battery, two DC/DC converters, an inverter, an ISG, auxiliary loads and a 12V Li-ion battery.

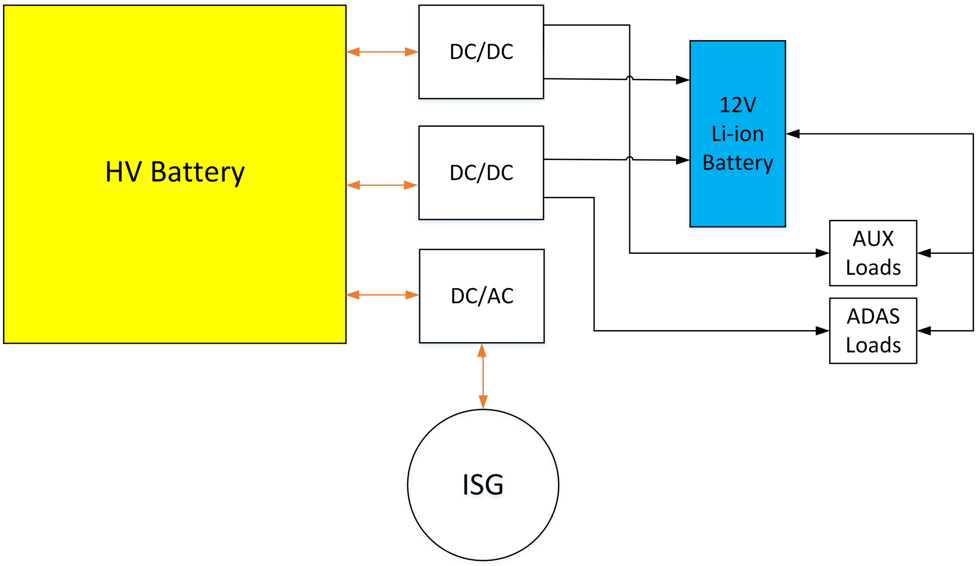


Figure 4.14: Complete system with the 12V Li-ion battery in the HEV/PHEV.

For the same connections, the converters and the components on the low voltage side can physically be located in various places in the vehicle. For example, since it is preferable to put the 12V battery together with a DC/DC, to reduce cable losses, space and weight, they can be united in one single box as a section of the HV-battery pack.

5

Conclusion

Nowadays, the auto-manufactures have not adapted the 12V battery to Li-ion technology in a large scale, because 12V Li-ion batteries were only found in two hybrid vehicles according to the benchmarking presented in this project. The Li-ion solution for the 12V battery is a merging technology. However, it does not mean the Lead-acid batteries would still play a major role in the future, even though it has been used for the last 100 years. The lithium-ion battery has many beneficial features, such as high specific power and energy, it has potential to be that chemistry that is replacing the Lead-acid in 12V batteries in vehicles the next coming years. Due to the low application use of 12V Li-ion batteries, its integration in a hybrid vehicle are, as for many, unexplored. This project proposes solutions to integrate the 12V Li-ion battery as a section of the HV-battery pack, which occurred in the platform of Kia Niro and Huyndai Ioniq Hybrid. It is possible to integrate the battery in a similar way in the hybrid vehicle under test, because of the Li-ion battery's high temperature range, low volume and weight allow the Li-ion battery packaging to be more flexible than it is for a Lead-acid battery.

Five driving cases were analyzed, where each case represents different conditions with different voltage and current profiles that the 12V battery must fulfill. During the emergency case a peak of current of 200 A is measured. Therefore, for transient loads the Li-ion battery fulfill the maximum current. Based on the loads current consumption, the battery capacity is calculated to 25 Ah. The total capacity value was adjusted with correction factors in order to achieve a realistic battery capacity, including SOC, SOH, temperature and self discharge. Due to Li-ion phosphate is the most common chemistry in the current market, a 12.8V Li-ion phosphate battery with 25 Ah is selected. The 12V Li-ion battery solution is suitable for the hybrid vehicle application HEV/PHEV, since the battery meets the 12V system requirements.

Packaging space is a big issue for the HEV/PHEV under study. The 12V Li-ion battery solution is 80.8 % smaller and 67.5 % lighter compared to the previous 12V Lead-acid battery. However, the initial cost of the Li-ion battery is higher. In the long term the cost per 2000 cycles shows that the Li-ion battery is a cheaper solution rather than the conventional Lead-acid.

The Li-ion phosphate solution was selected for the 12V battery pack design because of its safety properties among other different Li-ion chemistries. Prismatic cells was chosen over other cell formats (cylindrical and pouch) due to their high form factor, strength and stability, which make the packaging more flexible and the battery integration less complex. Based on the 37 Ah capacity, which includes the autonomous drive consumption, 64 cells are calculated and assembled together to a battery package with a volume of 3262 cm^3. For the same volume, different shapes of the battery pack are proposed as general shape solutions, because of high shape factor of the prismatic cells. Therefore, it is likely the battery integration can take place in several different locations such as in front hood, under front seat or in HV-battery pack in the future platform of the hybrid vehicle.

6

Future Work

6.1 Cranking Amps Result and Supercapacitor

From the energy consumption perspective, the transient cases (which involve transient loads), make a small contribution to the total battery capacity. Around 1.8% of transient energy contribute to the total capacity, according with the results showed in Chapter 3. However, the transient peak for the current can not be neglected, e.g. 200 A for emergency transient with a duration < 1 second, or 500A-800A for CCA. Therefore, for continuous loads e.g. quiescent current, the battery can be studied as an energy source. The 12V power source shall perform a balanced combination between energy and power requirements. Nowadays, some solutions approaches to a combination between a super capacitor, for transient support, and a battery for continuous loads.

A future vehicle's platform might include a supercapacitor, in order to provide high power in a short amount of time for the electrical loads in the vehicle. The supercapacitor can be used for transient loads or cranking the ICE in a HEV/PHEV.

A future platform that includes the Li-ion battery solution can work together with a supercapacitor. However, a future platform might not use the 12V system to crank the vehicle at all. Therefore, the requirement of CA can be not taken in account for the 12V system future platforms.

Furthermore, a test is performed in the current PHEV, in order to analysis the current and power needed to crank the ICE. According to the engineering development for the next platform this requirement can be fulfill by the high voltage-system or the supercapacitor.

6.1.1 Cranking Amps Test (CA)

The PHEV under test has three driving modes: pure, hybrid and power. Each driving mode is tested in two scenarios: full acceleration from 0 km/h and 7km/h. The ambient temperature during the test was 20 °C. The vehicle shall fulfill the torque requirement when the full acceleration is applied for the driver. Therefore, the ICE is cranked using the power from a 12V battery (Lead-acid). For all the scenarios tested the voltage and current profile were measured, obtaining similar results. The test result is shown in Figure 6.1 when the hybrid mode is set and the initial speed is 7km/h, then a full acceleration is applied by the driver. The cranking current (CA) and voltage in the battery terminals are measured as seen in Figure 6.1.

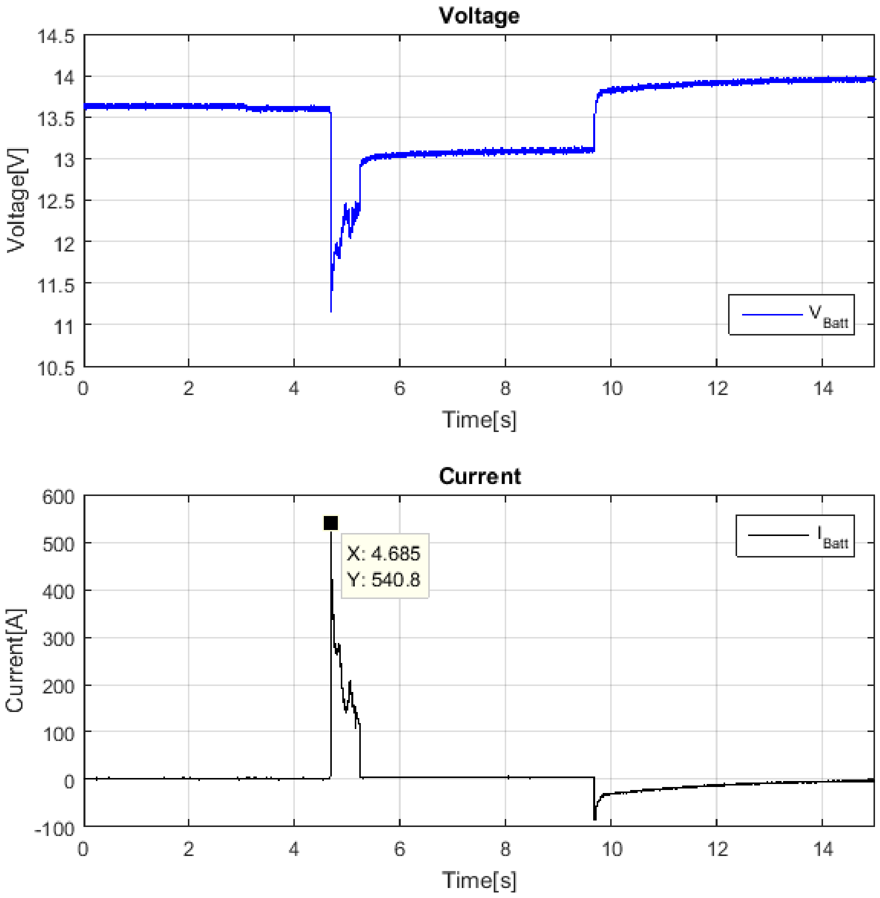


Figure 6.1: Voltage and current measurement in the battery terminals when cranking the ICE.

6.1.2 Supercapacitor Calculation

The peak of the current is 550.8 A @ 20 °C in the 12V battery terminals. The average range of CA is between 500A to 800A, for the PHEV model under test. The cranking current has a duration of approximately 0.6085 milli-seconds, as depicted in Figure 6.1. The charge needed to crank the ICE is calculated by integrating the current over the time, according to the next equation:

$$i(t) = \frac{dq}{dt} \tag{6.1}$$

$$Q = \int_{t_1}^{t_2} i_t dt \tag{6.2}$$

As shown in red color in Figure 6.2, the total charge is calculated by integrating the current over the time.

$$Q = 118.73As \tag{6.3}$$

where $i(t)$ is the current consumption, Q is the total charge in coulombs.

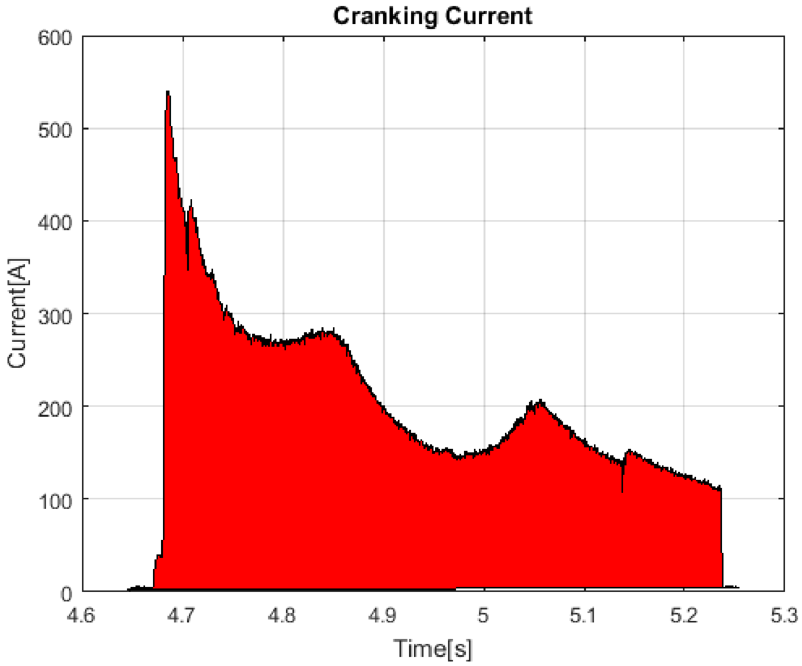


Figure 6.2: Cranking current result, in red the total charge.

The total charge in ampere-hour, so called capacity, can be expressed as:

$$Q = 33.1mAh \tag{6.4}$$

The capacitance is calculated as:

$$C = \frac{Q}{V} \tag{6.5}$$

Where C is the capacitance in farad (F) and V the system voltage. This calculation is done for one single pulse of current (CA). In practice the car can accelerate several times under the same case conditions. Therefore, the capacitor shall be able to provide enough power to crank the ICE for at least 3 times every 5 seconds, according our own estimation.

$$Q' = 33.1 \times 3 = 99.3mAh = 356.19As \tag{6.6}$$

$$C = \frac{Q'}{V} \tag{6.7}$$

$$C = \frac{356.19}{12} = 29.68F \tag{6.8}$$

6.2 Automatically Recharging the 12V Battery Every 10 Days

In the platform of Hyundai Ioniq Hybrid and Kira Niro, a reset button is available for recharging the 12V battery manually. Though, the recharging of the battery can be done by automatically. Also, in order to decrease volume and weight of the 12V battery even further, the number of parking days in the requirements can be reduced.
For example, after 10 parking days, the BMS is allowed to recharge the battery before a certain SOC-level, according to the specifications. Before the SOC-level reaches e.g. 20 %, the BMS could send a wake-up signal to the DC/DC converter which starts to recharging the battery. This can be done because there is no energy problem, i.e. the converter can always, more or less, provide power to the 12V battery from the HV battery. By designing the battery according to 10 days of parking, the nominal capacity will be reduced by 50 %, which corresponds to approximately 10 Ah. However, a capacity of this size would not manage the continuous loads consumption of 25 A. On the other hand, if the capacity was decreased by 20 %, the battery would at least cover the transient load consumption.

6.3 Packaging Optimization of the 12V Battery with Larger Cells

By applying a larger cell, assuming a prismatic cell with 5Ah capacity and a volume twice as big as the small prismatic cell with 3 mm growth allowance, the large prismatic cell volume is increased by 50 %. This means, since each large prismatic cell contains a doubled capacity, the half number of cells are required in the battery pack. However, this does not indicate the battery pack will be made smaller, the pack will more or less have the same volume. Because, regardless of the cell capacity and cell size, the specific energy in Lithium phosphate is the same, therefore, the total volume of the pack is not affected. Although, larger cells can optimize the packaging space of the 12V battery. Because larger cells requires less cell assembling, a few percentage of space might be saved. Even though, this is a trade off between size and safety. As larger cells have higher capacity that can be lost at a fault, there is a risk that the 12V battery pack can not deliver enough power to the loads. This could cause severe results in the electrical system during an emergency case, like the ADAS loads do not response correctly during autonomous driving-mode.

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