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Sizing and energy management of a hybrid source for an electric vehicle

Laïd Degaa

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Sizing and energy management of a hybrid source for an electric vehicle

*Dimensionnement et gestion d'énergie d'une source hybride pour un
véhicule électrique*

Thèse de doctorat de l'université Paris-Saclay

École doctorale n° 575: electrical, optical, bio : physics and engineering (EOBE)

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Titre : Dimensionnement et gestion d'énergie d'une source hybride pour un véhicule électrique

Mots clés : Véhicule électrique, Système de stockage d'énergie, Source hybride, Gestion de l'énergie, Modèles de vieillissement, Dimensionnement.

Cette thèse aborde des aspects cruciaux visant à améliorer les performances et la longévité des systèmes de stockage d'énergie (SSE) dans les véhicules électriques (VE). Le premier chapitre offre une revue exhaustive de l'état actuel de la technologie des systèmes de stockage d'énergie conçus pour les véhicules électriques. Cela englobe une analyse approfondie de diverses technologies, telles que les batteries lithium-ion et les supercondensateurs, ainsi qu'une exploration de leurs avantages, limites et innovations récentes.

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Title : Sizing and energy management of a hybrid source for an electric vehicle

Keywords : Electric Vehicle, Energy Storage System, Hybrid Source, Energy Management, Ageing Models, Sizing.

Abstract : This thesis addresses critical aspects of enhancing the performance and longevity of energy storage systems (ESS) in electric vehicles (EVs). The first chapter provides an exhaustive review of the current state-of-the-art in Energy Storage Systems (ESS) designed for electric vehicles. This encompasses a comprehensive analysis of various technologies, including lithium-ion batteries and supercapacitors, along with an exploration of their strengths, limitations, and recent innovations.

The subsequent chapters delve into specific areas, starting with an in-depth exploration of aging models for battery technologies in electric vehicles.

A thorough understanding of the aging processes is crucial for devising strategies to extend the lifespan of these critical components. The core of the thesis revolves around the sizing and management of Energy Storage Systems.

By evaluating key considerations such as weight, size, and scalability, the research aims to establish optimal sizing parameters for ESS in electric vehicles. This is complemented by experimental validation, employing practical testing to verify the proposed sizing and management strategies.

Finally, the thesis investigates the influence of energy management methods on the ageing of hybrid sources. By scrutinizing different energy management approaches, the research aims to uncover strategies that mitigate the impact of ageing on hybrid sources, contributing to the longevity and efficiency of electric vehicles.

Through this comprehensive exploration, the thesis seeks to contribute valuable insights to the evolving field of electric vehicle technology, specifically addressing the challenges and opportunities in the realm of energy storage and management.

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INTRODUCTION

Context and motivation

The imperative to tackle ecological and economic challenges looms large in the contemporary landscape. The call to action, commonly framed as the "energy and ecological transition," signifies a profound shift in our approach to all human activities. What was once a strategic consideration has now evolved into an inescapable necessity. This transformation is catalyzed by the dynamic growth of economies and populations in Asia and Africa, regions that have shifted from passive participants to central players in the global energy and ecological transition. At the core of this transition lies the recognition that the traditional transportation model has reached the limits of its sustainability. Global dynamics have undergone a seismic shift, driven by the rise of new economic powerhouses and swelling demographic trends, combined with the dwindling reserves of conventional fossil fuels. It is no longer a matter of contemplating 'if' the traditional transport model will be replaced but rather 'when' it will yield to an evolving paradigm.

The transport sector, responsible for a substantial 25% of global CO₂ emissions, occupies a pivotal role in the challenge of climate change. As a consequence, the electrification of vehicles has emerged as a compelling solution to reduce our reliance on fossil fuels. Achieving the goal of vehicle electrification necessitates a meticulous examination of its constituent components. Among these, the battery stands as a primary determinant of an electric vehicle's cost and

performance. Batteries are known to experience performance degradation over time due to the process of aging, resulting in a reduction in energy storage capacity and an increase in energy conversion losses. This degradation manifests in the form of a diminished range and compromised fuel [5]. The economic and ecological viability of electric vehicles is intricately linked to the cost-effectiveness and longevity of their batteries. While advanced energy storage technologies offer the promise of higher energy density and efficiency, immediate gains can be achieved through the optimization of existing lithium-ion battery technologies.

Against this backdrop, this research unfolds, adopting a user-centric perspective to investigate the implications of electric vehicle applications on the aging of energy storage systems. Furthermore, it explores strategies to maximize the potential of lithium-ion batteries, specifically by extending their lifespan. The central focus of this exploration centers on the concept of hybridizing energy sources. This approach leverages the strengths of two distinct technologies—one characterized by high specific energy and the other by significant power density—to enhance the performance of on-board energy storage systems with a particular emphasis on aging, weight, costs, and efficiency.

This study takes place within a broader context, emphasizing the imperative of the energy and ecological transition and the critical need to address the challenges of electric vehicle applications and energy storage. It contributes to the global pursuit of a cleaner and more sustainable energy future, offering insights into strategies for enhancing the longevity and efficiency of electric vehicle energy storage systems. Subsequent chapters will delve into the methodologies, findings, and implications of the dimensioning and energy management of a hybrid source for electric vehicles, shedding light on the path toward a more sustainable and efficient future for transportation.

Notably, the limitations of single-source energy storage are pivotal in this discussion. Monolithic energy storage solutions often fail to address the diverse demands and constraints of electric vehicle applications. These limitations encompass reduced energy density, restricted power output, and susceptibility to aging. The critical need to mitigate these limitations has driven innovation toward hybrid energy storage solutions that combine the strengths of multiple energy

storage technologies. These synergistic systems offer the prospect of enhancing energy density, power output, and overall system longevity. As such, this research serves as a beacon of hope and progress, striving to transcend the boundaries of current energy storage systems, ensuring a more sustainable and efficient electric vehicle future.

Hybridization of energy storage sources is emerging as an innovative solution to overcome challenges associated with resource limitations and constraints in the electrification of electric vehicles (EVs). By combining different energy storage technologies, such as lithium-ion batteries and supercapacitors, hybridization offers the opportunity to optimize the performance of energy storage systems. This approach not only increases energy density, thereby extending the range of EVs but also addresses instantaneous power requirements through the use of supercapacitors or high-power batteries. Furthermore, it helps mitigate issues related to rapid charging and discharging of batteries, thereby extending their lifespan. The hybridization of energy storage sources represents a promising step towards the continuous improvement of EV performance while addressing inherent constraints in their electrification. This contributes to a more sustainable and efficient transition to electric mobility.

Thesis outline

In this introduction, we have delved into the realm of energy and ecological transition, a matter of paramount importance in today's world. We have discussed the pressing need to reassess our actions in light of these global challenges. The focus has been on the central role of the transportation sector and the inevitable shift towards the electrification of vehicles.

From here, we will embark on our first stage: This chapter will serve as a vital starting point to comprehend the inputs and outputs of our research. We will explore the fundamentals of battery technology, the various energy storage sources, and the existing forms of hybridization.

The next stop on our journey will be Chapter 2. Here, we will delve into the science behind batteries. We will discuss the mathematical models used to understand their behavior, the characterization methods to assess their performance, and the aging studies to anticipate their

evolution over time.

After laying the conceptual groundwork, we will move on to Chapter 3. This chapter will address the practical aspect of our research. We will explore battery sizing methods, considering the specific needs of applications. We will also review conventional energy management methods and the innovative approaches we have developed to optimize battery utilization.

Our journey will then continue to Chapter 4. In this phase, we will transition from theory to practice. We will discuss the experiments conducted at ESTACA'Lab, the results obtained, and the insights gained from these trials that will inform our research approach.

Finally, in Chapter 5, we will analyze the impact of various energy management methods on the aging of the hybrid source. We will examine how these strategies influence the durability and performance of hybrid energy storage in the context of electric vehicles.

Publications lists

- **Degaa, L.**, Rizoug, N., Bendjedia, B., Saidane, A., & Larouci, C. (2019). Sizing improvement of hybrid storage system composed with high energy and high power Li-ion batteries for automotive applications. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, 233(7), 870-876.
- **Degaa, L.**, Bendjedia, B., Rizoug, N., & Abdelkader, S. (2017). Sizing of hybrid source battery/supercapacitor for automotive applications. In *2017 Conference Internationale des Energies Renouvelable, Proceeding of Engineering and Tecnology-PET (Vol. 28, pp. 17-22)*.
- **Degaa,L.**, Bendjedia, B., Rizoug, N., & Saidane, A. (2018, April). Energy secondary source technology effect on hybrid energy source sizing for automotive applications. In *2018 5th International Conference on Control, Decision and Information Technologies (CoDIT) (pp. 1040-1044)*. IEEE.
- **Degaa, L.**, Rizoug, N., Bendjedia, B., Saidane, A., Larouci, C., & Belaidi, A. (2019, April). Using of multi-physical models to evaluate the Influence of power management strategies

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CHAPTER 1

ENERGY STORAGE SYSTEM FOR ELECTRIC VEHICLES

1.1 Introduction

As we venture into the first chapter, we immerse ourselves in the dynamic Energy Storage Systems (ESS) field dedicated to electric vehicles. The landscape of electric transportation is rapidly evolving, demanding sophisticated solutions to enhance efficiency, range, and overall performance. This chapter serves as a panoramic exploration of the current state-of-the-art technologies and methodologies within the realm of ESS.

Our journey begins with an in-depth review of cutting-edge energy storage technologies, including but not limited to lithium-ion batteries, supercapacitors, and emerging innovations. We analyze their respective strengths, limitations, and the unique challenges posed by the electrification of transportation. Delving into recent research and advancements, we aim to uncover the pivotal role played by ESS in shaping the future of electric mobility.

Moreover, this chapter sheds light on the intricacies of integrating energy storage systems into electric vehicles, addressing key considerations such as weight, size, and scalability. By gaining insights into the current landscape, we lay the groundwork for subsequent discussions on the sizing and energy management of hybrid sources. Join us in unravelling the multifaceted world of ESS, where innovation and exploration converge to drive the future of sustainable transportation.

1.2 Hybrid Electric Vehicles

A Hybrid Electric Vehicle is a vehicle that has a primary energy source (usually "fuel") and a reversible energy storage system in another form, such as pneumatic, hydraulic, inertial, or electrical energy of a battery. This hybrid vehicle technology (see Figure 1.1) offers many advantages over the conventional vehicle while maintaining the autonomy offered by conventional fuel: lower fuel consumption and, therefore, emissions of greenhouse gases and other air pollutants, decreased noise in town. An internal combustion engine powers hybrid electric vehicles, and an electric motor uses energy stored in batteries [6]. A hybrid electric vehicle cannot be plugged in to charge the Battery. Instead, the Battery is charged through regenerative braking and the

internal combustion engine. The electric motor's extra power can potentially allow for a smaller engine. The Battery can also power auxiliary loads like sound systems and headlights, reducing engine idling when stopped. Together, these features result in better fuel economy without sacrificing performance. Hybrid vehicles can be classified according to architecture and level of hybridization. Classification according to the architecture.[7].

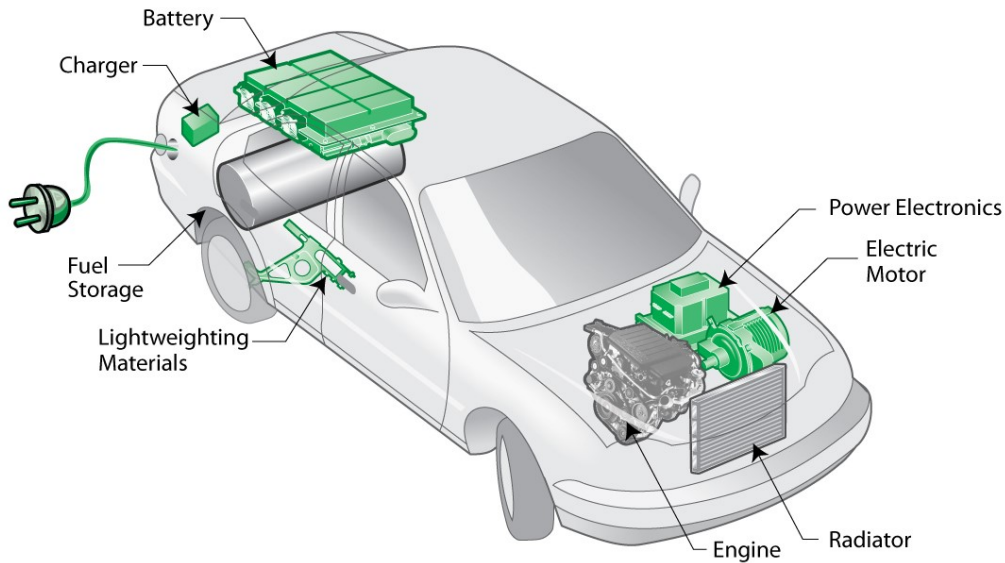


Figure 1.1: Hybrid electric vehicle.

1.2.1 Main Components of a Hybrid Electric Car

- **Battery (auxiliary):** In an electric drive vehicle, the auxiliary Battery provides electricity to start the car before the traction battery is engaged and powers vehicle accessories.
- **DC/DC converter:** This device converts higher-voltage DC power from the traction battery pack to the lower-voltage DC power needed to run vehicle accessories and recharge the auxiliary Battery.
- **Electric generator:** Generates electricity from the rotating wheels while braking, transferring that energy back to the traction battery pack. Some vehicles use motor generators that perform both the drive and regeneration functions. [8]

- **Electric traction motor:** Using power from the traction battery pack, this motor drives the vehicle's wheels. Some vehicles use motor generators that perform both the drive and regeneration functions[9].
- **Exhaust system:** The exhaust system channels the exhaust gases from the engine through the tailpipe. A three-way catalyst is designed to reduce engine-out emissions within the exhaust system.
- **Fuel filler:** A nozzle from a high-pressure hydrogen dispenser attaches to the receptacle on the vehicle to fill the tank.
- **Fuel tank (gasoline):** The engine needs this tank to store gasoline on board the vehicle until it.
- **Internal combustion engine (spark-ignited):** In this configuration, fuel is injected into either the intake manifold or the combustion chamber, which combines with air, and the spark from a spark plug ignites the air/fuel mixture.
- **Power electronics controller:** This unit manages the flow of electrical energy delivered by the traction battery, controlling the speed of the electric traction motor and its torque.
- **Thermal system (cooling):** This system maintains a proper operating temperature range of the engine, electric motor, power electronics, and other components. Traction battery pack: Stores electricity for use by the electric traction motor.
- **Transmission:** The transmission transfers mechanical power from the engine and/or electric traction motor to drive the wheels[10].

1.2.2 Classification of hybrid vehicles according to the nature of the junction point between ICE and electric motor

In this section, we are interested in classifying hybrid vehicles according to the nature of the junction point between the electric and thermal traction chains. Three types of hybrid vehicles

can be distinguished: series, parallel, and parallel series [11].

Hybrid series

The so-called "series" hybrid comes from the fact that the heat engine is directly linked in series with the electric motor[12]. Propulsion power is provided solely by the latter. The heat engine is used for low speeds to power the electric motor through an electric generator and/or recharge the batteries. The engine usually provides medium power, as the batteries provide power peaks. All electricity is used in the city. On the other hand, on the way, the heat engine ensures the recharging of the Battery as well as the power supply of the electric motor [13]. The general architecture of serial hybrid technology is given in. Figure1.2 [14].

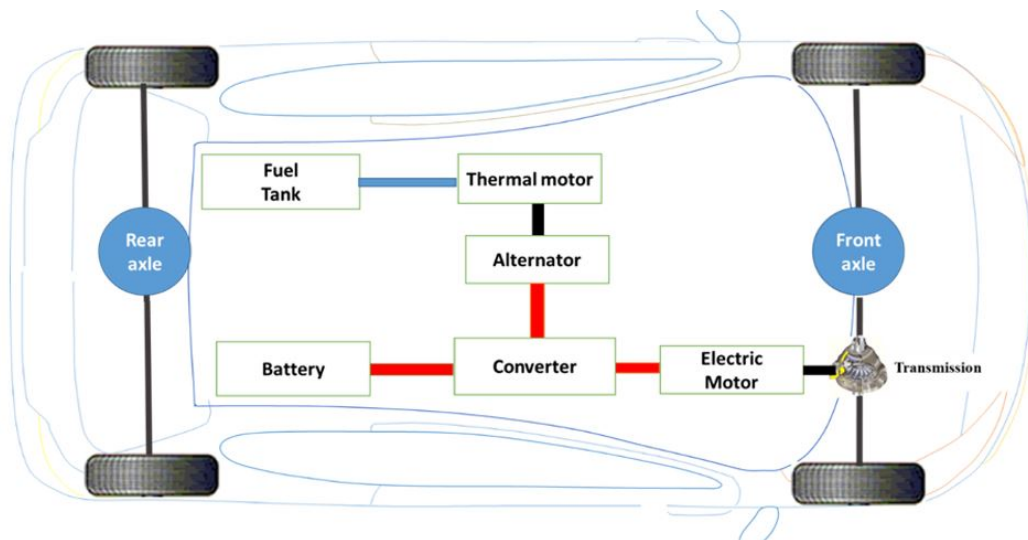


Figure 1.2: Hybrid series architecture.

Hybrid parallel

This architecture connects the two electric and thermal motors to the transmission (mechanical joint). The engine mainly moves the vehicle (mechanical transmission, clutch, gearbox)[15]. Otherwise, the electric motor that uses the battery energy allows operation in boost mode thanks to its high torque, available immediately to avoid situations where the engine is inefficient (starts, resumption) [16]. The general architecture of parallel hybrid technology is shown schematically in Figure1.3.

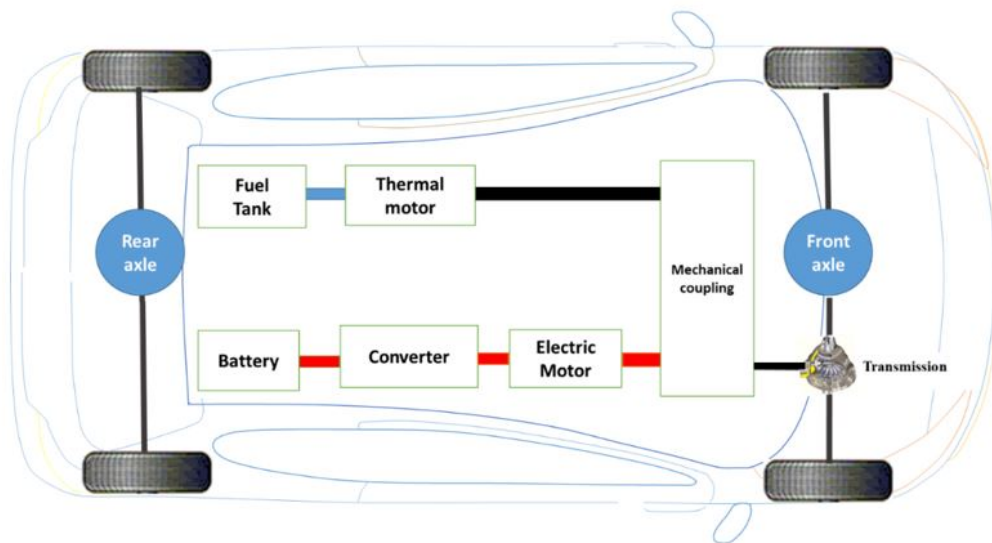


Figure 1.3: Hybrid parallel architecture.

Hybrid parallel series

Car manufacturers quickly realized the utility of merging the two configurations into a so-called hybrid series/parallel architecture to combine the advantages of the structures. This type of vehicle consists of a heat engine, two electrical machines, and a battery. The engine, electric machine can propel the vehicle, or both to obtain the best possible performance depending on the pipes (city, road ...) [17]. The first machine (a few kW) and the second (a few tens of kW) realize, respectively, the addition of speed and torque. This architecture also carries the name of hybrid power bypass because the mechanical energy is taken at a place of the chain of traction (eg, of the engine) and re-injected at another place of the chain (ex: the engine electric) [18]. The power bypass is achieved via a planetary gear used in the TOYOTA Prius. This concept is known as the Power Split Device [19]. This component makes a coupling between the heat engine, the electric motor, and the generator, as shown in Figure 1.4.

Hybrid complex

Hybrid complex (mechanical and electrical coupling) has an architecture similar to the series-parallel, but the difference is in the electrical coupling with the battery [20]. The general architecture of hybrid complex technology is shown schematically in Figure 1.5

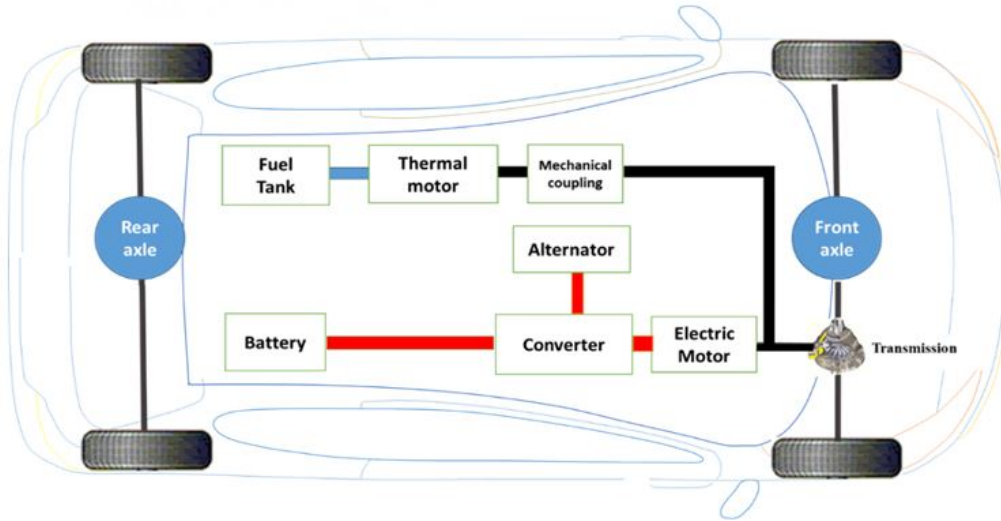


Figure 1.4: Hybrid Parallel series architecture.

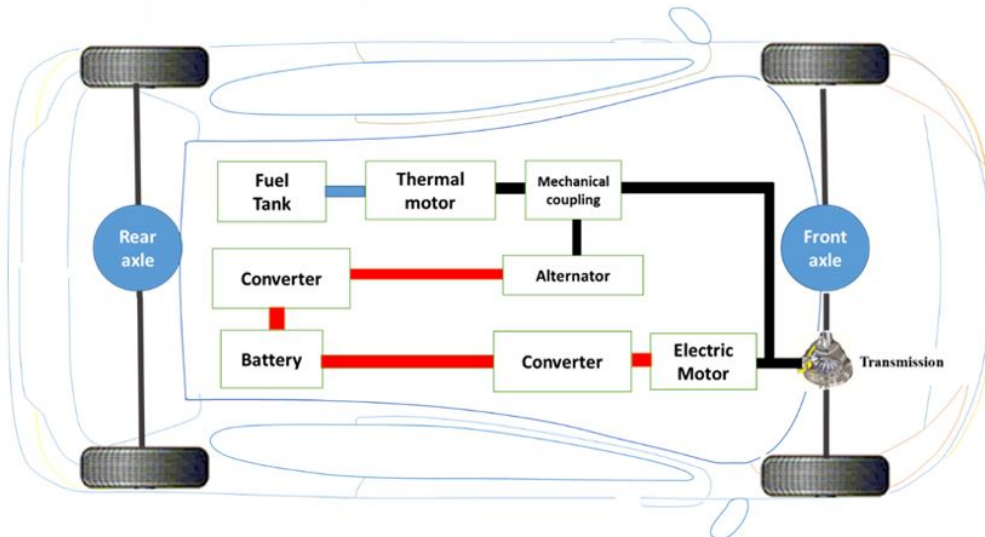


Figure 1.5: Hybrid Parallel series architecture.

1.2.3 Classification according to the level of hybridization

There are several types of hybrid vehicles, and according to the level of hybridization in the traction chain, we can classify them as:

Micro hybrid

In these vehicles, the electrical system that manages the so-called "Stop & Start" functionality (less than $10kW$) ensures the automatic start-up and shutdown of the engine during the shut-

down phases. Braking energy recovery is limited in this type of vehicle. This solution has the advantage of the economy of consumption in city mode (stop at the red light, congestion) of the order of 10% in urban use [21]. Several vehicles, such as the PSA C3, Renault Capture, and others, are equipped with this feature [22].

Mild hybrid

This category has a Stop & Start system with an electric power motor generally from 10 to 20kW. This allows, in addition to the functions provided by the reversible alternator in the "micro-hybrid", to recover energy during braking and to assist the engine by providing additional torque during the driving phases, such as acceleration and the ascent of a slope, also called Boost mode [23]. For example, Honda Insight fits this category with a parallel architecture. Insight's gain in power consumption can reach 20% and have autonomy in purely electric mode of 12.5 km [24].

Full hybrid

These vehicles are equipped with two thermal and electric engines. Their powers are of the same order of magnitude, and the electric mode called "Zero Emission" is more extensive than in the Mild hybrid version. The latest generation of Toyota Prius is equipped with a "Hybrid Synergy Drive" system and a 60kW electric motor. The result is a pollution reduction, which went from 120g/km of CO₂ for the first-generation Prius to 89g/km for the 2009 Prius model [25]. However, the major disadvantage of this category is the management of energy flows, which is more complex because recharging the Battery requires an additional electrical machine [26, 15].

Plug In hybrid

This category is known by the acronym *PHEV*, "Plug-in Hybrid Electric Vehicle", and is simply a hybrid vehicle with a high-capacity battery that can be recharged by connecting the vehicle to the power grid. *PHEV* achieves the performance of full hybrid and electric vehicles. It can maintain the battery's state of charge around an average value of 50 to 60%, it is the mode "Charge

Sustaining”, and drives $60km$ in all-electric mode [27]. From an ecological point of view, a study by *ACEEE* (American Council for an Energy-Efficient Economy) predicts that, on average, a typical American driver achieves a reduction of about 15% in net CO₂ emissions compared to conventional hybrids [28]. Different classes of hybrid vehicles are classified according to the architecture or the hybridization rate [29].

1.3 Electric Vehicles

1.3.1 Electric Vehicles History

An electric vehicle (*EV*), also referred to as an electric drive vehicle, is a vehicle that uses one or more electric motors for propulsion. Depending on the type of vehicle, motion may be provided by wheels or propellers driven by rotary motors or in the case of tracked vehicles, by linear motors. Electric vehicles include electric cars, trains, lorries, airplanes, boats, electric motorcycles and scooters, and electric spacecraft[30]. Electric vehicles first came into existence in the mid-19th century, when electricity was among the preferred methods for automobile propulsion, providing comfort and ease of operation that could not be achieved by the gasoline cars of the time [31].

Despite their relatively slow speed, electric vehicles had several advantages over their early-1900s competitors. They did not have the vibration, smell, and noise associated with gasoline cars. Changing gears on gasoline cars was the most difficult driving part, and electric vehicles did not require shifting gears. Electric cars found popularity among well-heeled customers who used them as city cars, where their limited range proved to be even less of a disadvantage. Electric cars were also preferred because they did not require a manual effort to start, as did gasoline cars, which required a hand crank to start the engine[32]. Due to this ease of operation, electric cars were often marketed as suitable vehicles for women drivers. Within decades, however, the internal combustion engine (ICE) had completely replaced the electric drive as a propulsion method for automobiles, but electric power has remained commonplace in other vehicle types, such as trains and smaller vehicles of all types [33].

Several factors contributed to the demise of the electric automobile early in the twentieth century[34]. First, there was a growing acceptance of the gas-powered car. In 1908, Henry Ford's Model T first appeared on the roads and sold over ten thousand in that model year alone. Previously, cars had been a luxury for the wealthy, but Ford applied assembly line production in 1913 and sold more than 308,000 Model Ts the following year. Charles Kettering invented the electric automobile starter in 1912, eliminating the inconvenience and danger of the unwieldy hand crank starter, which had been needed in gas engine cars [35].

Another problem for electric vehicles relative to gas-powered cars was that electricity was not as obtainable within America's infrastructure as gasoline had become. At the turn of the century, urban areas began using more electricity for appliances like street lamps; however, only the wealthy had it installed throughout their homes. In the more rural areas, electricity was virtually non-existent, keeping electric car drivers close to home. Large cities like New York created "swapping stations" for batteries, popular for around 1910, to accommodate distance travel. Still, electric vehicles' "sphere of usefulness" was within the city, while gas vehicles could go between cities. Gas vehicles, therefore, could easily infringe on the EV's sphere, but not the other way around.

At the turn of the century, 40% of American automobiles were powered by steam, 38% by electricity, and 22% by gasoline. In the United States, 33,842 electric cars were registered, making America the country where electric cars had gained the most acceptance. Sales of electric cars peaked in 1912.

Eventually, the expense of running an electric vehicle vs a gas-powered car became a decisive blow to the EV. Henry Ford's gas-powered cars had a relatively low cost compared to EVs. Recharging lead-acid batteries cost roughly 20 cents per kWh (about 2.07 today), compared with filling up with five cents a gallon of gas back then. The first filling station cropped up in St. Louis in 1905. Standard Oil of California (now Chevron) built its first in 1907 in Seattle. By 1920, gas stations made their way across the United States, and fuelling up a car became as easy as buying a loaf of bread. Switching to the internal combustion engine was a no-brainer[34].

All-electric vehicles (EVs) have an electric motor instead of an internal combustion engine. The vehicle uses a large traction battery pack to power the electric motor and must be plugged into a charging station or wall outlet to charge. Because it runs on electricity, the vehicle emits no exhaust from a tailpipe and does not contain the typical liquid fuel components, such as a fuel pump, fuel line, or fuel tank (see Figure 1.6).

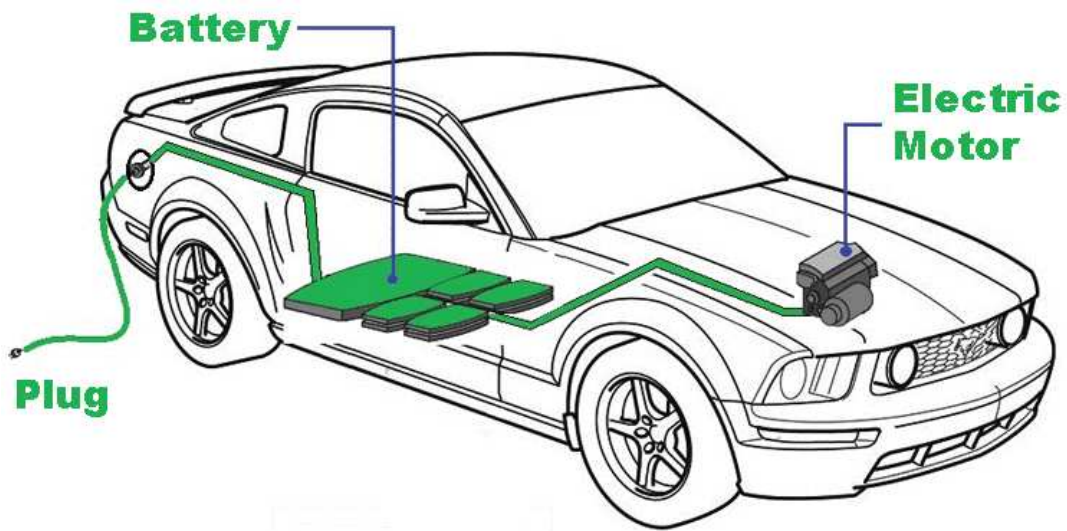


Figure 1.6: All-Electric Cars.

1.3.2 Main Components of an All-Electric Car

- **Battery (all-electric auxiliary):** The auxiliary Battery provides electricity to power vehicle accessories in an electric drive vehicle.
- **Charge port:** The charge port allows the vehicle to connect to an external power supply in order to charge the traction battery pack. (classic charge + fast charge)
- **DC/DC converter:** This device converts higher-voltage DC power from the traction battery pack to the lower-voltage DC power needed to run vehicle accessories and recharge the auxiliary Battery.

- **Electric traction motor:** Using power from the traction battery pack, this motor drives the vehicle's wheels. Some vehicles use motor generators that perform both the drive and regeneration functions.

The question is where in a car the electric motor is located. Most electric vehicles have a central motor in the front, permanently connected to the drive axle. The design is similar to combustion engine cars. However, it is also conceivable that future *4WD* vehicles might have one motor on the front and rear axle, each controlled individually, depending on the situation. Another much-discussed variation is the hub drive. Four (smaller) motors are installed directly behind the wheels in a hub drive. This solution is relatively lightweight because the cars don't need a power train with a gearbox and drive shafts. On the downside, this increases the overall mass of a vehicle: The wheels become rather heavy, which results in performance loss if the road isn't perfectly level [36].

The question of engines will only play a small role in the rate at which entirely electric or plug-in hybrid vehicles become established in the market. In general, electric motors have a simpler design than comparable combustion engines, making them more cost-effective to maintain. One of the main drawbacks, however, of the current electric vehicles is their large price tag, which is primarily caused by power storage requirements [37].

- **Onboard charger:** Takes the incoming AC electricity supplied via the charge port and converts it to DC power for charging the traction battery. It monitors battery characteristics such as voltage, current, temperature, and state of charge while charging the pack.
- **Power electronics controller:** This unit manages the flow of electrical energy delivered by the traction battery, controlling the speed of the electric traction motor and the torque it produces.
- **Thermal system (cooling):** This system maintains a proper operating temperature range of the engine, electric motor, power electronics, and other components.

The limited range of electric vehicles is additionally reduced through the thermal conditioning of the passenger compartment. Due to the vehicle mass' high thermal storage

capacity, the energy necessary for heating up and cooling the passenger compartment is comparatively high[38].

- **Traction battery pack:** Stores electricity for use by the electric traction motor. An electric vehicle battery is often composed of many hundreds of small, individual cells arranged in a series/parallel configuration to achieve the desired voltage and capacity in the final pack. A common pack is composed of blocks of 18-30 parallel cells in series to achieve a desired voltage. For example, a 400V nominal pack will often have around 96 series blocks (as in the Tesla Model 3).

Common nominal pack voltages in current vehicles range from 100V – 200V for hybrid/plug-in hybrid vehicles and 400V to 800V and higher for electric-only vehicles. The reason for this is higher voltages allow more power to be transferred with less loss over the same diameter (and mass) of copper cable [39].

- **transmission (electric):** The transmission transfers mechanical power from the electric traction motor to drive the wheels.

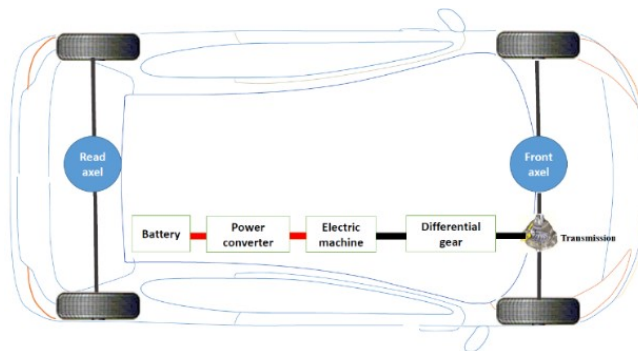
The electrification of road-going vehicles is gathering momentum like nothing the automotive industry has seen for a while. Which electric vehicle transmission to use is one of the questions automotive designers are grappling with as they rush to develop new electric cars to meet demand. As the company that supplied electric vehicle transmission solution to the Formula E race series at the start of the decade, it is no surprise we are also leading the charge to put electric cars on the road. Hewland supplied the full grid in the inaugural season of Formula E and is still a significant supplier in this series.

Outside of motorsport, Hewland has worked on a variety of Electric and Hybrid projects ranging from 3.5T commercial vehicles to niche volume EV supercars to working with the team that holds the electric land speed record, to name a few. Hewland has off-the-shelf high-performance EV transmissions, or our in-house design office can develop a new EV transmission to meet your requirements using the latest race-proven modelling software, ensuring optimal performance, weight, and packaging efficiency. Hewland's designers work closely with our customers to de-

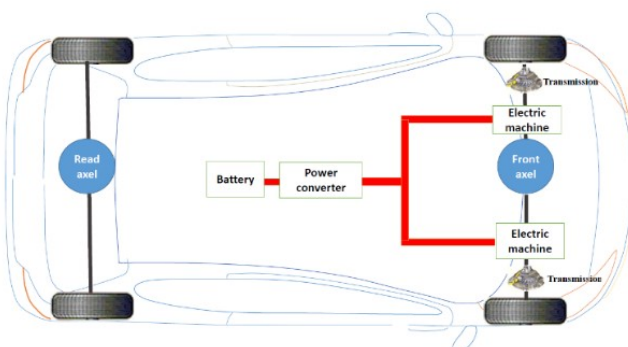
fine the best powertrain architecture, understanding the customer's end requirements, such as range, acceleration, or top speed.

1.3.3 Battery electric vehicles, BEVs

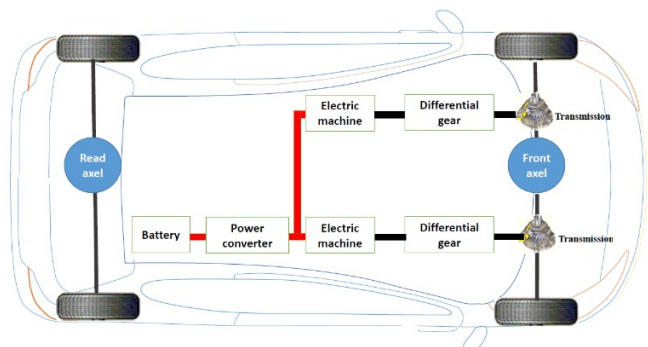
We leave the field of HEVs by switching to all-electric vehicles, also known as the rechargeable Battery or Battery Electric Vehicles (BEV). Unlike the hybrid vehicles, this type of vehicle has only an electric drive train, and its autonomy is directly proportional to the capacity of its rechargeable Battery. For environmental impact, these vehicles do not contain exhaust systems, which means that they do not generate emissions (zero emissions) like other vehicles. In literature, many all-electric vehicles classifications are proposed. According to the location of the electric machine in its transmissions, we can cite (figure 1.7) [40].



(a) Central drive



(b) Wheel-hub drive



(c) Wheel-hub drive derivatives

Figure 1.7: Classifications of BEVs according to the location of the electric machine

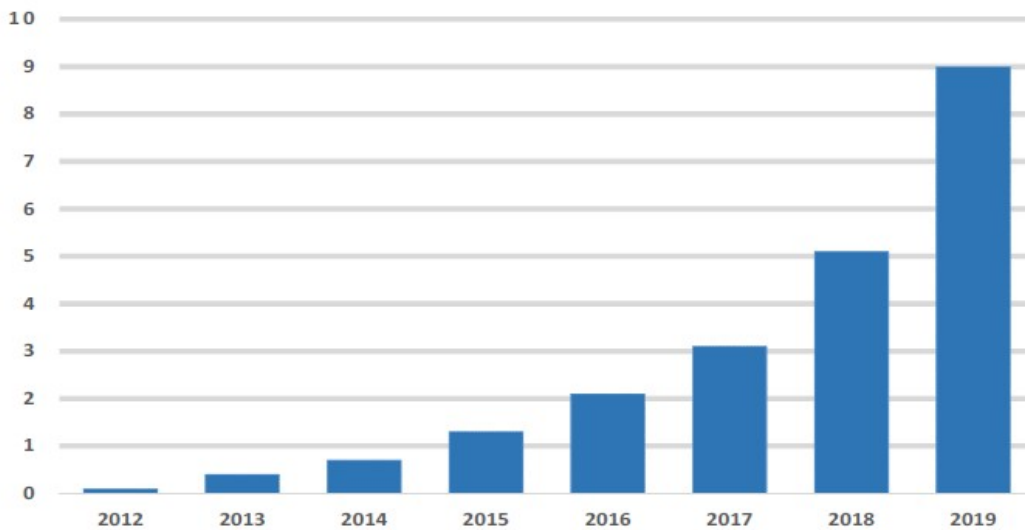


Figure 1.8: Number of electric vehicles in circulation worldwide between 2012 and 2019 in millions .

1.3.4 Current state and future potential of the electric vehicles

The market of electric vehicles may still be considered a niche market, but electric vehicles develop very dynamically around the world. As the graphic in Figure 1.8 illustrates, the growth rate of the electric vehicle market for the past *6 years* has been particularly dynamic. The fleet, i.e., the number of electric vehicles on the road, increased from approximately 100,000 vehicles in 2012 as the first vehicles of the current generation date from 2010-2011, which means that it became quite rapidly dynamic to over 9 million vehicles in circulation around the world today [41]. In 2012, the main market was primarily in Japan. It is indeed there that the first electric cars were launched, notably the Mitsubishi i-MiEV and the Nissan LEAF. In addition, the United States that were very dynamic, with California as a driving force, and Europe had a slow start but was still the third market, notably with France [42]. Today, we see that the growth was significant, but the players in this growth have changed, with one notable game changer: China. China has actively engaged in the electric vehicle market. Last year, 2019, they registered over 500,000 electric vehicles, a significant figure for a total market of 9,100,000 units. It must be understood that half of the global fleet is in China. The United States and Europe remain dynamic, with a good level of growth; however, Japan is in a slight decline compared to previous years. Europe has four main markets: the United Kingdom, Germany, Norway and France. These countries constitute

the vast majority of the electric vehicle market in Europe and are those of the European countries that, more or less long ago, put in place public policies to support large electric vehicles. The two main markets are Norway and France, as these are the countries where investment policies in electric vehicles are far ahead of those of other countries, the most important European fleet being France[38]. But also Germany, where it started a little later than in France but where the motivation is strong, the manufacturers and the State have made strong commitments, and the market is taking off. In the case of the United Kingdom, an ambitious investment policy in electric vehicles was implemented, particularly by the public authorities, and the effects were very strong in 2021, as shown in Figure 1.9 [43].

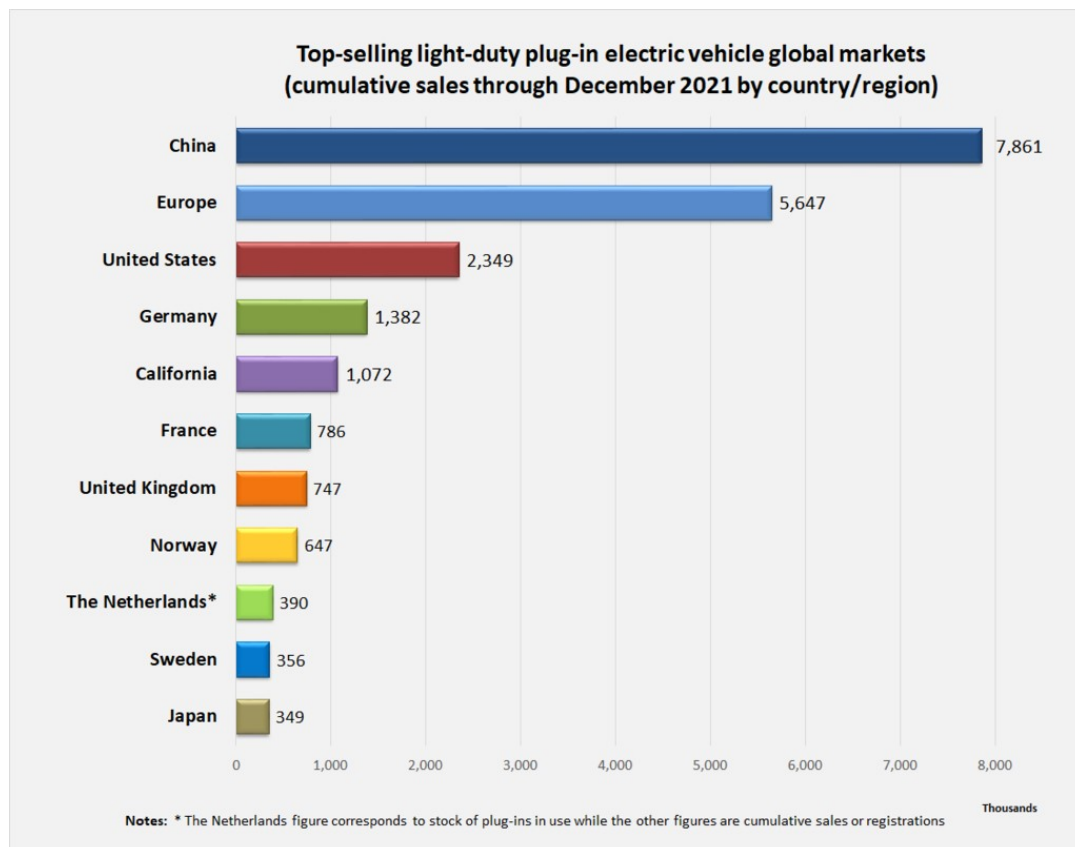


Figure 1.9: Electric vehicles matriculation by country in 2021.

To conclude, the statistics we have made show that the dynamics of electric cars still rely on a small number of countries worldwide. China and the United States are in the lead regarding fleet and annual sales. European countries are catching up, and several of these countries have nice dynamics in terms of market shares. Apart from this small number of countries that have

rather clear dynamics favouring electric cars on a global scale, several countries seem to have non-consolidated dynamics, especially those where electric cars have not yet been over the 1% threshold of annual private car sales. Electric cars are still relatively absent from some major markets, India in particular. Generally speaking, except for China, a major emerging country, electric private cars have not yet found specific outlets in developing countries.

1.4 Electrical energy storage systems

Energy storage systems installed outdoors must be capable of operating over a wide range of temperatures. Vehicle traction imposes the most serious challenge for high-power operation at low temperatures as well as operation at elevated temperatures caused by high external temperatures or by high-power operation. Stationary systems allow an easier control of operating temperatures. Electrochemical storage systems are particularly sensitive to temperature because the kinetics of chemical reactions change typically by a factor of two when changing the temperature by 10 K. In this case, low temperatures lead to limited power capabilities, whereas high temperatures limit charge retention and favor degradation mechanisms. Batteries have widely been adopted in ground vehicles due to their high energy density, compact size, and reliability characteristics.

1.4.1 Lithium-Ion Batteries

The lithium-ion Battery has proven excellent performance in portable electronics and medical devices [44]. The lithium-ion Battery has high energy density, has good high-temperature performance, and is recyclable. The positive electrode is made of an oxidized cobalt material, and the negative electrode is made of a carbon material. The lithium salt in an organic solvent is used as the electrolyte. The promising aspects of the Li-ion batteries include low memory effect, high specific power of $300W/kg$, high specific energy of $100Wh/kg$, and long battery life of 1000 cycles [45]. These excellent characteristics give the lithium-ion Battery a high possibility of replacing NiMH as next-generation batteries for vehicles. NiMH batteries were priced at about $1500/kWh$

in 2007. Since the price of nickel is increasing, the potential cost reduction of NiMH batteries is not promising. Li-ion batteries have twice the energy density of NiMH batteries, which are priced at 750 to 1000/ kWh [46].

1.4.2 Li-ion technologies, types

There are many lithium battery technologies, the most used being LCO, LMO, NMC, NCA, LFP, and LTO. The negative electrode is carbon for Li-ion batteries, except for LTO technology which uses titanate. Li-ion technologies mainly differ by the chemical composition of the positive electrode material.

LCO technology was the first to appear with a lamellar cobalt oxide positive electrode. Its performance is much better than non-Li-ion batteries. However, cobalt is highly reactive and above a temperature threshold, it releases oxygen, making the Battery unsafe. Similarly, the charge current is limited to avoid deterioration or overheating of the cell. Finally, the high cost of cobalt makes it a solution that is less and less used in favor of new technologies. LCO technology characteristics are summarized in the spider chart of Figure 1.10-(a).

LMO technology also has a spinel oxide positive electrode, manganese oxide. It is a much cheaper material compared to LCO, but in return has lower mass-energy, a very short calendar life, and a limited number of cycles. The main advantage of the spinel structure is the easier insertion of lithium ions which allows higher charge and discharge currents (“performance”). LMO technology characteristics are summarized in the spider chart of Figure 1.10-(b).

NMC technology has a positive electrode made of nickel, manganese, and cobalt oxide, whose proportions of each element can vary depending on the desired cell characteristics. It is one of the most used technologies, along with NCA, presented below. Compromises are made in the percentages of each element to guarantee best the objectives of mass and volumetric density, safety, cost, calendar life and number of cycles to perform. This technology benefits from increasing maturity driven by mass usage in the mobile device market. NMC technology characteristics are summarized in the spider chart of Figure 1.10-(c).

NCA technology[47] is equivalent to NMC technology, where the aluminum component re-

places manganese at the positive electrode. The compromise chosen in the proportion of these three chemical elements also provides variable performance depending on the percentages chosen. Nickel, cobalt, and aluminum oxide are highly reactive and allow for better energy density (mass and volumetric) and longer calendar life, to the detriment of slightly lower safety and slightly shorter cycle life at 100% DOD, compared to NMC technology. NCA technology characteristics are summarized in the spider chart of Figure 1.10-(d)

LFP technology has an iron phosphate positive electrode, which is a very stable material and thus provides very good safety in use. Its performance is slighter than NMC or NCA oxides but retains a very good number of cycles. Unlike other technologies, LFP technology exhibits a voltage plateau at 3.3V during use in the 10 to 90% SOC range, facilitating energy management by power electronics. This technology should be cheaper than NMC and NCA but has equivalent costs due to lower production volumes. LFP technology characteristics are summarized in the spider chart of Figure 1.10-(e).

LTO technology is one of the few Li-ion technologies that does not use a carbon-negative electrode but titanate, very often associated with an iron phosphate (LFP) positive electrode. Titanate allows much faster lithium ion insertion and charge currents, approximately four to ten times higher than carbon electrodes. The stability of titanate also allows the Battery to be used over a wider temperature range, from -30°C to +50°C compared to a range of 0°C to +40°C for a carbon-negative electrode. However, with the same positive electrode chemical composition, LTO has half the energy density. In addition, LTO technology is much more expensive. It can be suitable for buses or marine applications but less for light vehicles. LTO technology characteristics are summarized in the spider chart of Figure 1.10-(f).

New battery technologies are currently under development: Lithium-sulfur, Sodium, or Lithium-Air batteries have promising characteristics. Solid electrolyte technologies are also under study and prove very promising, both in terms of safety with solid components that would be much more stable than liquid electrolytes and in terms of energy density that is theoretically much higher. However, it appears that these technologies still require considerable development time before being usable. The different battery technologies are shown according to their specific

energy and power in Figure 1.10. The technologies detailed above are summarized in the spider charts of Figure I-8. For the cost scale, a high value corresponds to an attractive cost. Thus for all the characteristics expressed, a high value favors the technology. Therefore, The technology with the largest area is the most interesting.

Lithium-ion battery cells are usually classified into 3 types (Figure 1.10 [48]): High energy (HE) cells are characterized by high energy densities but lower charge and discharge currents (around 1C). High power (HP) cells are characterized by lower energy densities than HE cells but with high permissible charge and discharge currents.

Finally, ultra-high power density (UHP) cells are cells with low energy densities, very high permissible charge, and discharge currents but which have a much shorter life than HE and HP.

Cells are assembled into modules, in series on the one hand, to obtain the desired nominal voltage, and in parallel, on the other hand, to obtain the nominal energy and current. All the modules form the final Battery. In the field of traction batteries for electric vehicles, the cells used are usually HE or HP-type cells in order to have a decent energy density and service life.

1.4.3 Ultracapacitors

The UC stores energy by physically separating positive and negative charges. The charges are stored on two parallel plates divided by an insulator. Since there are no chemical variations on the electrodes, UCs have a long cycle life but low energy density. Figure 1.11 shows the structure of an individual UC cell [49]. The applied potential on the positive electrode attracts the negative ions in the electrolyte, whereas the potential on the negative electrode attracts positive ions. The power density of the UC is considerably higher than that of the Battery; this is due to the fact that the charges are physically stored on the electrodes. Low internal resistance gives UC high efficiency but can result in a large burst of output currents if the UC is charged at a very low SOC [50].

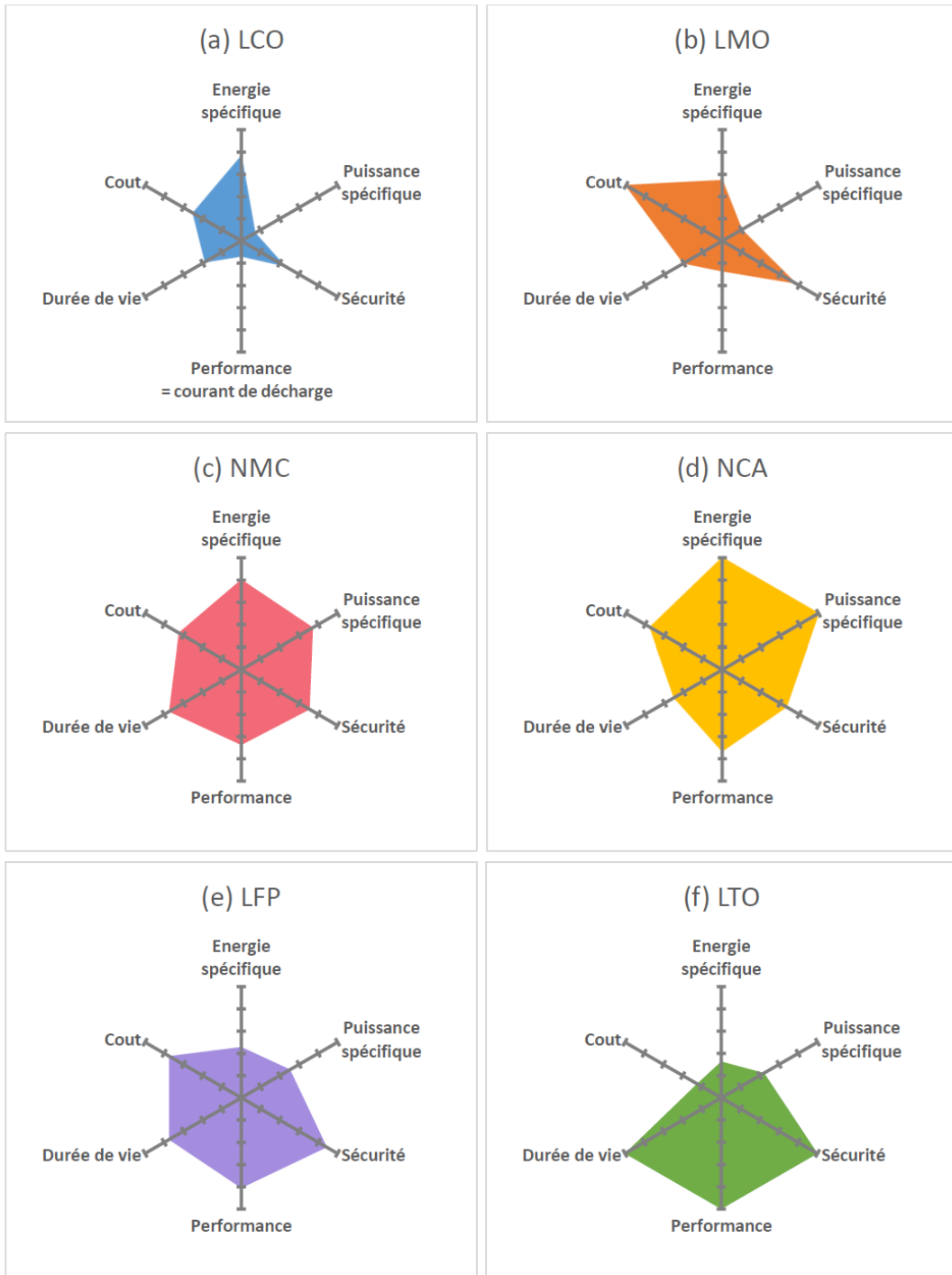


Figure 1.10: Li-ion battery technologies

1.4.4 Fuel Cells

The FC generates electricity from the fuel on the anode and the oxidant on the cathode and reacts in the electrolyte. During the generation process, the reactants flow into the cell, Figure

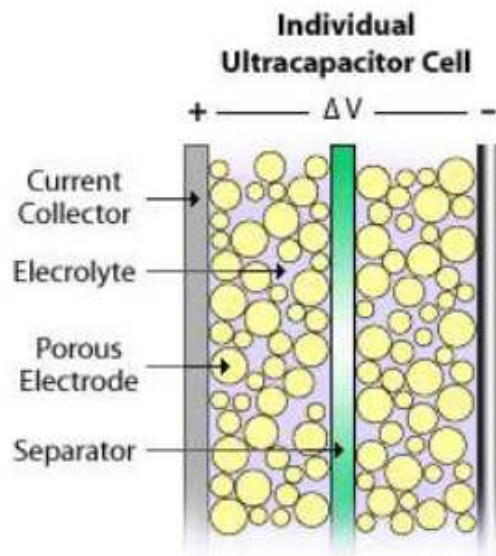


Figure 1.11: Internal Cell Construction.

2.8c Configuration of a hydrogen FC. Whereas the products of the reaction flow out. The FC is able to generate electricity as long as the reactant flows are maintained. Advantages of the FC include high conversion efficiency of fuel to electrical energy, quiet operation, zero or very low emission, waste heat recoverability, fuel flexibility, durability, and reliability.

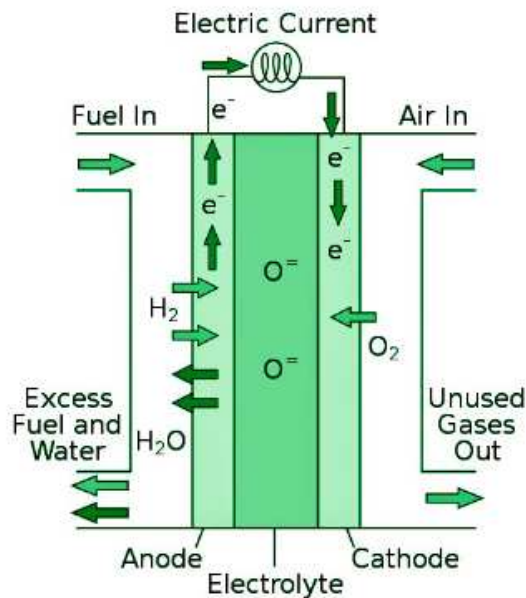


Figure 1.12: Fuel Cell Construction

1.5 Principle of hybridization of energy sources

In a HESS, typically, one storage (ES1) is dedicated to cover “high power” demand, transients, and fast load fluctuations and, therefore, is characterized by a fast response time, high efficiency, and high cycle lifetime. The other storage (ES2) will be the “high energy” storage with a low self-discharge rate and lower energy-specific installation costs (see Figure 1.13 [51]). The main advantages of a HESS are:

- Reduction of total investment costs compared to a single storage system (due to a decoupling of energy and power, ES2 only has to cover average power demand).
- Increase of total system efficiency (due to the operation of ES2 at optimized, high-efficiency operating points and reduction of dynamic losses of ES2).
- Increase of storage and system lifetime (optimized operation and reduction of dynamic stress of ES2) [52].

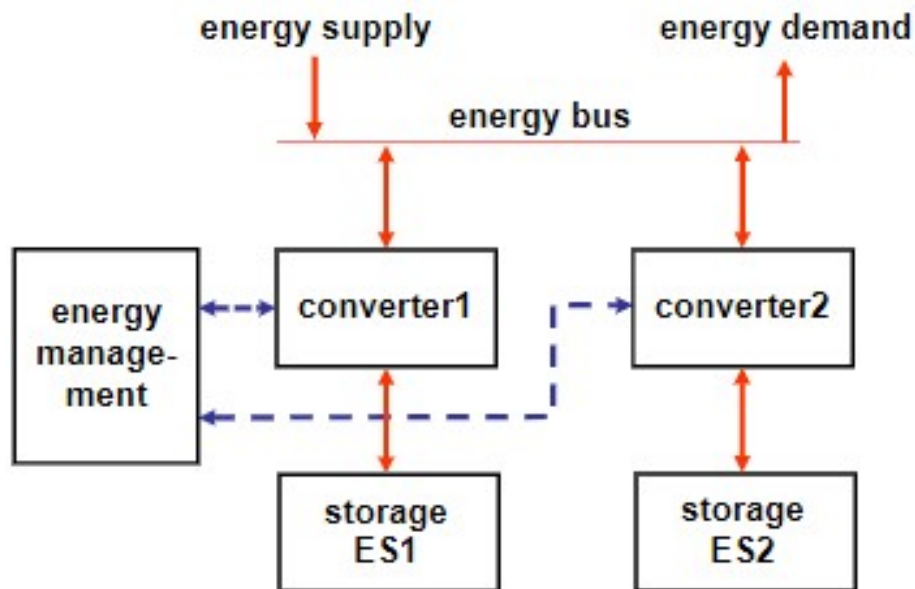


Figure 1.13: Basic structure of a HESS.

We have many types of Hybrid Energy Storage System:

- HESS in hybrid and fuel cell powered electric vehicles (supercap/battery-HESS [53], or battery/fuel cell-HESS).
- HESS-applications in renewable autonomous energy supply systems mainly based on a battery/hydrogen-combination [54].
- Grid-connected HESS on a household, district or regional level (e.g. lithium-ion/redox-flow battery application for the island Pellworm).
- HESS for large-scale wind- and PV-park power management.
- Other specific HESS-configurations, e.g. SMES/battery-HESS, CAES/battery-HESS and flywheel/battery-HESS [55] .

Batteries, particularly lithium-ion batteries, are key in many HESS applications. They can be utilized as the “high energy” and the “high power” storage. Supercaps and flywheels are characterized by even higher power densities, efficiencies and cycle lifetimes than batteries. Redox-flow batteries are a promising technology due to their storage immanent decoupling of power and stored energy (similar to the hydrogen and power-to-gas storage path) and due to their good cycle lifetime and recycling capability. Renewable hydrogen (H₂) and methane (CH₄) are promising long-term energy storage options. Also, heat storage and power-to-heat concepts will be important in future HESS applications. The storage of heat produced from excessive renewable energy (via electric heating cartridges or heat pumps) and from power-to-gas conversion processes (e.g. electrolyzer or fuel cell) will increase the overall utilization rate of renewable energies. Moreover, power-to-heat will enable HESS to perform peak shaving and significantly reduce the stress for the other storage components and the public grid. Optimizing design, control and energy management strategies for HESS at the interface between the electricity, heat and gas sectors will play an important role and will unfold significant potentials for further improvements in cost, efficiency and lifetime of renewable energy systems [56].

1.5.1 Hybrid storage systems

Hybrid energy storage systems represent a significant advancement in managing and optimizing energy resources. These systems combine different storage technologies to maximize efficiency, reliability, and versatility, addressing the complex needs of modern applications. Here are key aspects of hybrid energy storage systems:

High-Efficiency (HE) with High-Power (HP):

This configuration Table 1.1 involves intricate optimization. The High-Efficiency (HE) storage component, often utilizing advanced chemistries like lithium-ion with high energy density, focuses on [57]efficiently storing substantial energy over extended periods[58]. This is crucial for applications with steady-state power demands, like grid energy storage. On the other hand, the High-Power (HP) element, which may employ technologies such as ultracapacitors or high-power lithium-ion cells, specializes in providing bursts of energy rapidly[59]. This is particularly beneficial in applications where sudden, high-power demands occur intermittently, such as in electric vehicles during rapid acceleration or in certain industrial processes[60].

High-Efficiency (HE) with Ultracapacitors(UC)[61]:

This combination involves meticulous consideration of energy dynamics[62]. High-Efficiency (HE) storage ensures optimal energy utilization over extended periods, often leveraging advanced battery technologies [63]. The Ultracapacitors (UC), with their high-power density and rapid charge/discharge capabilities, complement this by handling instantaneous power demands and responding swiftly to variations in load requirements[64]. This hybrid configuration is ideal for applications where both sustained energy supply and rapid response to dynamic power demands are critical, as seen in certain types of electric vehicles and grid stabilization systems [65].

Fuel Cell with Battery and Ultracapacitors (UC)[66]:

Integrating a fuel cell with a battery and Ultracapacitors (UC) requires intricate system orchestration. The fuel cell, functioning as a continuous and efficient energy source, often involves hydrogen conversion to electricity[67]. The battery, typically a high-energy-density solution, provides stability and can handle moderate power demands. Ultracapacitors complement the sys-

tem by managing peak power demands and efficiently capturing energy during regenerative braking or deceleration. This sophisticated trifecta is advantageous in applications demanding a seamless balance between sustained power delivery and rapid adaptation to dynamic loads, as exemplified in certain electric vehicles and grid applications[68].

In essence, these highly detailed configurations underscore the engineering precision and adaptability required to create hybrid energy storage systems. Each component is carefully selected and integrated, considering the intricate balance between energy density, power output, and the specific demands of the application at hand[69].

In summary, hybrid energy storage systems play a crucial role in transitioning to more sustainable and efficient energy solutions, offering significant benefits in performance, adaptability, and intelligent energy management.




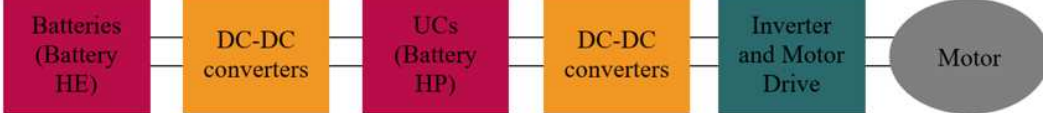
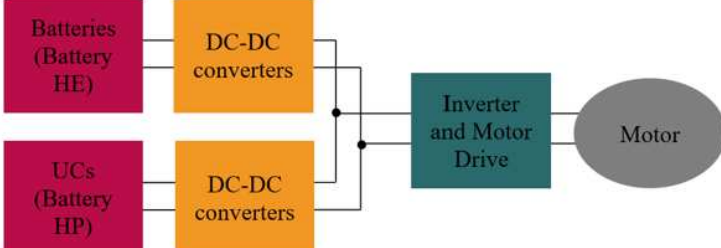
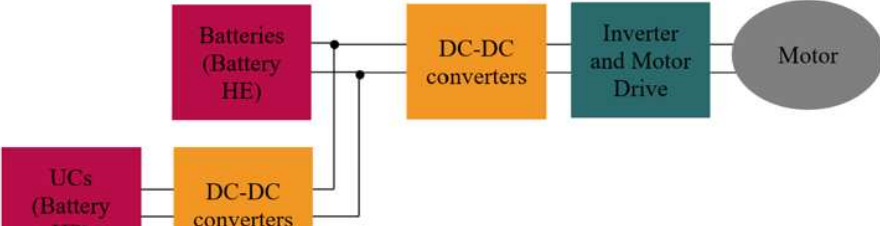


1.5.2 Energy management

EVs run on power from batteries, FCs, UCs, and hybrid energy sources [70]. EESs must be recharged from ultimate or temporary energy resources after every life cycle. An energy management system (EMS) manages all possible energy resources to feed the power to ESSs in EV. EMS deals with energy resource systems, ESSs, and power electronics [71]. The possible energy resources for recharging ESSs in EV are grid power, solar energy, hydrogen energy, regenerative braking, thermal energy, vibration energy, flywheel system, SMES, and other energy sources [72]. Modern EV systems are designed to effectively and intelligently manage all energy resources, given that energy availability and demand by means of EMS could optimize energy economy and efficiency[73].

1.6 Conclusion

In conclusion, this chapter has shed light on the energy landscape within the transportation sector and underscored the imperative for an energy transition. As the demand for clean and zero-emission vehicles intensifies, the integration of innovative solutions becomes paramount.

Table 1.1: Structures of HSSs: a) two ESSs in parallel (passive), b) one bidirectional DC-DC converter in series; c) two bidirectional DC-DC converters in series, d) two-input two bidirectional DC-DC converters in parallel

Hybridization	Architecture
HE/UC	
	
HE/HP	
	
	
	
	
FC/batteries/UC	

While hybrid and electric vehicles emerge as promising long-term alternatives, it is evident that the current market offerings fall short of matching the performance benchmarks set by traditional internal combustion engine cars.

Addressing the constraints faced by both consumers and manufacturers is crucial for the widespread adoption of electric vehicles. Consumers grapple with concerns such as limited range, extended charging times, and the high upfront costs associated with purchasing electric vehicles. Simultaneously, manufacturers face challenges related to optimizing vehicle energy consumption and enhancing energy recovery levels. It is within this context that the significance of hybridization becomes apparent.

The integration of hybrid technologies in energy storage systems presents a compelling solution to bridge the performance gap between electric and conventional vehicles. By combining different storage technologies, such as batteries and supercapacitors, hybridization offers the potential to augment range, reduce charging times, and enhance overall efficiency. This not only addresses the concerns of consumers but also aligns with manufacturers' goals of improving energy consumption and recovery. The next chapters will delve deeper into the principles and applications of energy storage systems, with a particular focus on the role of hybridization in advancing the capabilities of electric vehicles.

CHAPTER 2

AGEING MODEL OF BATTERY TECHNOLOGIES FOR EVS

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1.3	Electric Vehicles	29
1.4	Electrical energy storage systems	37
1.5	Principle of hybridization of energy sources	43
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2.1 Introduction

The objective of modelling is to predict the behaviour of the batteries in terms of electrical, thermal and then ageing. These three models will together form the multi-physics model of the battery, which will be used in this thesis. The ageing model will consist of two parts: a calen-

dar ageing model and a cycling ageing model. The two types of ageing are added together to form the overall ageing model [74]. This chapter begins by elucidating batteries' essential characteristics and parameters, providing a foundation for comprehending their behaviour and performance. We will explore key factors such as capacity, voltage, internal resistance, and efficiency, shedding light on how these properties influence a battery's performance in different applications. Furthermore, the chapter delves into the critical role of modelling in simulating battery behaviour, optimizing their usage, and devising innovative strategies for their advancement [75]. In the following sections, we will explore battery modelling, addressing electric, thermal, and ageing aspects. The modelling of electric behaviour encompasses understanding the dynamic responses of batteries to different load profiles and operating conditions. On the thermal front, we will explore the intricate thermal management systems essential for maintaining battery health and safety. Furthermore, battery ageing, a critical consideration in practical applications, will be addressed, as it directly impacts a battery's longevity and overall performance [76].

2.2 Battery Characteristics

Battery characteristics encompass critical attributes that define how batteries operate. Capacity quantifies the total energy storage, voltage indicates electrical potential, internal resistance affects efficiency, and efficiency measures energy conversion. These attributes collectively shape a battery's performance and application [77].

2.2.1 Battery capacity

The amount of free charge generated by the active material at the negative electrode and consumed by the positive electrode is called the battery capacity. The capacity is measured in Ah ($1Ah = 3600C$, or coulomb, where 1 C is the charge transferred in 1 s by 1A current in the MKS charge unit) [78].

$$Q_T = x.n.F \tag{2.1}$$

Where:

- x is the number of moles of limiting reactant associated with the complete discharge of the battery, n is the number of electrons produced by the negative electrode discharge reaction,
- $F = L.e_0$ Where
 - L is the number of molecules or atoms in a mole (known as the Avogadro constant), $L = 6.02210^{23}$
 - e_0 is the electron charge. $e_0 = 1.601 * 10^{(-19)}C$
- $F = 96412.2C/mol$

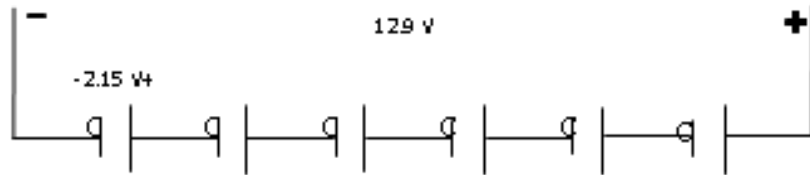


Figure 2.1: Battery cells connected in series

- The cells in a battery are typically connected in series (Figure 2.1, and the capacity of the battery is dictated by the smallest cell capacity. Therefore, $Q_{Tbattery} = Q_{Tcell}$. The theoretical capacity in Ah is:

$$Q_T = 0.278F(m_R n) / M_M \tag{2.2}$$

Where m_R is the mass of the limiting reactant (in kg), and M_M is the molar mass of the limiting reactant in (g/mol) .

2.2.2 Discharge rate

The discharge rate is the current at which a battery is discharged. The rate is expressed as Q_T/h rate, where Q_T is rated battery capacity, and h is discharge time in hours. For a battery that has a capacity of Q_T Ah and that discharges over Δt , the discharge rate is $Q_T/\Delta t$. For example, let the capacity of a battery be $1Q = 100Ah$. ($1Q$ usually denotes the battery's rated capacity.) Therefore,

$$Q/5 \text{rate is } \frac{100}{5} = 20A \quad (2.3)$$

$$2Q \text{rate is } Q/0.5 = \frac{100}{0.5} = 200A \quad (2.4)$$

2.2.3 State of charge

The State Of Charge (SOC) is the present capacity of the battery. It is the amount of capacity that remains after discharge from a top-of-charge condition [79].

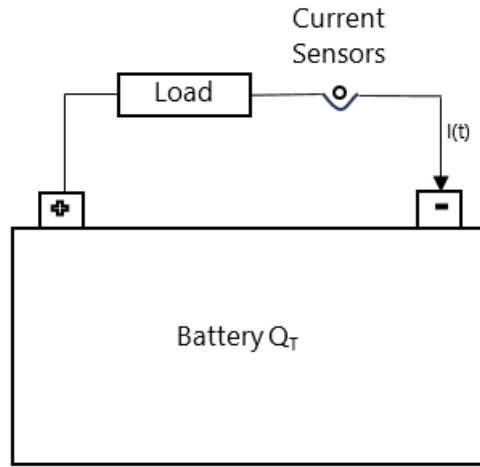


Figure 2.2: Battery SOC measurement

Figure 2.2 shows the battery SOC measurement circuit. The current is the rate of change of charge given by:

$$i(t) = \frac{dq}{dt} \quad (2.5)$$

Where q is the charge moving through the circuit.

The instantaneous theoretical state of charge $SOC_T(t)$ is the amount of equivalent positive charge on the positive electrode. If the state of charge is Q_T at the initial time t_0 , then $SOC_T(t) = Q_T$. For a time interval dt .

$$dSOC_T = -dq \quad (2.6)$$

$$dSOC_T = -i(t)dt$$

Integration from the initial time t_0 to the final time t , the expression for an instantaneous state of charge is obtained as follows: Integration from the initial time t_0 to the final time t , the expression for an instantaneous state of charge is obtained as follows:

$$\text{SoC}_T(t) = Q_T - \int_0^t i(\tau) d\tau \quad (2.7)$$

2.2.4 State of discharge

The state of discharge (SoD) is a measure of the charge that has been drawn from a battery. Mathematically, the state of discharge is given as follows show Figure 2.3 :

$$\begin{aligned} \text{SoD}_T(t) &= \nabla q = \int_0^t i(\tau) d\tau \\ \Rightarrow \text{SoC}_T(t) &= Q_T - \text{SoD}_T(t) \end{aligned} \quad (2.8)$$

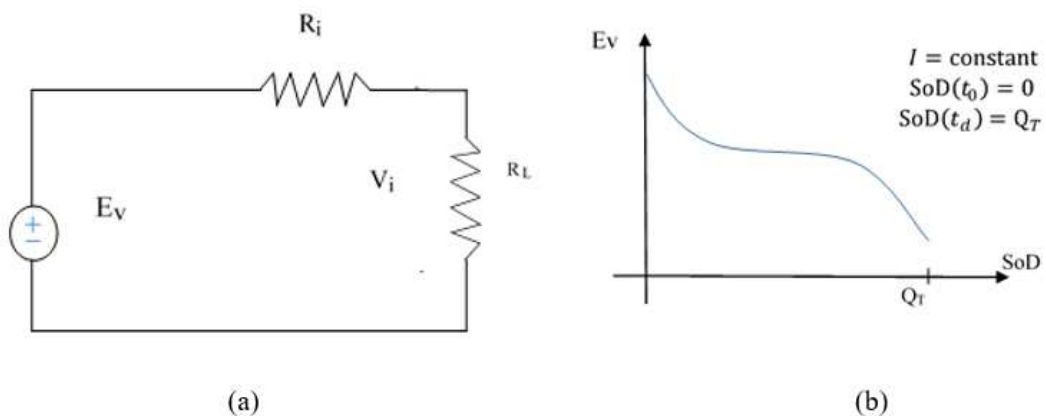


Figure 2.3: (a) Steady-state battery equivalent circuit. (b) Battery open circuit voltage characteristics

2.2.5 Depth of discharge

The depth of discharge (DoD) is the percentage of battery capacity (rated capacity) to which a battery is discharged [80]. The Depth Of Discharge is given by:

$$DoD_{(t)} = \frac{Q_T - S_o C_T(t)}{Q_T} * 100\% \quad (2.9)$$

$$DoD_{(t)} = \frac{Q_T - S_o C_T(t)}{Q_T} * 100\% \quad (2.10)$$

2.3 LI-ION battery and Cells Selected for Study

In recent years, Li-ion technology has become a dominant market for autonomous portable energy devices for which the mass/energy ratio is essential (mobile telephony, IT, etc.). Its introduction in the field of Transport has made it possible to revive the interest in electric vehicles by providing a solution realistic to the technological lock due to the low autonomy of the other electric storage units [81]. Nevertheless, manufacturing a powerful Li-ion battery pack for an electric vehicle is a completely different affair. A battery pack in the traction field consists of several individual cells, or elements, of nominal voltage 3,2 to 3,7V depending on the technology used, as well as electronic assembly and protection devices representing a mass and additional volume [82], taking into account safety criteria and quantity energy. Currently, several global battery manufacturers have launched their Li-ion technology products for electric and hybrid vehicles.

Table 2.1: Energy sources Kokam cells specifications

Parameters	Kokam HE	Kokam HP
Capacity C _{elb} (Ah)	40	13
Voltage U _{elb} (V)	3.7	3.7
Discharge current I _{elb Dis} (A)	40	104
Charge current I _{elb C} (A)	40	39
Weight W _{elb} (kg)	0.885	0.325
Volume V _{elb} (L)	0.441	0.174
Cost (Euros)	20.63	30.36

2.4 Multi-physical modelling of the battery cell

Modelling of storage components is well covered in the literature using several methods. There are many electric, thermal and ageing models of different levels of complexity, from the most generic to the most specific. Due to the multitude of accumulator, format, energy and composition techniques, a specific model for a given application is often necessary. This work aims to model an electrochemical cell of High-energy NMC technology with a multi-physical model. Figure 2.4, includes a thermal part, an electrical part and the parts of calendar and cycle ageing. Nicolas Damay's work deals with the advanced thermal study of an accumulator identical to that of our study case [83] via modelling by the finite [84], different approaches for thermal modelling of accumulators are possible such as partial differential equations 2.11, linear systems with variable parameters [85] or equivalent electrical circuits [86]. However, the very complete models are difficult to set up and configure in our case of use since they require many tests that we cannot perform and the execution of the calculations would prove too long to quickly simulate the behaviour over a lifetime in the current state. Therefore, an equivalent electrical circuit is a model better adapted to our needs.

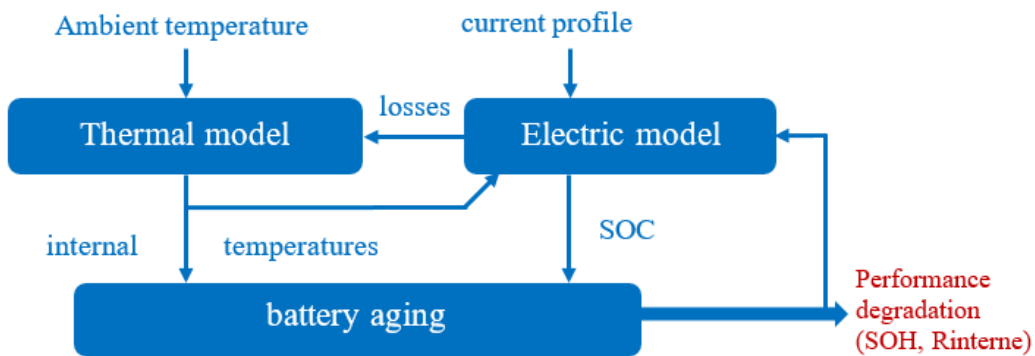


Figure 2.4: Principle of multi-physical modelling of the battery

Regarding the electrical model, there are also several types of models representing batteries that are complex electrochemical components with non-linear and non-stationary properties. Electrical models therefore have different levels of complexity with different modeling

approaches. The first approach, physico-chemical, uses the electrochemical laws that come into play in the battery cell. This model, which precisely characterizes intracellular interactions, makes it possible to obtain precise results [87] but requires a perfect knowledge of the composition of each cell element (electrodes, electrolyte, etc.) chemically and structurally.

This modelling is based either on experimental results used in tables of correspondence by interpolation or even by extrapolation or by assimilating the system to an equivalent electrical circuit whose parameters will be determined from test results [88]. The objective of the modeling, desired in our case, is to be able to carry out safe, fast simulations of long periods; therefore, the modelling chosen for the electrical part of the battery is an equivalent electric circuit model. The literature is also full of work on modelling the ageing of lithium-ion batteries. Similarly, different modelling approaches are studied according to the desired results and the legal complexity. Electrochemical modelling of ageing is the most complex to implement and requires strong expertise in the chemical mechanisms that may occur when using the cell. Other models of black box type describe the evolution of cell characteristics by abacus or laws of variation of model parameters and characteristic cell quantities (capacity, internal resistance, etc.) according to different inputs (temperature, current, elapsed time, STR, etc.).

Similar work to ours was carried out in parallel but on another type of cell with LFP and NCA technology and lower capacities [89]. The objective in our case is to arrive at a model capable of characterizing cell ageing for any possible entry mission profile. The characterization tests make it possible to identify the parameters and the behaviour of the cell to model it. The method chosen is to carry out an initial acceptance test of the cells to verify the characteristics of the cells at the beginning of the test campaign. Performance characterization tests are then carried out to determine the characteristics of the cells in the face of stresses. Finally, the cells undergo accelerated ageing according to the established protocol and test conditions. Accelerated ageing is of two kinds: calendar ageing and cycle ageing. For each ageing, the cells undergo periodic checkups under identical conditions to characterize the evolution of the parameters.

2.5 Electrical model

The electrical modelling of the cell was made from a conventional electrical model. The chosen electrical model is based on an equivalent electrical circuit (Figure 2.5) already well described in the literature [90], which consists of a voltage source (U_{OCV}), a variable internal resistance (R_0) which represents the voltage drop induced by the charge current, and two parallel R/C circuits in series which represent the dual layer effect behaviour (R_{dl}, C_{dl}) and the ion diffusion behaviour (R_{diff}, C_{diff}) in the battery [91].

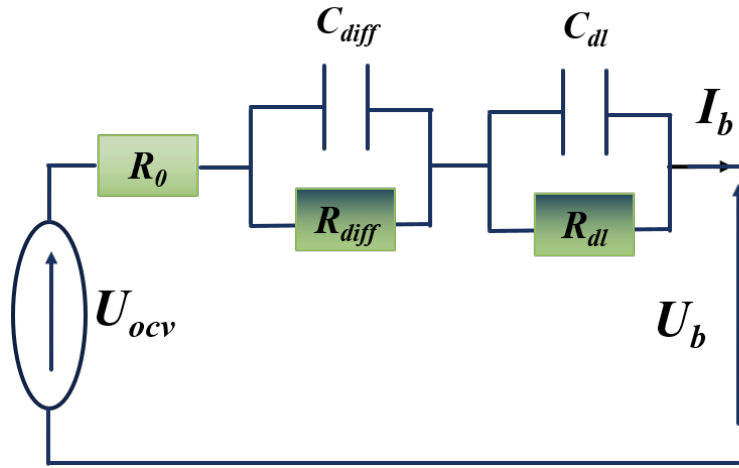


Figure 2.5: Equivalent electrical circuit of the cell

The voltage source is the open circuit voltage of the electrochemical cell and depends on the SOC as described in equation 2.11.

$$\begin{aligned}
 U_{OCV} = & x_1 + x_2 \cdot e^{c_1(1-SOC)} + x_3 \cdot e^{c_2 \cdot SOC} + x_4 \cdot e^{c_3(1-SOC)^2} + \\
 & x_5 \cdot e^{(c_4 \cdot SOC)^2} + x_6 \cdot e^{c_5(1-SOC)^3} + x_7 \cdot e^{(c_6 \cdot SOC)^3}
 \end{aligned} \tag{2.11}$$

The behaviour of the internal resistance can be described by equation (2.12):

$$R_{\Omega} = \frac{x_8}{\sqrt{\text{soc} (1 + c_7 \cdot \text{sign}(I)) + c_8}} \tag{2.12}$$

The model parameters based on equivalent electrical circuits can be determined using particular tests or electrochemical impedance spectroscopy, as well as temporal identification utilizing Chrono potentiometry [92]. The frequency characterization Figure 2.6 allows the identification of the electrical circuit representative of the behavior of the battery. The circuit parameters Figure 2.6 depend on the SOC state of charge and temperature.

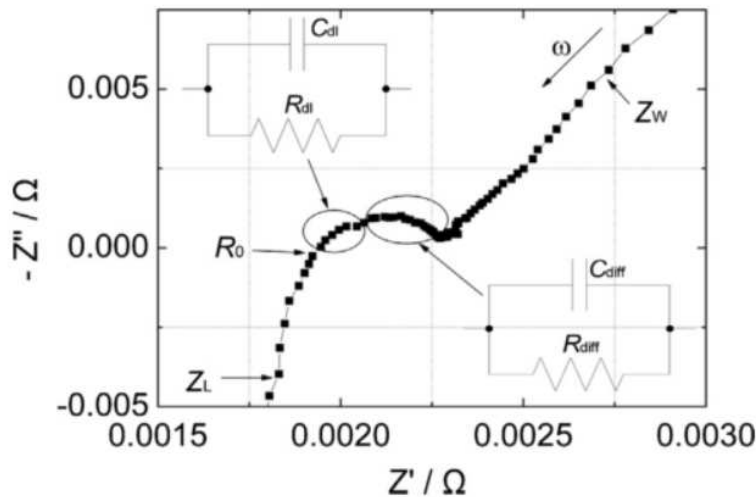


Figure 2.6: Electrochemical impedance spectroscopy and its equivalent circuit

2.5.1 Electrical modelling of Li-ion battery 40HE cell

In Figure 2.7-b, a comprehensive examination is undertaken to elucidate the cycle simulations subsequent to the meticulous determination of Kokam HE settings for the cell batteries. The nuanced details of this analysis extend to the voltage calculations derived from the electric model, which are meticulously compared to the real voltage obtained under a specific current cycling profile, as illustrated in Figure 2.7-a. The primary objective of this rigorous comparison is to discern any subtle differences between the two voltage profiles.

Upon close inspection of the results, a nuanced distinction between the modeled and actual voltage responses becomes apparent. Figure 2.7-c offers a detailed depiction of the relative error, expressing the variance between the modeled and actual voltage values. The relative error, confined within the range of -2 to 2 , reflects a minor disparity between the two sets of data points.

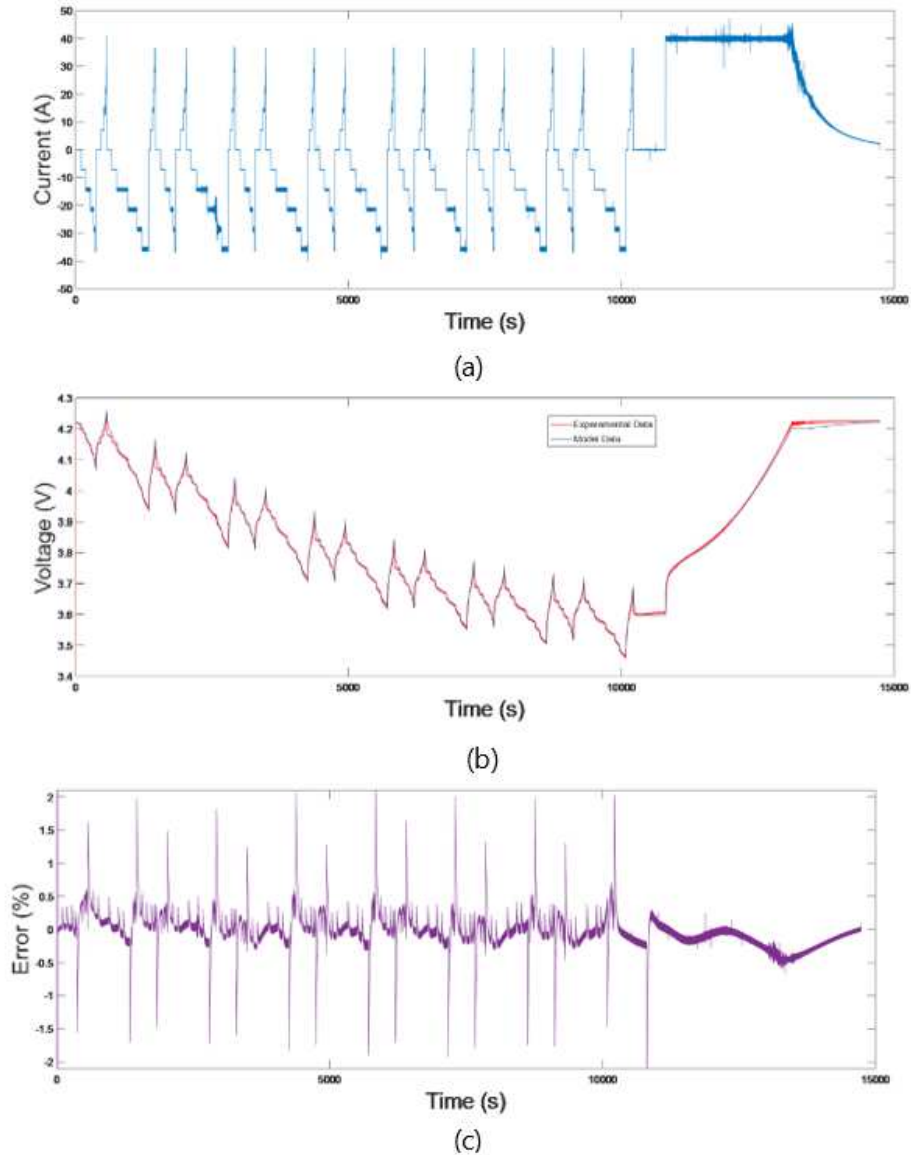


Figure 2.7: HE Battery Test: profile of current (a): (b): Battery voltages real and estimated. (c): Relative voltage error

This narrow range underscores the precision of the chosen model topology and parameters tailored for Li-ion HE batteries. The minimal relative error observed in this comparison serves as compelling evidence, affirming the validity and accuracy of the electric model in capturing the intricacies of voltage behavior during cycling simulations for Kokam HE cell batteries.[93][94].

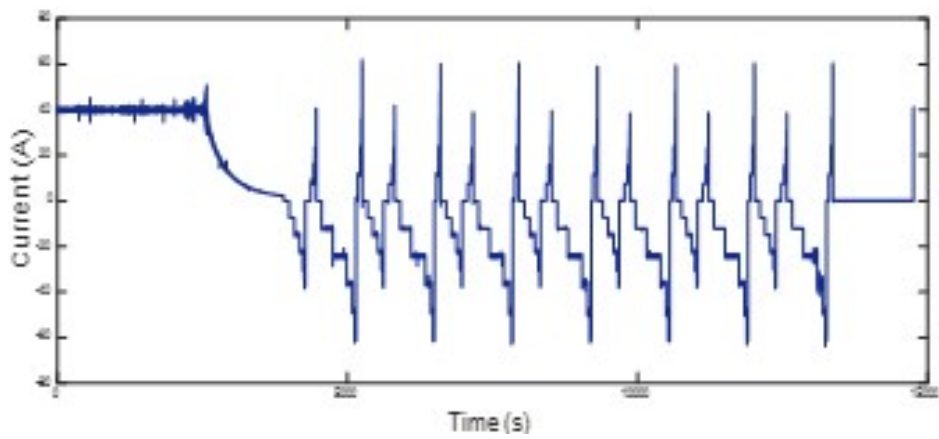
Table 2.2: Optimization parameter values for the electrical model for the *NMC* HE battery

X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
6e-4	0.610	8e-3	1e-4	3.44e-05	8.11e-05	0.005	0.109	57.98	0.703
C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
6e-4	0.610	8e-3	1e-4	3e-05	8e-05	0.005	0.109	57.98	0.703

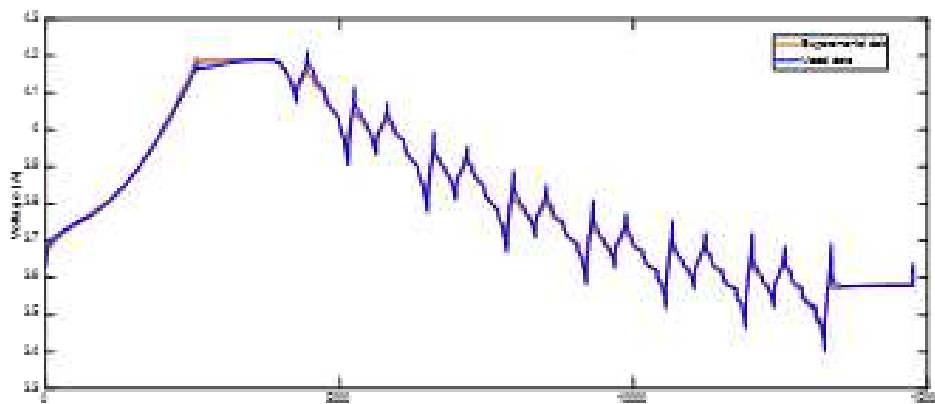
2.5.2 Electrical modelling of Li-ion battery 40HP cell

In Figure 2.8-b, we delve into the intricacies of the cycle simulations conducted subsequent to the meticulous identification of Kokam HP cell battery parameters. The granularity of this analysis extends to the voltage predictions derived from the electric model, which were subjected to an exhaustive comparison with the actual voltage measurements obtained during a specific current cycling profile, meticulously illustrated in Figure 2.8 -a. This comparative scrutiny aimed to ascertain the electric model's true fidelity in replicating the nuanced intricacies of the Kokam HP cell battery's real-world behavior. Upon closer scrutiny of the results, a strikingly harmonious alignment between the modeled and actual voltage responses emerges. The discerning eye will appreciate the meticulous attention to detail, revealing a negligible gap between the two sets of data points. This underscores and accentuates the electric model's precision in capturing the subtle nuances and intricacies inherent in the battery's performance.

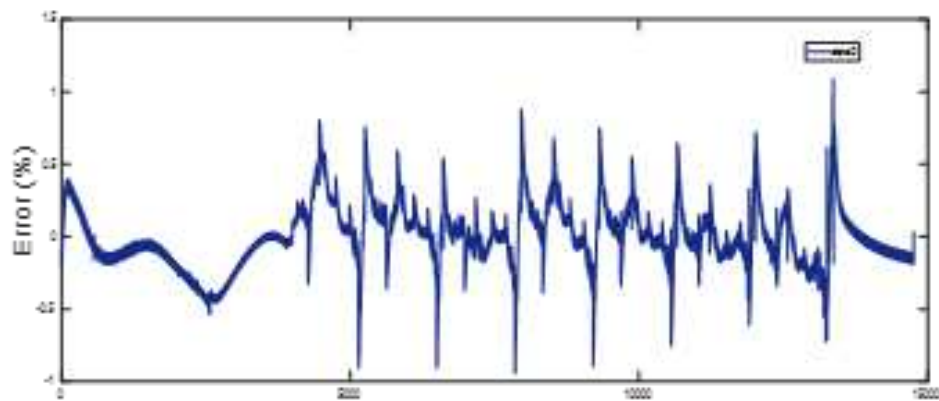
Figure 2.8-c unfolds a comprehensive panorama of the relative error between the modeled and actual voltage values to quantify and qualify this precision with utmost granularity. Expressed as a percentage, the relative error occupies an exceptionally confined space, oscillating between -1 and 1 percent. This minute range serves as a resounding endorsement, a testament to the meticulous calibration of the chosen model topology and the finely tuned parameters specifically tailored for the nuances of Li-ion HP batteries [8]. The result is an electric model that not only replicates but faithfully predicts the intricate voltage characteristics during cycling simulations, establishing an unparalleled standard of reliability for understanding and foreseeing the behavior of Kokam HP cell batteries under the dynamic and diverse conditions of real-world operation.



(a)



(b)



(c)

Figure 2.8: HP Battery Test: profile of current (a): (b): Battery voltages real and estimated. (c): Relative voltage error

Table 2.3: Optimization parameter values for the electrical model for the *NMC* HP battery

X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
0.034	0.210	0.008	1e-3	3e-05	5e-05	0.065	0.329	22.48	1.710
C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
3e-4	-4e-1	5e-3	-1e-4	-1e-05	-1e-05	0.005	0.109	57.98	0.703

2.6 Thermal model

An equivalent thermal model complements the electrical model to translate heat dissipation of losses within the battery (Figure 2.9) [95]. The thermal power is directly induced from the ohmic losses of the battery Equation 2.15. Equation 2.13 represents the relationship between thermal resistance and SOC with a_1 and a_2 optimization coefficients. The thermal model is presented by an equivalent thermal circuit by analogy to the equivalent electrical circuit and is shown in Figure 2.9. This circuit consists of a P_{th} thermal power source, a C_{th} thermal capacity that accumulates heat and a variable R_{th} thermal resistance that will limit the transfer of heat to the outside. The thermal power comes from the joule effect losses in the resistors ($R_{\Omega}, R_{dl}, R_{dif}$) of the equivalent electrical circuit representation Figure 2.9. The equivalent internal resistance of the R_{int} cell is estimated by the potential drop ($U_{OCV}-U$) divided by the current I Equation 2.13.

The thermal resistance R_{th} is described by a polynomial function of order 3 of the SOC Equation 2.14 [96], where the coefficients a_1 and a_2 are determined by identification with the experimental results.

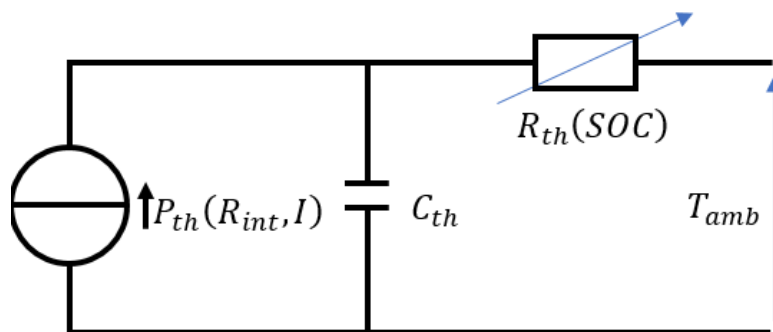


Figure 2.9: Simplified equivalent thermal circuit of a battery cell [1]

$$P_{th} = R_{int} I^2 = (U_{OCV} - U) \cdot I \quad (2.13)$$

$$R_{th} = a_1 + a_2 \cdot SOC^3 \quad (2.14)$$

2.6.1 Thermal model of Li-ion battery 40HE cell

The thermal model for the high-energy (HE) battery relies on a set of meticulously defined parameters, as outlined in the accompanying table. These parameters likely encompass specific thermal properties such as the thermal conductivity of the battery’s constituent materials, thermal capacity, thermal resistance, and other critical characteristics.

The associated figure (Figure 2.10) provides a visual representation of how these parameters interplay to influence the thermal distribution within the HE battery. This graphical depiction may include temperature profiles over time or across different locations within the battery, offering a visual insight into thermal dynamics during various operating conditions. Accurate calibration

Table 2.4: Optimization parameters for the thermal mode of NMC HE battery

a1	a2
12.21	1.76^{-4}

of these parameters within the thermal model is essential for precise thermal simulations. For instance, misjudged thermal resistance may result in underestimating heat generation during demanding cycles, while inaccurately assessed thermal capacity might lead to unreliable predictions of temperature fluctuations.

In summary, the combination of the parameter table and the thermal model figure offers a comprehensive approach to understanding and optimizing the thermal performance of high-energy batteries. This analytical process is instrumental in designing effective thermal management systems that can maintain the battery within optimal temperature ranges, ultimately contributing to the overall reliability and longevity of the energy storage system.

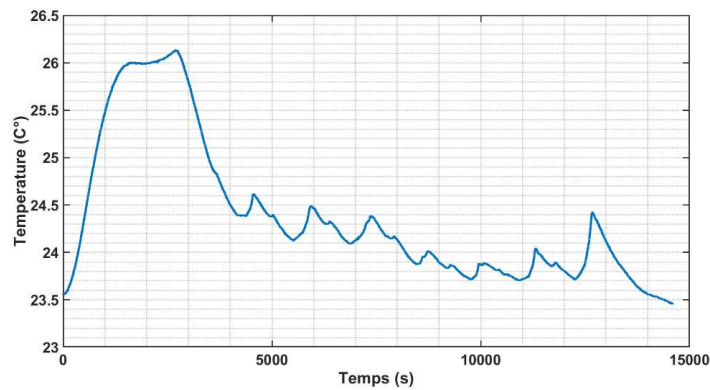


Figure 2.10: Battery internal temperature evolution for HE cell

2.6.2 Thermal model of Li-ion battery 40HP cell

The thermal model for the high-performance (HP) battery relies on a set of carefully defined parameters, as presented in the associated table. These parameters likely include specific thermal properties such as thermal conductivity of the battery's constituent materials, thermal capacity, thermal resistance, and other essential characteristics.

The figure associated with this model provides a graphical representation of how these parameters interact to influence the thermal distribution within the battery. This graphical representation may include temperature curves over time or position within the battery, offering a visual understanding of thermal variations during different usage phases.

Precise tuning of these parameters in the thermal model is crucial to ensure accurate thermal simulation. For example, improperly calibrated thermal resistance might underestimate the heat generated during intensive cycles, while incorrect thermal capacity could lead to inaccurate predictions of temperature variations.

Overall, the combination of the parameter table and the thermal model figure provides a holistic approach to understanding and optimizing the thermal performance of high-performance batteries. This process can also be crucial for designing effective cooling systems that maintain the battery within safe temperature ranges, contributing to the overall reliability and durability of the energy storage system.

Table 2.5: Optimization parameters for the thermal mode of NMC HP battery.

a1	a2
7.93	4.65^{-3}

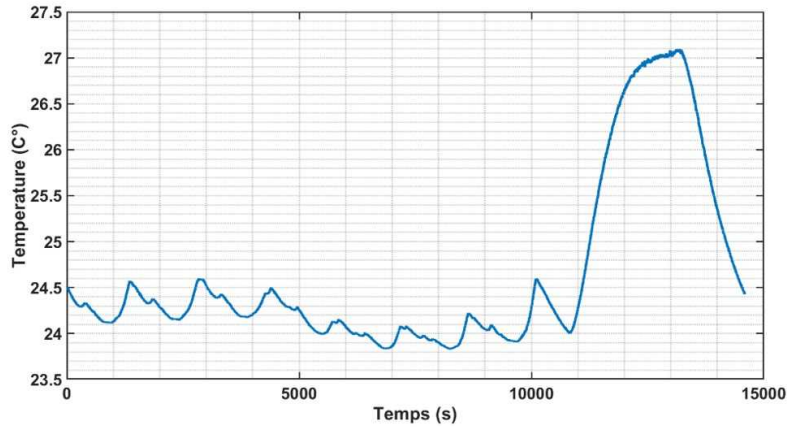


Figure 2.11: Battery internal temperature evolution for HP cell

2.7 Ageing model

This last part of the multi-physical model of the battery cell is the most consistent and consists of two sub-models: a calendar ageing model and a cycle ageing one. Figure 2.12 represents the principle adopted for modelling cell ageing. The electrochemical cell's total degradation is considered the sum of the degradation of these two sub-models. The choice was made to separate the ageing of the battery of calendar nature and cycling, without complex interaction of one ageing on the other. Calendar ageing corresponds to the ageing of the resting cell, while cycling ageing corresponds to that of cell use. Because of this choice and according to The results of our ESTACA laboratory, [97], the calendar degradation affects the battery permanently, while the degradation due to cycling acts only when there is an exchange of energy. Both types of degradation are temperature-dependent. In addition, the calendar degradation depends on the state of charge of the battery (SOC), and the degradation in cycling depends on the current rate, the depth of discharge (DOD depth of discharge; the variation of SOC) but also on the current state of health of the battery (SOH state of health).

These aging models are semi-empirical models and require parameterization to match the ex-

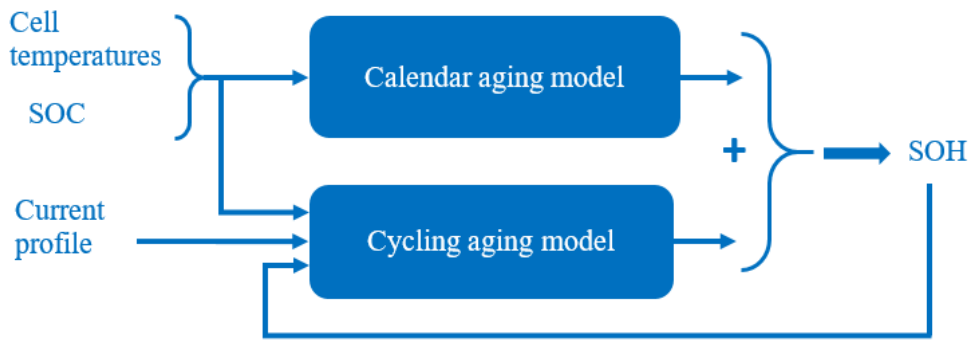


Figure 2.12: Diagram of the modeling of cell ageing

perimental results. Based on the selected missions, the vehicle’s electrical and fuel models are used to estimate typical current levels.

2.7.1 Modeling of calendar ageing

Battery aging consists of two main components: calendar aging and cycling. In the specific context of calendar aging, it is influenced by factors such as state of charge (SOC) and temperature. This aspect of aging occurs over time, even when the battery is not in use, and it is exacerbated by high or low SOC levels as well as extreme temperatures. Understanding and mitigating calendar aging is crucial to extending the useful life of batteries, especially in High Efficiency (HE) and High Power (HP) applications using Nickel-Manganese-Cobalt (NMC) technology.

Calendar ageing appears to be favoured by high temperatures and high SOC levels but with a secondary impact. The calendar modelling used Equation (2.15) is inspired by the scientific literature [98] and adapted to the battery technology studied (NMC). This equation is usually used in voltage instead of state of charge (SOC). NMC has a relatively constant voltage curve and the characterization with respect to SOC has been more representative. Moreover, the coefficient α is usually fixed at 1/2 but had to be adapted for this technology.

$$a(t, T, SOC) = C_a \cdot t^\alpha \cdot C_T^{\frac{T-T_0}{dT}} \cdot C_{SOC}^{\frac{SOC-SOC_0}{dSOC}} \quad (2.15)$$

- a : ageing rate (-), (-)
- C_a : coefficient of ageing ($s^{-\alpha}$),
- t : time (s)
- α : the power of time dependence (-)
- C_t : temperature coefficient (-)
- T : temperature (K)
- T_0 : reference temperature (K)
- dT : temperature delta (K)
- C_{SOC} : SOC coefficient (-)
- SOC : State Of Charge (-)
- SOC_0 : SOC reference (-)
- $dSOC$: delta SOC (-)

2.7.2 Modeling of cycling ageing

Our objective is to obtain a means of predicting the ageing of Li-ion batteries as part of automotive use and hybrid power supply. The ageing should allow the evolution over time of both parameters to be estimated electrical (capacity/resistance) used to characterize the ageing of the battery. The so-called calendar ageing must also be considered because, for a particular vehicle, the rest time (at a standstill) is estimated at 90%. A semi-empirical model of battery ageing Li-ion, input-output type, has been chosen here for its simplicity and usability in real-time. This model proposed by [99] provides a forecast of the cycle life with the aid of calendar ageing tests. Lifetime estimation is based on this associated semi-empirical model with the electric model.

- The model is parameterized based on cycling ageing tests.
- During the ageing process, the resistances of the electric model develop in a similar manner.
- The battery's calendar ageing progresses according to the square root of time, with a slow-down of the form (A-X) depending on temperature and voltage.

On the basis of these assumptions and simplifications, capacity degradation or the increase in internal resistance may be expressed as:

$$\alpha(t, T, SOC) = C_{\alpha} \cdot t^{\alpha} \cdot C_T^{\frac{T-T_0}{dT}} \cdot C_{SOC}^{\frac{SOC-SOC_0}{dSOC}} + C_b \cdot e^{(C_{chr} \cdot I_{chr})} + C_{e-} \cdot e^{(C_{dech} \cdot I_{dech})} \quad (2.16)$$

Where is the C or State of Charge (SOC) capability after a certain time t under a temperature T and a Capacity of charge C_{chr} , capacity of discharge C_{chr} and current of charge and discharge are I_{chr}, I_{dech} . T_0, SOC_0, dT , and SOC constants can be chosen arbitrarily as reference points for the ageing model. C_{α}, C_T and C_{SOC} are the model parameters to be determined from tests. With this model, the dynamics of the ageing parameters of the calendar cell and cycling take into account the decrease in capacity, the effect temperature and voltage evolution. The end of life of a battery is generally defined by the loss of 20% of its nominal capacity or the increase in its resistance internal value up to twice its initial value.

The calendar model used Equations (2.15) is inspired by the scientific literature and adapted to the studied battery technology. This equation [100] is usually used in voltage instead of the state of charge (SOC) [101]. The ratio (in %) between the capacity available at the time of amount and the initial capacity of the two Ko40HP and Ko40 HE battery cells is shown in Figure 2.13. During cycling, we can see the presence of two separate ramps for each technology. The ramp is low at the start of cycling (first phase) until roughly 1000 cycles. The slope then becomes increasingly essential until the components reach the end of their lifespans. By definition, the end of life is defined as a 20% reduction in capability compared to its initial value. The capacity loss of the Ko40HP cell is larger than that of the Ko40HE cell after 1500 cycles.

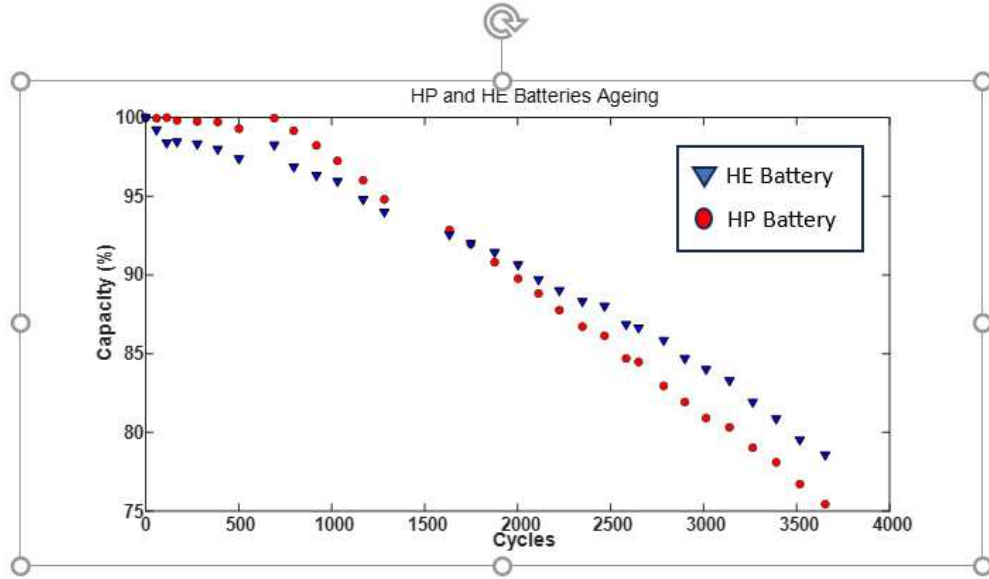


Figure 2.13: Evolution of the capacity as a function cycling number

In Figure 2.13, capacity is decreasing at cycling. According to [102], in addition to depending on the protocol used, the alteration of the capacity also depends on the temperature and the discharge current. Specify that the protocol is how the cell is discharged and recharged, depending on the voltages and boundary currents. also confirms, experimentally, that the loss of capacity varies greatly depending on the discharge cycle. Figures 2.14 show battery He tests, the capacity drops as a function of the number of cycles, we notice after 3500 cycles, we have capacity degradation of more than 20% (see Figures 2.14-A). The Modeling error, as shown in the Figures 2.14-B, is between -3 and 2 percent.

Table 2.6: Optimization parameters for the ageing mode of the NMC HE battery

C_α	C_T	C_{SOC}	C_B	C_{chr}	C_c	C_{dech}
1e-3	1e3	1e-3	0.92	1e-8	8e-3	5e-5

Table 2.7: Optimization parameters for the ageing mode of the NMC HP battery

C_α	C_T	C_{SOC}	C_B	C_{chr}	C_c	C_{dech}
0.0019	6e-4	8e-6	0.01	4e8	1.5e-8	0.01

The optimization parameters for enhancing the ageing characteristics of (NMC) high-energy (HE) (Table 2.6) and high-performance (HP) (Table 2.7) batteries are pivotal in ensuring pro-

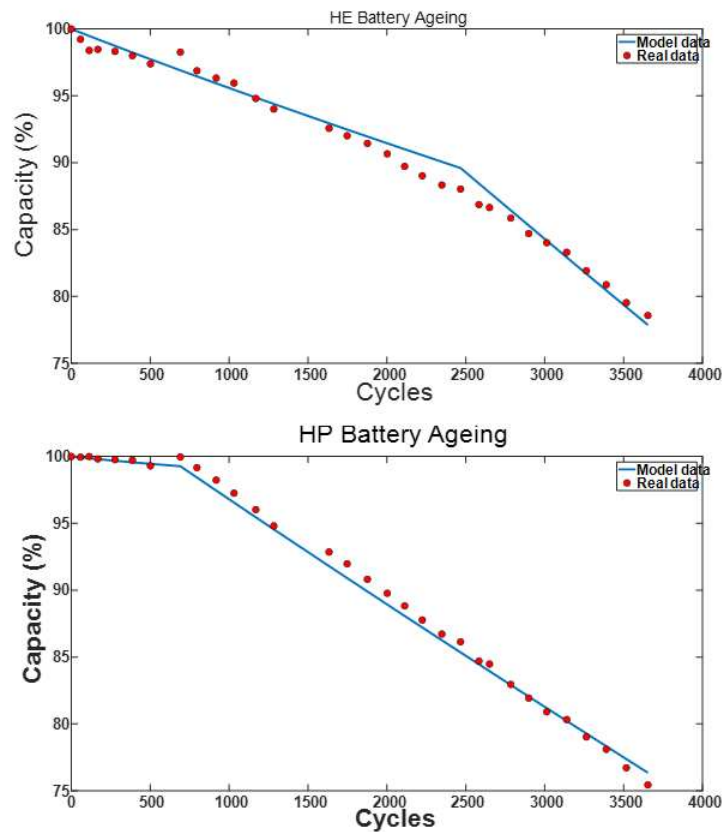


Figure 2.14: Modeling (HE) and (HP) with actual operational data.

longed lifespan and optimal functionality of these energy storage systems. Table 1 delineates the specific optimization parameters tailored for the ageing mode of the NMC HE battery. These parameters encompass crucial factors such as cycling rate, depth of discharge (DoD), operating temperature, state of charge (SoC), charge and discharge voltage limits, current limit, cooling system specifications, and the calendar ageing factor. Each parameter is meticulously paired with its corresponding value or range, offering a comprehensive insight into the nuanced adjustments required to optimize the ageing performance of NMC HE batteries. Similarly, this table articulates the optimization parameters for the ageing mode of the NMC HP battery, emphasizing the unique adjustments necessary for high-performance batteries. These tables serve as invaluable references for researchers and engineers seeking to fine-tune these optimization parameters for enhanced ageing performance in both NMC HE and HP batteries.

The results in Figures 2.14 show that the developed model represents battery ageing well. This Figure showcases the modeled performance of (HE) and (HP) modules utilizing real op-

erational data. The curves in the figure represent the dynamic responses of both HE and HP modules under various operational scenarios, providing a detailed insight into their behavior.

The HE module's curve reflects its efficient energy delivery and sustained performance, mirroring the characteristics optimized for prolonged operation and consistent power output. On the other hand, the HP module's curve illustrates its capability for rapid and intense power delivery, showcasing steep spikes during high-demand periods.

The utilization of actual operational data enhances the fidelity of the modeling, ensuring that the curves align closely with the real-world behavior of HE and HP modules. This figure serves as a valuable reference for understanding and predicting the performance of these modules under diverse operational conditions, contributing to the refinement of hybrid system design and optimization.

2.8 Conclusion

After a presentation of the context, the problem and the study product, this second chapter presents the modelling and identification of the battery. The battery modelling is carried out as a multi-physics model to be able to take into account the electrical, thermal and ageing characteristics of the cell. While the electrical and thermal models are based on equivalent circuit theory, the ageing model is carried out empirically from the literature of previous works and through a characterization test campaign of the energy storage component used. This study chose to distinguish between calendar and cycle ageing to identify battery degradation due to driving and charging due to calendar ageing. Each model was parameterized by identification with the vehicle and battery component test results to ensure that the model was consistent with the case study. The test results and ageing modelling provided a better understanding of the factors involved. Calendar ageing is strongly mitigated by low temperatures and, in a second order, by a low charge level. Regarding cycling ageing, high currents accelerate ageing and even more so when cycling is coupled with low temperatures close to 0°.

CHAPTER 3

SIZING AND MANAGEMENT OF ENERGY STORAGE SYSTEM

Contents

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3.1 Introduction

The HEV is a strategic solution to one of the most significant challenges of our future energy needs. Nevertheless, there are many indicators affecting the performance of this type of vehicle from the point of view of its design, the type of powertrain, the configuration of components, the mass of the EV and especially the mass of each storage tank system as well as the precision in the estimation of their operating states at each moment. Moreover, the achievement of an energy-efficient powertrain requires tackling complex objectives such as the type of driving, minimizing conduction losses, the weight of the sources and, most importantly, the PMS strategy chosen when sharing the load power between the SSEs [103]. However, this chapter first deals with the global modelling of our hybrid system in order to predict the kinematic behaviour of the HEV before its implementation. Second, a review of the literature on existing management strategies in several studies and studies. The description of these methods applied to PMS is based on its principles, advantages and disadvantages. In this work, the vision was oriented towards strategies and controllers sufficiently simple with fast execution in real-time. Indeed, the method of limitation and the frequency method based on deterministic rules were introduced in this study in order to manage the distribution of the vehicle's energy demand between HE and HP Li-ion batteries within a parallel topology. Beyond that, we distinguish two main categories of management in the light of a controller indicator which is the SOCHP parameter [104].

3.2 Technical specifications

3.2.1 Vehicle dynamic modelling

A dynamic model of the vehicle, developed at ESTACA'LAB under Matlab-Simulink software, is used to estimate the power and energy needed for the proposed profile [86]. Parameters of the bolero vehicle are shown in Table 3.1, and acting forces are shown in Figure 3.1.

To estimate energy and power consumption, one has to integrate the sum of net forces temporarily in the opposite direction of vehicle movement, such forces are aerodynamic drag force

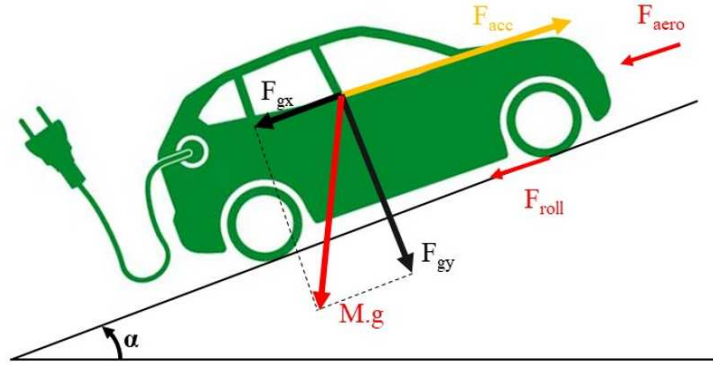


Figure 3.1: Acting forces on the vehicle

Table 3.1: Vehicle characteristics

Parameters	Value
Vehicle mass (kg)	860
Frontal area (m ²)	2.75
Air density (kg /m ³)	1.2
Penetration coefficient	0.3
Rolling resistant coefficient	0.008

F_{aero} , rolling resistance force F_{roll} , and gravitational force F_{gx} . Power consumption is estimated using:

$$P = \left(M \frac{dV_{veh}}{dt} + F_{aero} + F_{roll} + F_{gx} \right) V_{veh} \quad (3.1)$$

With

$$\begin{cases} F_{aero} = 0.5\rho SC_x V_{veh}^2 \\ F_{roll} = Mg (C_0 + C_1 V_{veh}^2) \\ F_{gx} = Mg \sin(\alpha) \end{cases} \quad (3.2)$$

To estimate the required tractive forces for vehicle movement, we find force load as [105].

$$F_{res} = F_{aero} + F_{roll} + F_{gx} + F_{acc} \quad (3.3)$$

Where F_{acc} is the acceleration force. These forces are detailed in the literature [106].

3.2.2 Driving cycle's profiles

A driving cycle commonly represents a set of vehicle speed points versus time. It is used to assess a vehicle's fuel consumption and pollutant emissions in a normalized way so that different vehicles can be compared. The driving cycle is performed on a chassis dynamometer, where the vehicle's tailpipe emissions are collected and analyzed to assess the emissions rates [107]. In commercial vehicle areas, the driving cycle is not performed on a vehicle dynamometer but on an engine dynamometer and is evaluated through a set of engine torque and speed points instead of vehicle speed points [108]. There are two kinds of driving cycles, the modal cycles as the European standard NEDC, or Japanese 10 – 15 Mode and the transient cycles as the FTP-75 or Artemis cycle. The main difference is that modal cycles are a compilation of straight acceleration and constant speed periods and are not representative of real driver behaviour, whereas transient cycles involve many speed variations typical of on-road driving conditions [109].

The NEDC

The NEDC (see Figure 3.2) is used as a reference cycle for homologating vehicles until the Euro6 norm in Europe and some other countries. It comprises an urban part called ECE, repeated four times, and an extra-urban part, the EUDC. The main characteristics of the cycle are given by Table 3.2.

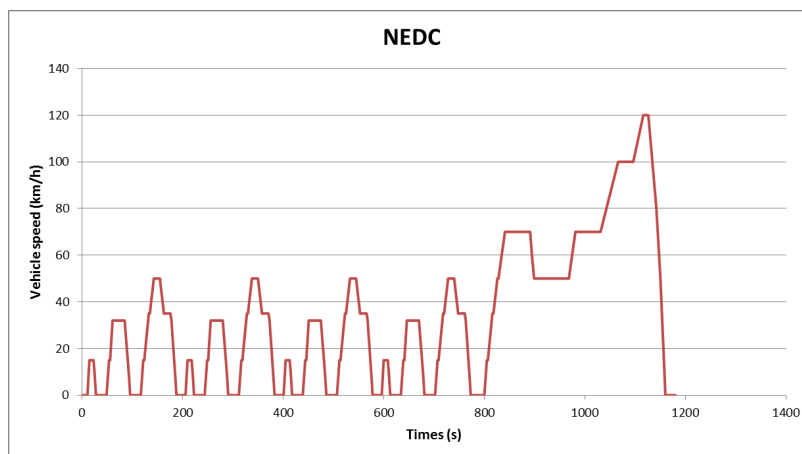


Figure 3.2: NEDC Cycle

Table 3.2: NEDC Characteristics

Distance	11023 <i>m</i>
Duration	1180 <i>s</i>
Average speed	33.6 <i>km/h</i>

This cycle is criticized by experts as it doesn't represent real-life driving conditions. Indeed, accelerations are very soft; there are a lot of constant speed cruises and many idle events. This makes it impossible to obtain certified values when driving with the vehicle in real conditions. For those reasons, a solution to replace the NEDC is being explored by European authorities. The new cycle called Worldwide Harmonized Light Vehicle Test Procedure (WLTP) will probably appear for the upcoming norm *Euro7* [110].

The Artemis driving cycle

This cycle is based on a European statistical study within the so-called Artemis project. It is made of 3 different configurations, plus an additional variant: the urban cycle, the rural one, the motorway 130 *km/h* and the motorway 150 *km/h*. motorway 130 *km/h* and the motorway 150 *km/h* (Figure 3.3).

Here are the main characteristics of the cycles:

Table 3.3: Artemis Characteristics

	Urban	Rural	Motorway 150	Motorway130
Distance	4870 <i>m</i>	17272 <i>m</i>	29545 <i>m</i>	28735 <i>m</i>
Duration	993 <i>s</i>	1082 <i>s</i>	1068 <i>s</i>	1068 <i>s</i>
Average speed	17.6 <i>km/h</i>	57.5 <i>km/h</i>	99.6 <i>km/h</i>	96.9 <i>km/h</i>

Artemis cycles are not used for certification of pollutants or fuel consumption. However, car manufacturers use this kind of cycle to understand real driving conditions better and assess their vehicles' real performances. Note that it exists several other cycles are more or less used by car manufacturers, like the modem-Hyzem cycle, which will not be described in this featured article [111].

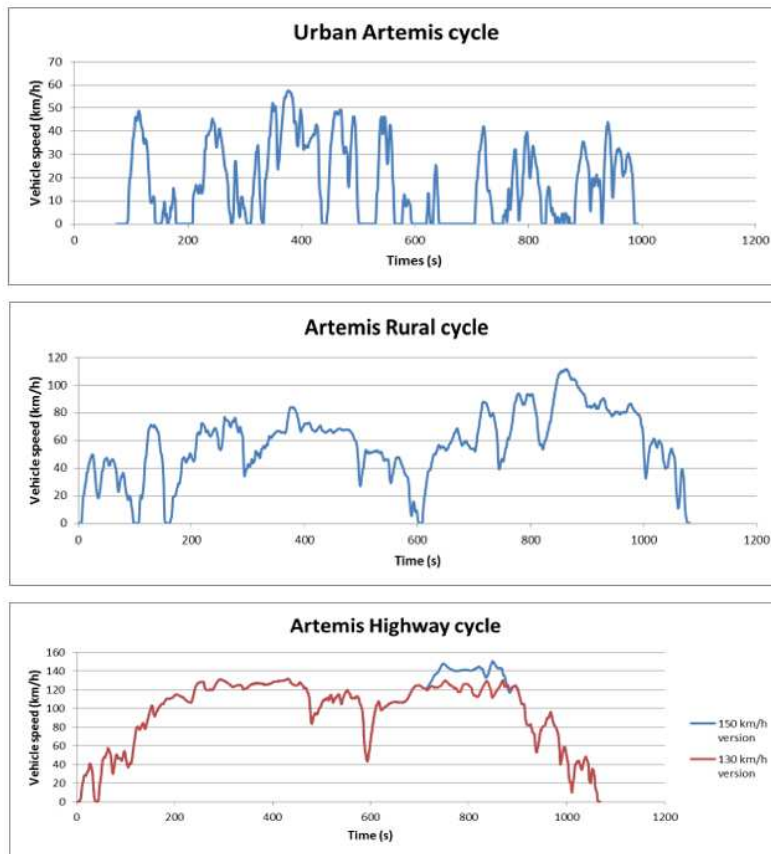


Figure 3.3: Artemis cycles

3.3 Sizing methodology

Sizing energy storage sources is a critical step in the design of electrical systems, whether it's for hybrid vehicles, renewable energy systems, or other applications. It involves finding the optimal balance between storage capacity, weight, cost, and volume. To achieve this, various parameters need to be considered, including the specific energy requirements of the application, charge and discharge profiles, space constraints, and budgetary considerations. The sizing algorithm must determine the size of the energy storage source, taking into account the weight and volume constraints imposed by the application while minimizing costs [112]. This often involves a trade-off between storage capacity and the materials used, as well as iterations to optimize system performance. Sizing energy storage sources is a complex process that requires precise modelling, sophisticated calculations, and a deep understanding of the application's needs to arrive at energy-efficient, cost-effective, and space-efficient solutions [113] [114].

3.3.1 Sizing of ESS based on battery only

In this scenario, the Li-ion battery must provide the necessary energy for the EV's autonomy while meeting the constraints in propulsion and braking power. However, the current Li-ion battery technology meets the demand for power peaks. In the case where the EV is provided only by the main source, the problem of the limitation of the power of discharge, an oversize in energy with a pack too voluminous and too heavy, is also necessary. The sizing algorithm (Figure 3.4) is based on the following three equations using the three sizing criteria [115].

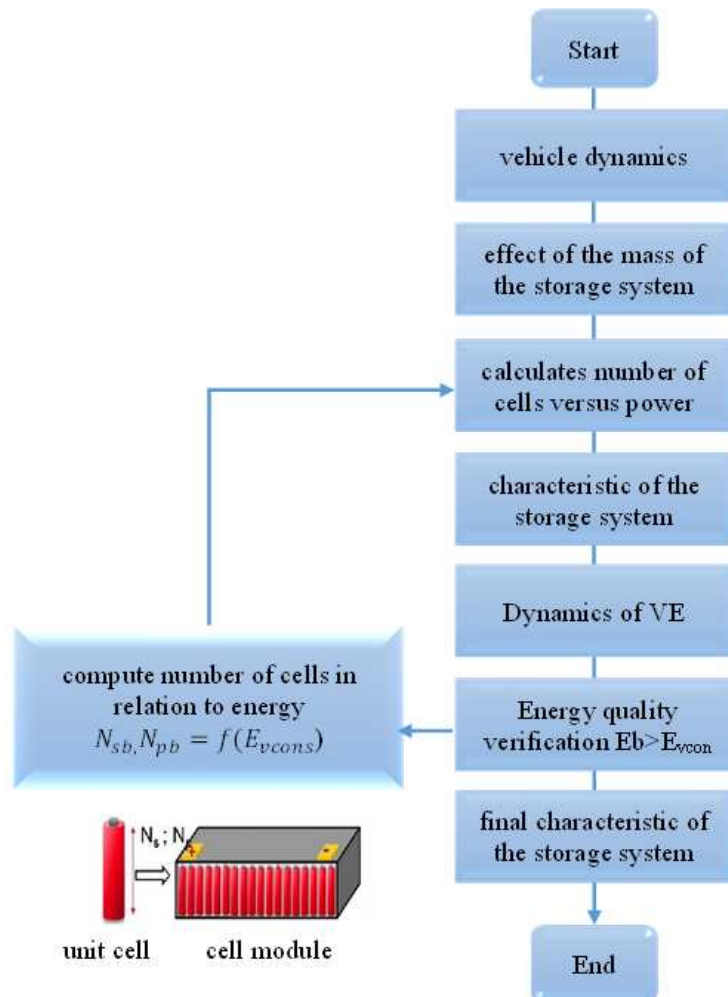


Figure 3.4: Algorithm for sizing an EV equipped with a single source [2]

The battery ensures total braking power recovery:

$$N_{s;b} : N_{p;b} = \frac{P_{VE,rec} \left(1 + \sqrt{1 + 4 \left(P_{max,b}^{el} - 1.4\sigma^{rec}m_b^{el} \cdot \frac{R_0^{el}}{U_{b,min}^2} \right)} \right)}{2 \left(P_{max,b}^{el} - 1.4\sigma^{rec}m_b^{el} \right)} \quad (3.4)$$

Or $N_{s;b}$; $N_{p;b}$ represent respectively the number of elements in series and the number of branches parallel to the battery pack. $P_{VE,rec}$ receives the power recovered by the vehicle, P_{max} ; maximum charge power of a battery cell, m_b mass of a battery element, R_0 internal resistance of a battery element, U_b ; minimum voltage of a battery element. The battery ensures maximum propulsion power: $P_{(VE,cons)}$ is the power consumed by the vehicle and $P_{(dech,b)}^{el}$ discharge of a battery cell.

$$N_{s;b} : N_{p;b} = \frac{P_{VE,cons} \left(1 + \sqrt{1 + 4 \left(P_{max,b}^{el} - 1.4\sigma^{rec}m_b^{el} \cdot \frac{R_0^{el}}{U_{b,min}^2} \right)} \right)}{2 \left(P_{dech,b}^{el} - 1.4\sigma^{rec}m_b^{el} \right)} \quad (3.5)$$

Or $E_{VE,cons}$ the energy consumed by the vehicle, E_{max} ; the maximum energy of a battery cell. We can then calculate the number of elements $N_{s;b}; N_{p;b}$ pack of batteries by considering the variations of the consumption according to the source mass.

3.3.2 Sizing of HESS

The sizing of HEV energy storage systems is a complex problem that is difficult to solve using a classic sequential approach. In each sizing process, there are strong interactions between the mission of the vehicle (driving cycle), the characteristic, the performance of each ESS and the management of the energy processed on board the HEV. The determination of a certain number of series ($N_{s,b}$) or parallel ($N_{p,b}$) cells of the battery and cells ($N_{s,Hp}$; $N_{p,Hp}$) of the hp must adapt to the needs. user data and the vehicle's mission profile (see Figure 3.5) [116].

To resolve this problem, we resort to the hybrid optimization study (PSO/NM) developed in the work of Mesbahi [117] within the S2ET team of lab ESTACA-LAVAL. This algorithm succeeded in bringing together the dimension criterion and another effective power criterion with the same

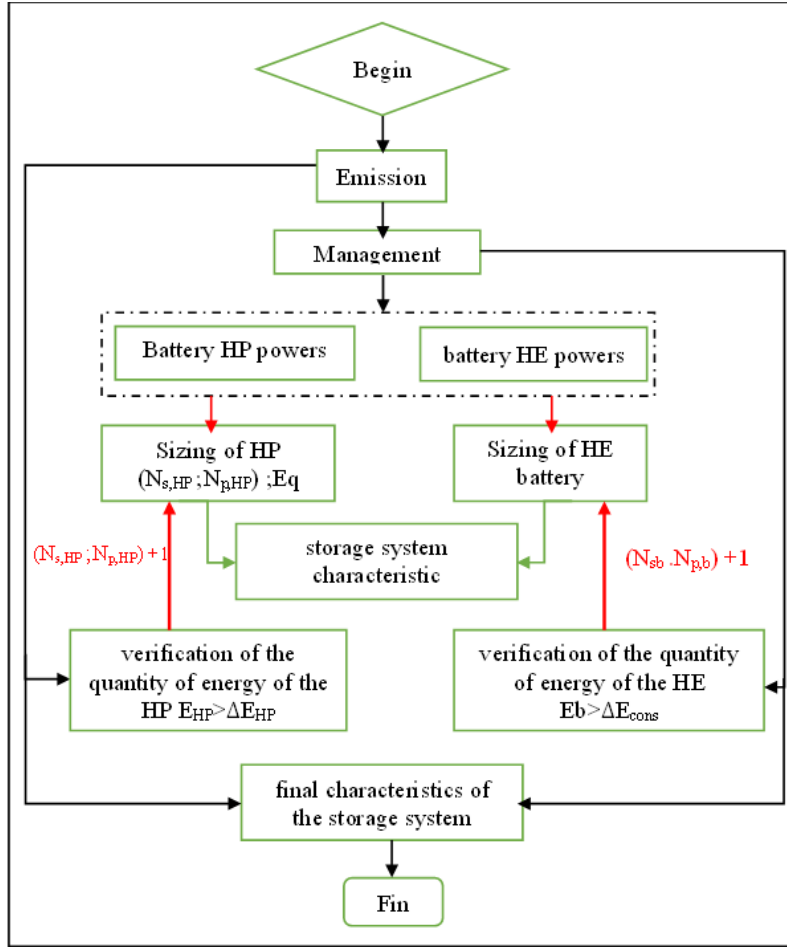


Figure 3.5: Power follow diagrams for global system

objective for a process of identifying the multi-physics model. In this work, we will develop a method Generic sizing methodology for a single battery-powered system or a hybrid source-powered system[118].

In summary, the sizing algorithm (Figure 3.5) in the figure’s flowchart has two main parts. The first step of this algorithm is to identify the energy and power needs for a given mission. This will then introduce the battery pack’s number of elements ($N_s; b: N_p; b$). The PV E load power limit can then be repeated. If the vehicle’s braking power exceeds the battery’s absorption capacity, the regenerative braking power is limited. This implies a reduction in the amount of energy recovered. A second step is then necessary to verify that the energy of the dimension pack previously is able to ensure the desired autonomy. This verification step is carried out several times until the source characteristics meet the energy requirements of the EV: The source of the

vehicle must be able to recover the full braking power (this condition is valid only in the case of a hybrid source) [119].

The source of the vehicle must be capable of providing all the power necessary for the propulsion of the vehicle. Finally, the source must carry the necessary energy to ensure the autonomy of the vehicle recommended by the specifications (Figure 3.6).

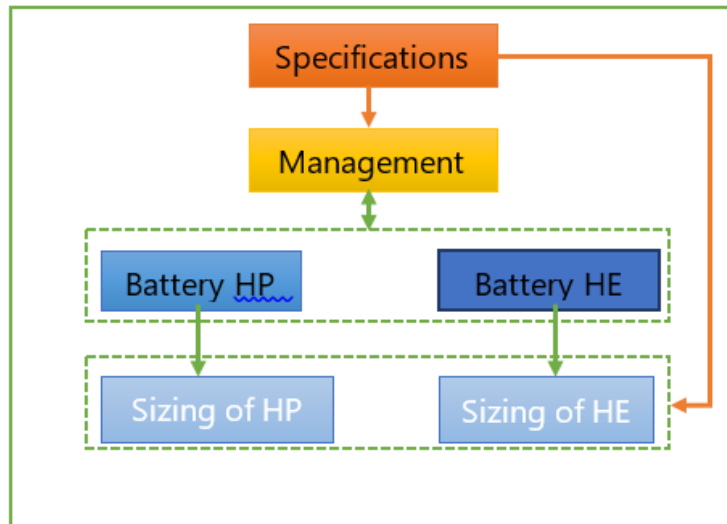


Figure 3.6: Relationship between design basis and management of a hybrid source [3]

3.4 Energy Management Strategies

The presence of two energy sources with two bidirectional converters introduces additional degrees of freedom in the Electric Vehicle (EV). However, these advantages can only be realized if a Power Management System (PMS) ensures the proper health of the vehicle's structure and the smooth operation of all employed resources. This PMS incorporates system information necessary to monitor the operation of various EV components with the goal of efficiently managing energy exchange safely. In general, the algorithms of this PMS oversee all the EV's components to determine the optimal power distribution between energy sources and the load at each moment [120].

The main functions of this manager are designed for efficient switching between different operating modes within an EV to extend the lifespan of Energy Storage Systems. (SSEs) and protect against potential damage. To achieve this, research into the best PMS strategy in terms of cost, robustness, reliability, optimization, and ease of implementation has led to numerous approaches over the last decade [121].

Figure 3.7 [122] summarizes the relationship between design basis and hybrid source management[?]. This process’s input variable is the electric vehicle’s power profile and the characteristics of batteries and supercapacitors. The output variables are the power instructions distributed on both sources.

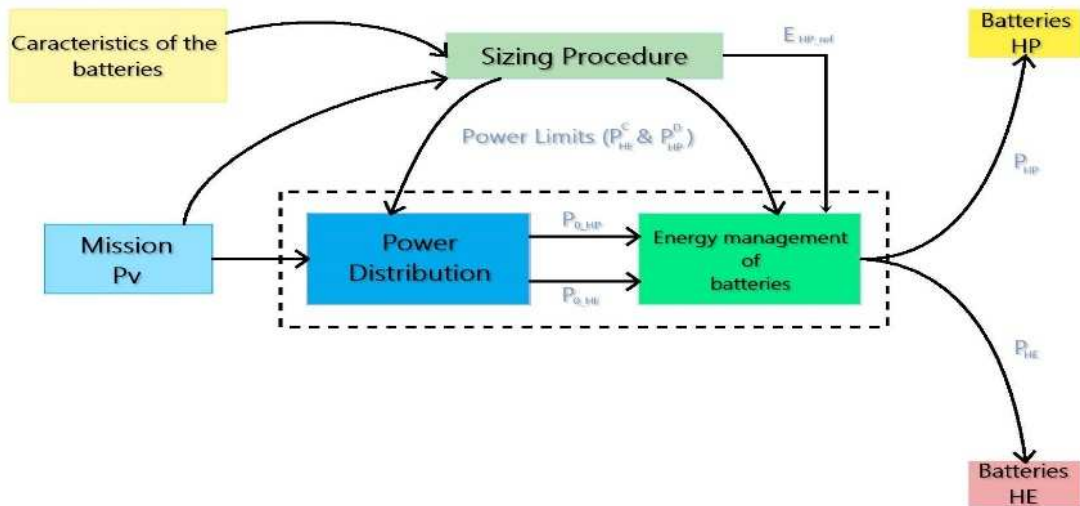


Figure 3.7: classification of energy management strategies

- Strategies are based on predefined rules (SR).
- Strategies based on optimization (SO).
- Strategies based on learning or machine learning (SL).

In Figure 3.7, all SR strategies are based on an intuitive control approach capable of translating engineers’ knowledge and experience into concrete results. This means these SRs consistently produce output signals to the drive train based on predefined rules.

Power-sharing control resulting from these strategies is generally based on information defined according to performance requirements, expectations, component constraints, state of charge of SSEs, projected results, mathematical models, and characterization of the cycle conducted without prior knowledge of the journey. These SRs are traditionally used by automobile manufacturers due to their simplicity and effectiveness in real-time supervisory control since these strategies do not require lots of computing power[123]. However, SRs strategies are easy to implement on a real vehicle, but because of these predefined control rules, they lack adaptability to different conditions. variable loads. So, developing analytical control mechanisms according to specific objectives requires a lot of effort to calibrate the VEH parameters carefully. Typically, SR approaches could be associated with deterministic, non-deterministic, or fuzzy rules [124, 125].

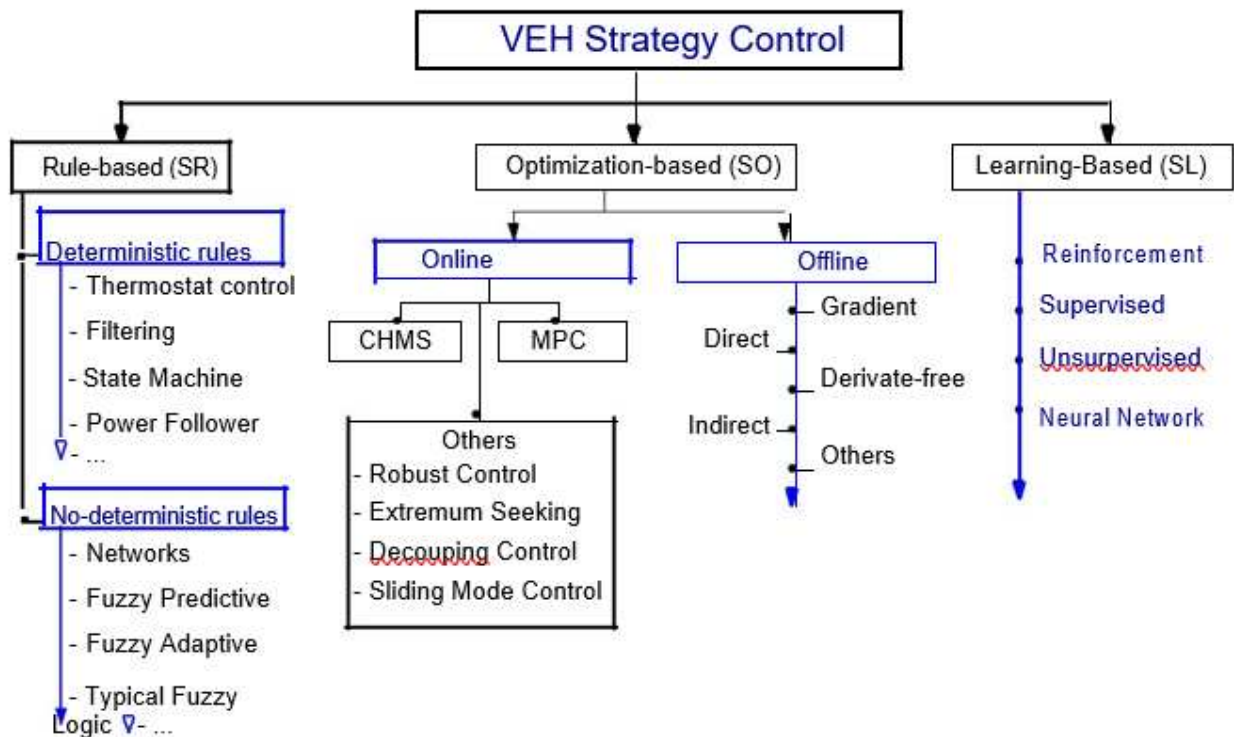


Figure 3.8: Classification of HEV control strategies

3.4.1 Rule based EMSs

- **Deterministic algorithms:** The thermostat and power follower strategies are among the first deterministic control strategies, and until today, they are still used in the industry. The thermostat strategy consists of controlling the state of the load by imposing hysteresis on it. It alternates the loading and unloading phases within a load operating range. Generally, deterministic strategies are based only on the present moment in decision-making and not on the entire driving path to be carried out. A comprehensive understanding of the physical system is usually required, as is a thoughtful anticipation of various scenarios to ensure a robust control strategy. The main advantage of this type of algorithm, which has attracted the attention of automobile manufacturers, is its easy and robust implementation. Take the example of Toyota Prius and Honda Insight, which chose energy control based on deterministic management strategies such as the power follower strategy. The best-known deterministic approaches are those generally called as follows [126, 127]:

- Thermostat control strategy (on/off).
- Power follower power saturation strategy (Baseline).
- Modified power saturation strategy (baseline).
- Strategy frequential.
- Strategy state machine.

- **Non-deterministic algorithms:**

Non-deterministic strategies include grouping algorithms such as fuzzy logic (FL), artificial neural network (NN), vector machine, etc. These approaches, such as Deterministic approaches, include intuitive heuristic algorithms, which generally ensure simple, reliable and robust control. An expert's knowledge can be encoded into a rule base and used in decision-making.

A fuzzy-based controller is a natural extension of many rule-based controllers implemented via lookup tables of many vehicle tests. FL represents a good alternative to control prob-

lems of non-linear and complex systems. The fuzzy logic system includes four main components, which are explained using the architectural diagram presented in Figure 3.9 [128].

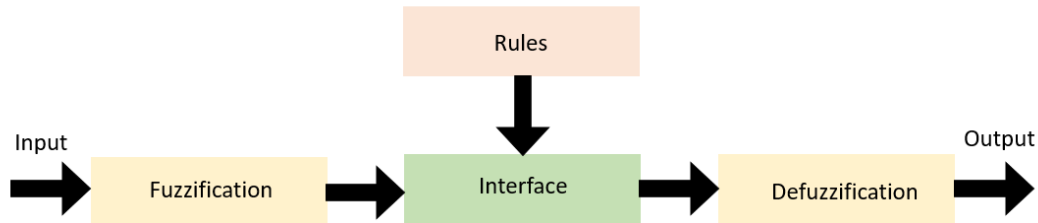


Figure 3.9: Architecture of fuzzy logic

In fuzzy logic, the input and output variables are characterized by fuzzy linguistic terms like weak, medium, and strong and are assigned membership functions, unlike in deterministic logic, which performs a binary classification 0 or 1. The fuzzy logic supervision strategy is considered suitable to create a global management of energy flows between electrical equipment and ESS devices. [129] [130] show the energy efficiency of the fuzzy strategy than that of the original strategies based on rules just for one cycle specified driving conditions, but this FL cannot automatically adapt to different driving cycles. In addition, the solutions proposed for these strategies are also sensitive to model uncertainties, measuring noise and disturbances, which requires a faster microcontroller with larger memory. However, the performance of such a strategy can also vary depending on the function of the driving type as well and an error can usually occur when designing such an *FL* controller, particularly for the construction of membership functions. Consequently, the optimality of this approach is not cannot be guaranteed for different driving scenarios [131].

3.4.2 Strategies based on optimization

Strategies based on optimization use mathematical tools to find the optimal operating sequence of a system with respect to a cost function to be minimized. In recent years, researchers have carried out numerous works on the optimization control of HSSE. Among the different applications of the optimization control algorithm, the power loss of a HESS (PHSSE, losses) is generally

considered a function of optimization objectives which can be defined as follows:

$$P_{\text{HSSE}; \text{losses}} = P_{\text{HE}; \text{losses}} + P_{\text{HP}; \text{losses}} + P_{\text{DC/DC}; \text{losses}} \quad (3.6)$$

In other words, these methods make it possible to obtain the mathematical optimum with precise knowledge of the rolling cycle. But, it is very difficult to imagine a case where the speed cycle would be known in advance and exactly. In reality, the uncertainty is great because the speed cycle depends on several factors, such as road conditions (traffic, signs, type of road) and the user's driving style. In general, the optimization-based control method has high algorithmic complexity, low robustness in changing the speed cycle and is difficult to implement in time-lapse applications. So, knowledge of vehicle driving information is necessary in improving projects for these optimization strategies (see Figure 3.10 [132]).



Figure 3.10: Concept of intelligent energy management for a HEV .

Many researchers have proposed different forecasting techniques to recognize and predict future driving conditions, including GPS or ITS-based techniques, statistical analysis and clustering techniques, and techniques based on the Markov chain. But the big drawback in order to build the Markov model for power demand, a large number of driving cycles is needed to obtain enough data. If the dataset is not rich enough to cover the entire state space, the transition prob-

ability may be zero, which will affect the control policy. In other words, if the driving conditions are known, it is possible to obtain the necessary information to predict the energy demand based on the vehicle dynamic equations [133].

Optimization strategy can be classified into offline and online optimization depending on the level of driving conditions information used. online optimization strategy: Control strategies applied to power-sharing problems of an HSSE, optimized and implementable in real time for automotive applications, is a d challenge and several problems must be resolved for its effectiveness and practicality. In parallel, the consumption minimization strategy (ECMS) and the model predictive control (MPC, LMPC) are widely used as online SO. As an example, the predictive control methodology (MPC) calculates an optimal control solution, in real time, based on a dynamic system model and its predicted future evolution. Briefly, only the calculated control inputs associated with the current time step are actuated on the physical system. With new measurements of the physical system, a new state of the dynamic system is estimated and the real-time optimization procedure is repeated (see figure 3.11 [134]).

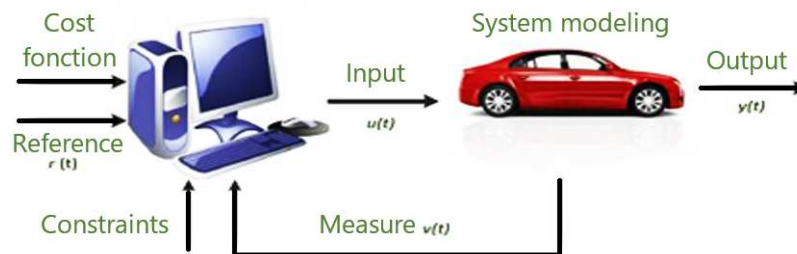


Figure 3.11: MPC method function principle.

To reduce the computational cost of this nonlinear optimization problem, the nonlinear power plant model (traction chain model) and the nonlinear constraints are in lost at each sampling time. In the MPC-based control strategy, the optimization is solved over a future prediction horizon of 5 seconds. With this short prediction horizon, he is likely to make short-sighted decisions. On the other hand, with a long prediction horizon, the solution of the optimal control problem requires a high computational effort.

Offline optimization strategy: Offline methods assume knowledge performance of the entire driving cycle. These methods make it possible to calculate a reference solution, that is to say, the

lowest possible consumption, which can also be analyzed to design an appropriate online strategy. Among the SOs developed offline, dynamic programming (DP), Pontryagin’s optimization principle (PMP) and metaheuristic search methods (i.e. the algorithm Genetics (GA), hot particle optimization (PSO) and simulated annealing (SA) are widely used.

3.4.3 Strategies based on Machine Learning

SL approaches have shown promising potential due to recent advances in machine learning and artificial intelligence techniques for data-driven network training approaches. online. *SLs* can learn historical data or use previous driving data for online learning. In an intelligent transportation system, traffic information in a global positioning system (GPS) and a cloud database can be integrated into a PMS to improve vehicle performance. vehicle. A massive amount of real-time data can be obtained via intelligent infrastructure, as shown in Figure 3.12 [135] [136].



Figure 3.12: MBM Formulation Flowchart.

In the reference [137], the author addressed the problem of energy management of a plug-in hybrid electric bus using deep deterministic policy gradients, which searches for optimal solutions in a continuous state and a space for action. The training driving cycles are generated from the traffic simulation. The traffic information collected by the traffic sensors is used to improve the performance of the proposed algorithm. networks have acquired explicit knowledge about energy management. Existing reinforcement learning approaches have shown that they are entirely feasible for study simulation and potentially beneficial for designing real energy management rules for hybrid electric vehicles. However, the direct use of reinforcement learning approaches on real-world hybrid electric vehicles is hampered by the reality gap. The reality gap is a subtle but important discrepancy between reality and simulation that prevents the simulated experience from directly enabling real-world performance. The reality gap in this study is due to the difference between the simulation and the real powertrain and driving cycles. A superficial solution directly uses a real vehicle to train the reinforcement learning model. However, direct use of a real vehicle will result in high costs and uncontrolled risks. Therefore, learning about the energy management of HEVs is a rich area of research for the coming years, and it requires more effort for real implementation within this type of vehicle.

Furthermore, some recent studies related to energy demand modelling transport such as Refs [138] imply the methods NN_s for forecasting long-term energy demand considering various indicators such as socio-economic indicator, energy consumption short-term EV_s on different segments of the road network, dependence of the energy consumption of vehicles on the mass of the vehicle and the cycle of driving etc.... The learning algorithm tends to create hidden neurons with output values as a function of the input parameters from the learning functions, like the example in diagram 3.12. The good choice of neural networks as a technique comes from their capacity for automatic learning, the efficiency of their synaptic weight, which allows the transmission of signals from one neuron to another, the functions of learning, their capacity for classification and generalization, etc.. The main advantage of these NN strategies is their deep computing model and ability to automatically learn the functionalities of the given inputs to trans-

fer knowledge of the basic task to others. On the other hand, overfitting and/or underlearning are mainly the disadvantages and limits of these methods of NN-based management, according to Ref [139].

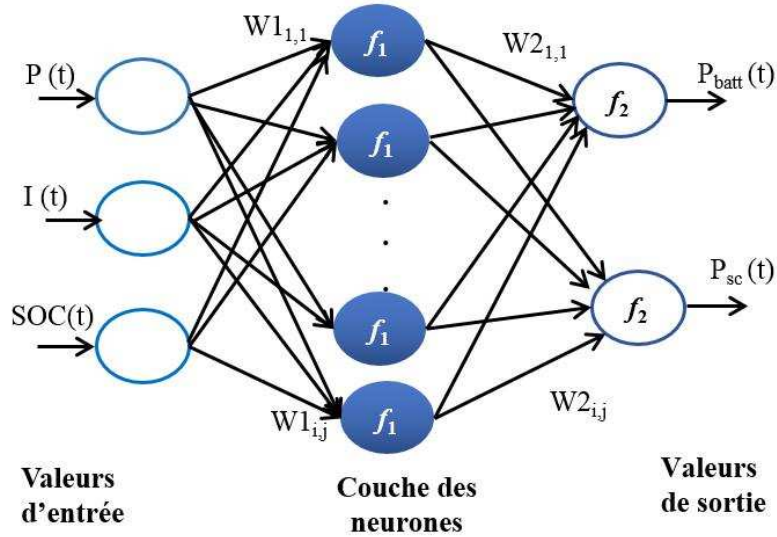


Figure 3.13: Neural network structure.

3.4.4 Developed EMSs

According to Refs [140] and figure 3.13, the comparison of the performances of various PMS algorithms shows that none of these existing strategies can meet all the requirements control objectives simultaneously in terms of energy efficiency and vehicle performance. Furthermore, rule-based strategies presented successful features in terms of real-time adaptation, while the major problem of SO and SL is their real-time applications with a very complicated calculation time. However, the best-known RS_s strategies, such as the Limitation method (ML), Filtering method (MF) and the hybridization of these two Filtering-Limitation methods (MFL), are incorporated in our HEV application according to the point of view of their simplicities and their ease of implementation in real-time [141]. The basic idea of these power methods is sharing the power required by the load between the two energy sources in real-time. Then, the stress of the Li-ion battery can be released because part of the power is transferred to the HP bank [142, 143]. In this situation, we risk completely unloading the secondary source at the end of each driven cycle

or loading the HP bank without any control algorithm[144]. As we know, *HPs* have extremely low internal resistance compared to Li-ion batteries, which allows them to be recharged much faster or deliver a very high current. e. Each *HP* has a maximum voltage limit that must not be exceeded because charging at a voltage higher than the nominal voltage will damage it and can go so far as to make it explode by increasing its rate of voltage. self-discharge and will shorten its lifespan. In this case, the *HP* can then swell and emit a gaseous release, harming the uncontrollable *HPs* of *SOCHP* (See the section 3.4.4). To avoid taking risks and guarantee a long lifespan of the *HPs*, we recommended maintaining a safety margin and increasing the loading of the *HP* up to a *SOCref* even ' at the end of the driving cycle. Our study aims to improve the *ML*, *MF* and *MLF* strategies by inserting another algorithm called Control *SOCHP*, which aims to control the hp state (See section 3.4.4) and control the risks.

Management strategies without Control SOCHP

The three techniques *ML*, *MF* and *MLF* are based on the DC bus voltage regulation loop (V_{bus}), which implements a PI corrector which generates a load current reference called $I_{ch\ddot{y}ref}$ and is intended to control the current of reference of the HP (I_{HPref}) and the Li-ion battery ($I_{battref}$) through the chosen management strategy (see figure 3.14). The efficiency of the *VEH* is therefore increased by controlling the current flow of the load.

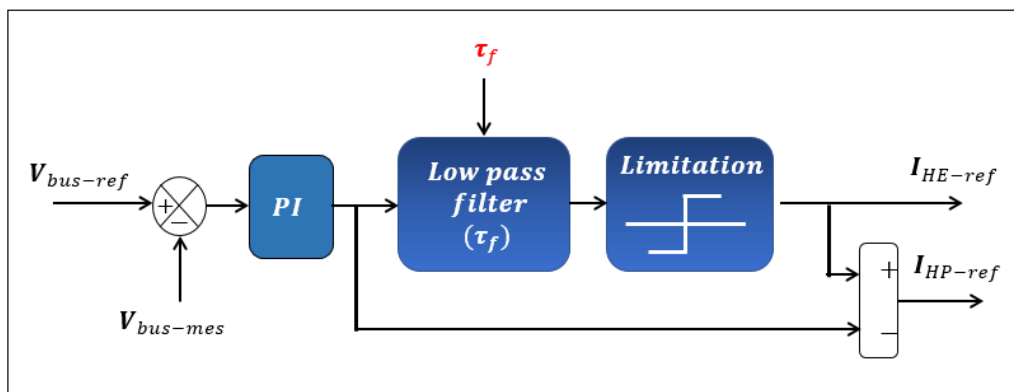


Figure 3.14: Principle of Limitation Method.

- **Limitation Method:** This ML strategy [Limitinf /LimitSup]) makes it possible to limit the power/current within a well-defined range. The two thresholds LimitSup and Limitinf, are defined in advance to limit the power/current of the Li-ion battery. On the other hand, HPs take care of the difference between each threshold and the power/current of the load. Generally, the choice of these power thresholds is based particularly on the characteristics of the storage systems used [145]
- **Filtering Method:** The *MF* method is an open loop control scheme for battery power/current. The required power (*PV* EH) is broken down into two parts via a low-pass filter. This type of sharing requires the *HP_s* to take charge of power peaks according to the time constant (*τ_f*). The high-frequency part is also dedicated to the hp bank, and the Li-ion battery operates at low frequency (see Figure 3.15) [146].

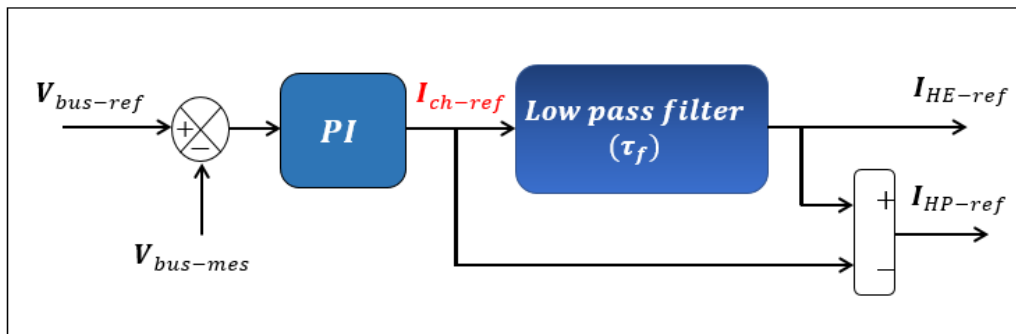


Figure 3.15: Principle of Filtering Method.

- **Filtering-Limitation Method:** This strategy (*MFL*) is an association between the previously presented techniques. The concept of flow distribution is the same. However, it offers more flexibility since the power limit threshold on the battery side is variable depending on the quantity of energy in the *HP_s*. This strategy offers more degrees of freedom in manipulating power flows and, consequently, better performance. The goal is for the battery to provide the low frequencies of the traction power and the *HP_s* to provide the rest (see Figure 3.16) [147].

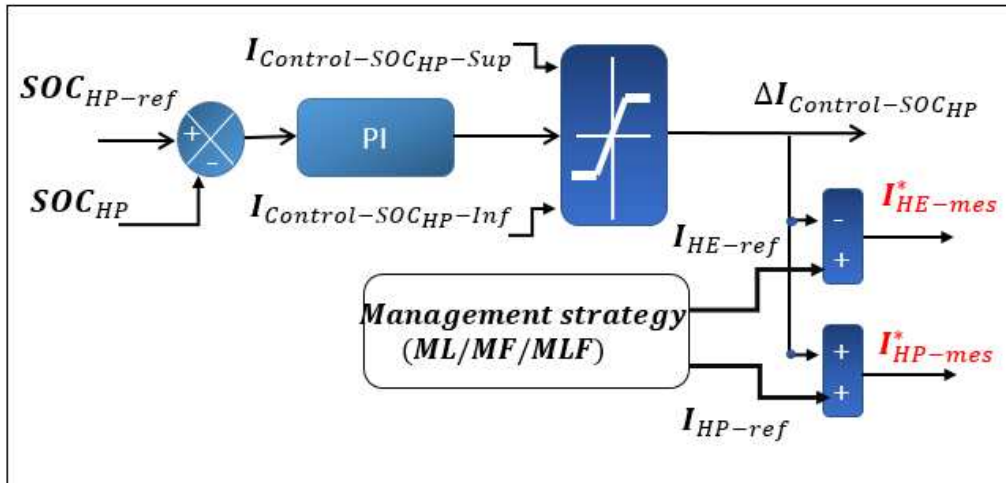


Figure 3.16: Principle of management strategies without Control SOCHP.

Management strategies with Control SOCHP

The three methods mentioned above each generate a reference current from the Li-ion battery without considering the state of the charge of the HP. These three algorithms were improved by adding another SOC_{sc} control block, illustrated in figure 3.17. The principle of this management is to manage the profile distribution of the power/current of the VEH between the Li-ion battery and the HP by ensuring the charging of the latter SSE at the end of each. The PI regulator aims to make the SOC state due coincide with the SOC_{ref} reference value, which is predefined.

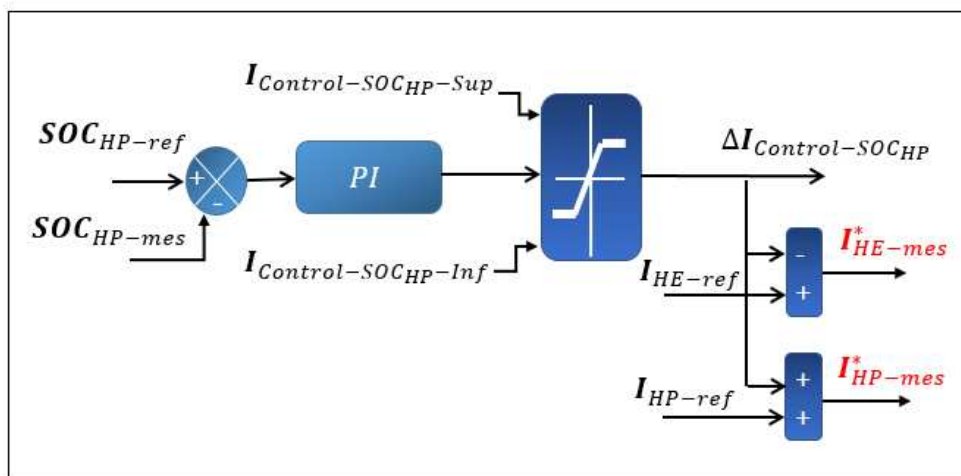


Figure 3.17: Principle of Management Strategies with Control SOCHP.

3.5 Simulation Result

The problem of energy management is, in this case, to find the best distribution of the requested power between the various energy storage costs of the system. The system can be based on the consumption of fuel, pollutant emissions, component life, driving comfort, etc. In this context, a series of optimization techniques were applied last year to solve the problem of energy management in electric vehicles hybrid programming, such as linear or non-linear programming (*LP* and *NLP*), dynamic programming (*DP*), linear-quadratic optimal control (*LQ*), and genetic algorithm (*GA*). The main objective of these optimization techniques is to continuously provide the requested power along a mission profile, minimizing the system's "cost" function as much as possible. Regarding the energy regulation of secondary sources, a criterion optimization that considers several parameters simultaneously (especially the maintenance of the state power source load) is generally used in these power source management strategies energy based on optimization. In the following two parts, we analyse two groups of commonly used methods for optimal energy management.

3.5.1 Power distribution methods based on rules (without Control SOC)

Rules-based energy management methods have the advantage of being more simply implementable in real-time and do not require, a priori, to know the cycle [148] contrary to optimization-based strategies. The energy management rules used in this category are defined in advance by the expertise or analysis of the behaviour of system components. We present in this section the main rules-based energy management methods for a hybrid automotive storage source.

Strategies based on frequency energy

Frequency energy management consists of making sources of complementary energy and power (battery HE/ battery HP), considering the characteristics intrinsic to each source to ensure the vehicle's overall mission. The guiding idea of this strategy consists of distributing the low-frequency components of the traction power to the power source (*PHE*) and high frequencies at the power

source (PHP) [149].

They focused on sizing methods for hybrid sources for powering an electric vehicle. Therefore, we have chosen the optimal value of the cutoff frequency ($F_c = 1Hz$) to obtain the best mass of our hybrid source with frequency strategy.

Figure 3.18 illustrates the principle of frequency energy management. The power (P_v) required for the propulsion of the electric vehicle is broken down into two parts by the low pass filter.

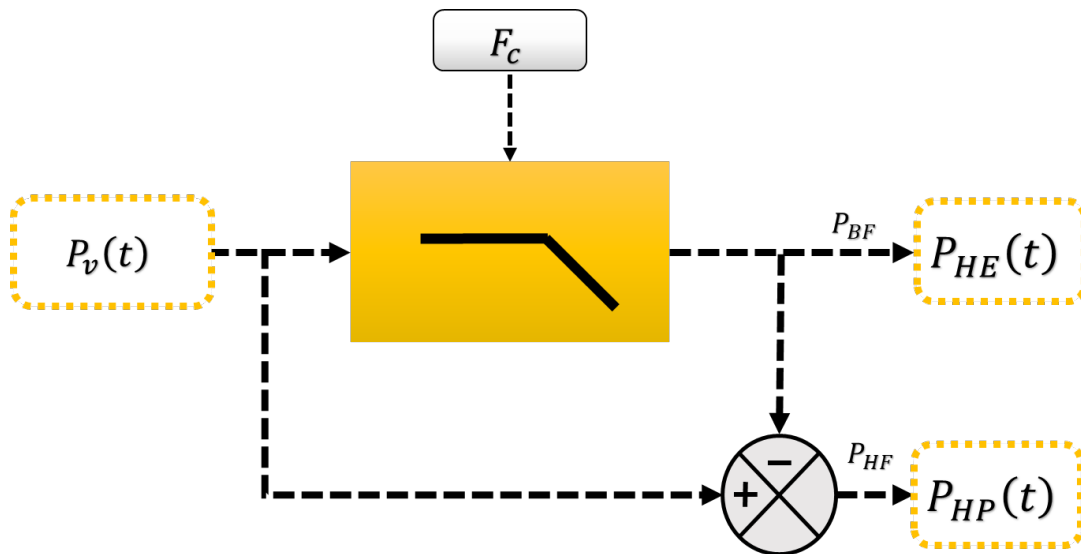


Figure 3.18: Principle of the frequency energy strategy.

One of its main contributions is to filter a priori with a smoothing filter digital the power requested so as to affect the low-frequency traction powers at the main source (fuel cell), the storage element supporting the high-frequency positive powers on the one hand and for negative powers, ensures the possibility of de-stocking braking energy[150].

Application:

The mission profiles (power and energy) of the batteries HE and HP, given by the filtering, are shown in Figure 3.19. It can be seen that the power recovered by the batteries HE is zero and that the batteries HP have, most of the time, the task of recovering this energy. In addition, the high powers returned to the batteries HP are not necessarily high-frequency harmonic powers.

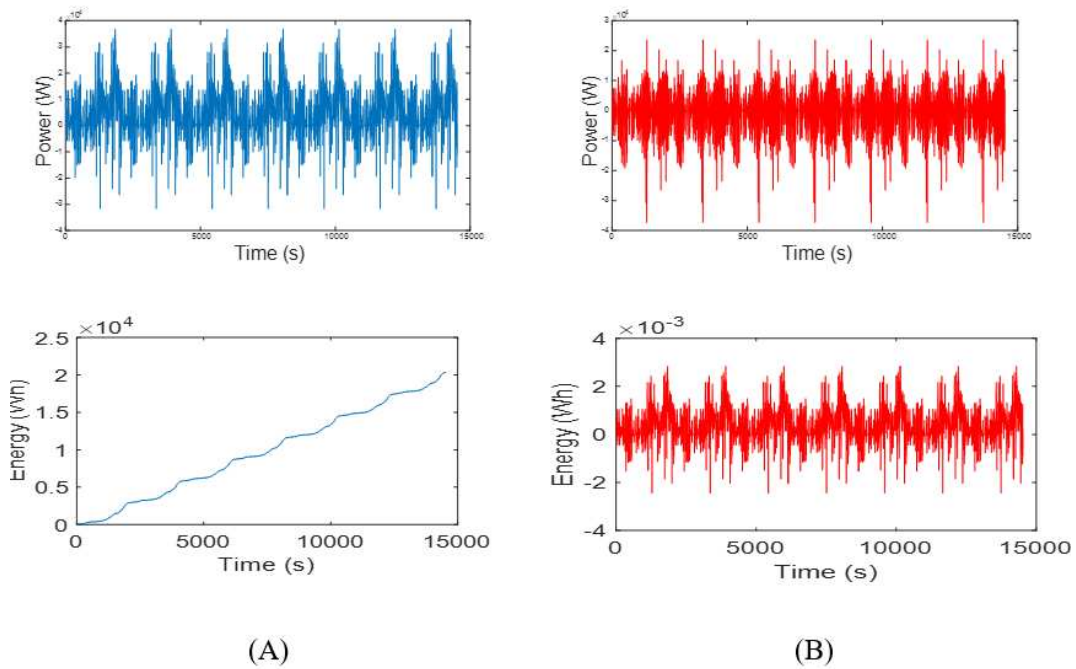


Figure 3.19: Power and energy profiles from filtering strategy. (A) batteries HE, (B) Batteries HP.

Strategies based on power limitation

This strategy uses a classic power saturation approach. It consists of limiting the charging and discharging power of the HE battery in advance over the entire route considered. The use of power limits then makes it possible to maintain the state of charge HE battery power within an acceptable range and provides an additional degree of freedom to help optimize the operation of the hybrid storage system. Indeed, the choice of the limits of battery power is generally related to the average mission power and the internal characteristics of the two components. Figure 3.20 presents energy management in a hybrid source where the instantaneous power is broken down into two missions. This example of power profiles shows that the energy management algorithm limits the battery power in both phases (charge/discharge). The HP battery then ensures the power difference between the mission of the vehicle (P_v) and that of the battery (P_{HE})[151].

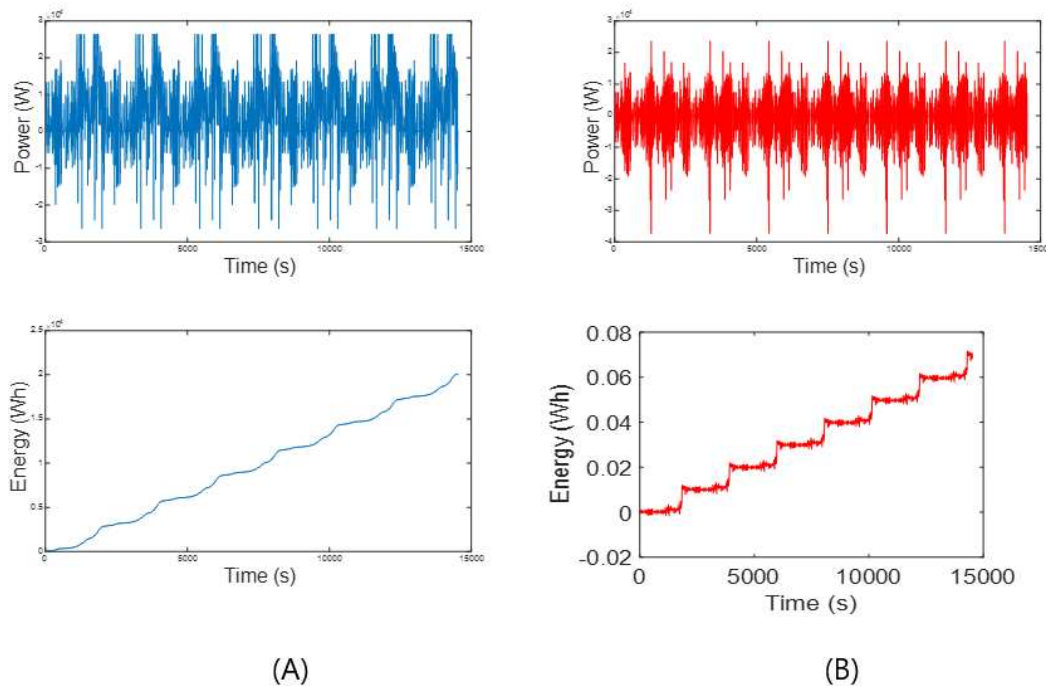


Figure 3.20: Power and energy profiles from limitation strategy. (A) batteries HE, (B) Batteries HP

3.5.2 Strategy based on power limitation with SOC control

To meet the same objectives imposed for the power limitation method, namely using batteries to ensure autonomy and HP batteries for power peaks. These should be recharged to energy balance at the end of the driving cycle. To do this, modifications have been made to the frequency management strategy by integrating battery power saturation and management of the battery's state of charge *HP* (see Figure 3.21)[152].

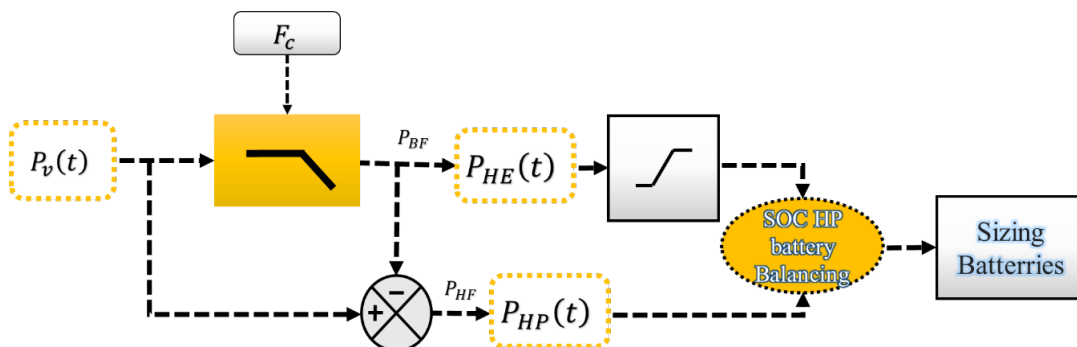


Figure 3.21: Principle of the power limitation with SOC control strategy

In fact, the mission profile imposed by the filtering makes it possible to pre-sizing the battery pack and thus obtain these charge and discharge limits (PHE_C, PHE_D).

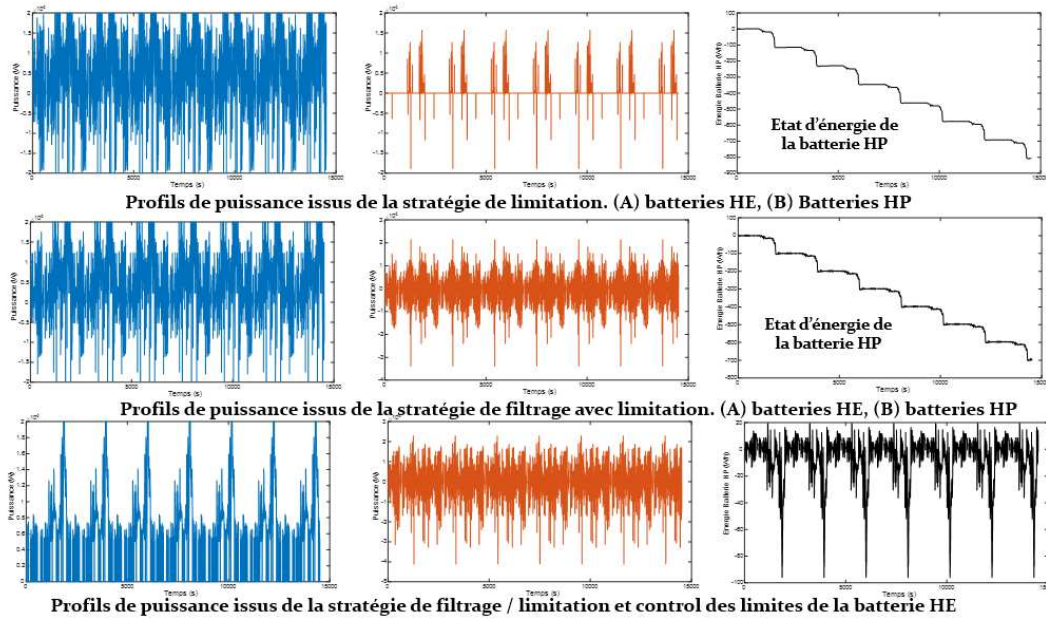


Figure 3.22: Comparative Analysis of Power, Energy, and State of Charge (SOC) Profiles for Various Energy Management Strategies in Hybrid Sources.

3.5.3 Comparison of results

Table 3.4: results of management methods

Method	Pe _{eff} _HP (W)	Wh <i>Exch</i> * HP (Wh)	Pe _{eff} _HE(W)	Wh <i>Exch</i> * HE (Wh)
Battery alone	/	/	10,66	93,81
Hybrid source with power limitation	33,67	22,98	9,94	90,09
Hybrid source with filtering and power limitation	72,63	185,45	9,46	87,29
Hybrid source with fixed limitation filtering and HP battery SOC regulation	117,07	295,63	9,81	71,76
Hybrid source with variable filtering/limiting and HP battery SOC regulation	134,11	351,05	8,38	71,00

*Exch: Exchanged

In the graphical representation (Figure 3.22) showcasing the evolution of power and energy,

as well as the State of Charge (SOC) for both High-Energy (HE) and High-Power (HP) battery technologies under various management methods, distinct patterns emerge.

When employing power limitation, the constraints on battery power are notably low. However, it's observed that the battery's energy state diminishes with usage and does not return to its initial state. This indicates that energy retention remains a challenge while power constraints are effectively managed.

Introducing the filtering method increases power constraints on the HE battery, with a moderate smoothing effect on its power profile. This implies a more controlled power delivery but comes at the cost of higher constraints on the battery power.

The developed method showcases a maximum smoothing effect on the power profile of the HE battery. This reduces constraints on this component, demonstrating an effective strategy to manage power fluctuations. Additionally, it's noteworthy that the energy state of the HP battery consistently returns to its initial state. This highlights the efficiency of the developed method in maintaining both power delivery stability and the energy state of the HP battery.

In summary, these graphical representations provide valuable insights into the trade-offs and benefits of each management method. The developed method stands out for its ability to mitigate power constraints, especially for the HE battery, and ensure the recovery of the energy state of the HP battery.

The comparison Table 3.4 provides a detailed overview of the constraints results obtained with various management methods for both hybrid and single-source configurations. The findings from this analysis underscore the advantages of hybridization in general, demonstrating a substantial reduction in constraints imposed on the High-Energy (HE) battery.

In particular, using the variable limits method yields a significant gain of 21.4% in effective power and a 25% improvement in exchanged watt-hours (Wh). These results highlight the enhanced efficiency of this dynamic energy management approach, enabling a substantial optimization of hybrid system performance. These benefits are evident in the reduction of constraints and more efficient utilization of exchanged energy, reinforcing the overall advantages of hybridization in this specific context.

3.6 Conclusion

In this chapter, after comparing the different energy management strategies for a hybrid storage source, the different elements of (HE and HP batteries) have been sized to meet the demands of propulsion power and full energy recovery during vehicle braking. The results of hybrid source sizing with different management strategies showed an interest in hybridization and the importance of choosing the management method for optimizing the energy source. It was then demonstrated the value of a new approach to energy management based on the variation of power sharing according to the state of charge of the HP battery. Energy management strategies for the hybrid storage source were presented and compared with a literature reference method regarding physical constraints seen by the HE and HP battery components. The comparison showed that the constraints of efficient power and quantity of energy exchanged, as seen by the batteries, can be reduced with the proposed management methods by more demanding HP batteries. This small increase is far from preventing HP from ensuring the power demands imposed by the vehicle.

CHAPTER 4

EXPERIMENTAL VALIDATION

Contents

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4.1 Introduction

The complexity of the HEV studies that they associate two systems of storage with a parallel architecture necessitates a control, in real-time, of the controllers of management in order to answer to the demand of the load while respecting the various constraints related to source characteristics and system security. In other words, the key to our work is the development of robust and efficient control laws for powertrain energy management. However, the present study aims to improve the strategies of methods controls (LM, FM, LFM) to minimize the stress of the battery compared to the stress of a vehicle only by a single source. In addition, this study also aims to integrate the SOC Control strategy to regulate the intervention of the battery during the rolling cycle, with better overall performance. These laws have been implemented and validated on a real prototype, taking into account additional constraints such as driving aggression, operational safety, etc...

This chapter begins with a brief description of the test bench developed in the laboratory breast to ESTACA in order to validate the proposed management approaches. In all the practical works carried out in our thesis, we consider that the ambient temperature is, on average equal to 25°C HEV is negligible provided the temperature is between 10°C and 30°C but at very high or low temperatures, a precise thermal model is necessary for the Li-ion battery. This problem will not be considered because it is not one of the major objectives of this topic. In n, presenting the main experimental results led to a comparative study between the proposed energy strategies. Finally, we will present the main experimental results for judging the performance of the two energy management strategies and their influence on ESS in terms of mass, volume and constraints seen by components of storage [153].

4.2 Test Bench

This work is concretized by implementing a laboratory prototype S2ET ESTACA-Laval to implement the batteries that are dealt with in these. This experimental platform allows the testing and

evaluation of the management laws from the control and coordination between the energy production units, the converters and the load. This bench integrates the Li-ion battery pack but an emulator of the HP battery pack. This emulator includes a model of the HP battery with control loops to emulate the stable and dynamic characteristics of the HP battery in EVs applications by reproducing the same voltage/current characteristic of the real battery. The main objective of exploiting such an emulator in the test bench is to avoid safety problems generally caused by misuse within the practical experience [154].

The complete model of the HEV, which is relatively complex and highly non-linear, was implemented under the environment Matlab-dSPACE.

The experimental platform consists of an emulator of the HP battery system with a lithium-ion (180Ah, 24V) and an electric vehicle emulator with an output of (1kw, 150V). An interface between the dSPACE and MATLAB-Simulink ensures the test bench control and supervision, as shown in Figure 4.1. At execution program, the Matlab-dSPACE interface known by the name ControlDesk allows to entry of the parameters related to the command, the acquisition, as well as the graphs, and also allows to follow the evolution of the system as the load states of sources[155] (SoC_{HE} and SoC_{HP}), profiles of currents (I_{ch} , I_b , I_{HP} , I_{emul} ,...) and profiles voltages (V_{HP} , V_{bus}).

In addition, voltage and current sensors have been used to recover real-time all measurement data in order to monitor and control the energy flow during the various tests. The test bench, which is photographed in Figure 4.1, is a reduced scale, and the range of usable power is 2000W. Figure 4.2 presents the synoptic of the test bench.

In our hybrid topology, two converters (CV_1) and (CV_2) are needed as power interfaces for the HP battery bank. The hybrid source consists of lithium-ion batteries HE as the primary source and HP as a secondary source connected to the DC bus.

This bench consists of a Li-ion battery pack as the main source and an emulator of the battery HP module or supercondensator. The latter's behaviour is ensured by a model embedded in the rapid prototyping system, which controls the voltage at the converter's output (CV_1) according to the current measured at the latter's output. This emulation of the supercondensator allows



Figure 4.1: Test bench.

secure use of the system with a representation of the actual behaviour of this component[156]. Figure 4.3 shows the principle of emulation of the SC using a dS1104 board and a Semikron converter.

The test bench is supervised by a dSPACE 1104 board programmed under MATLAB-Simulink, as shown in Figure 4.4. A ControlDesk tool developed by Mathworks allows us to configure and display curves. This tool also allows the acquisition of data, such as the charge states of the battery and supercapacitor (SOC_{HE} and SOC_{HP}), the current profiles of the charge (I_{ch}), the battery (I_b), the HP (I_{HP}) and the one at the input of the HP emulator (I_{emul}). The HP voltage profiles (V_{HP}) and the continuous bus voltage (V_{bus}) can also be displayed and saved.

The acquisition of this data allows us to feed the control loops used to ensure the emulation of the superconductor as well as the energy management between the different storage systems. With this bench, one can pass a power of less than $2kW$ [?].

In our hybrid topology, two converters (CV_1) and (CV_2) are required as power interfaces for the HP battery emulator. The first CV_1 converter is used to reproduce the behaviour during the

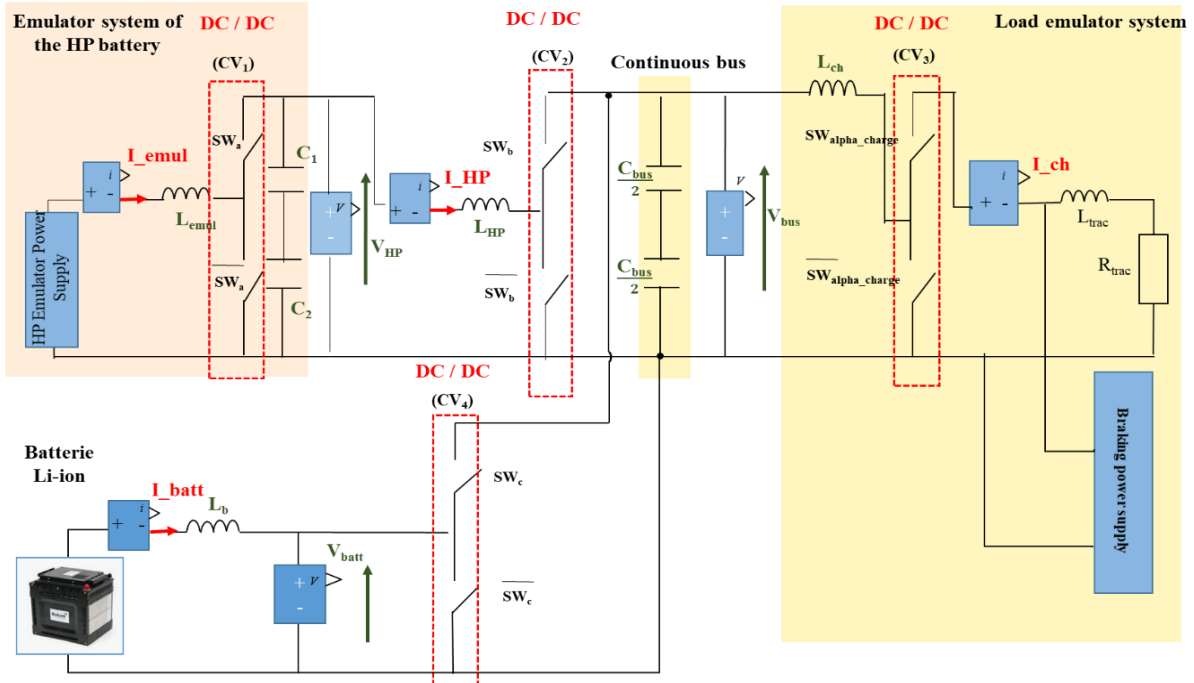


Figure 4.2: Synoptic of the test bench.

charging phase of the SC . While the second CV_2 converter will manage the phase of discharge. In our case, the battery and the battery emulator are connected to the DC bus through two bidirectional converters (CV_4 and CV_5). The tensile current imposed by the load is ensured through the converter CV_3 , which dissipates the power in a resistance. While the braking phase is emulated using a programmable power supply.

The control of the converters (CV_1 , CV_2 , CV_3 , CV_4 and CV_5) is ensured by using regulators of type Proportional Integral controller (PI). The effect of variations in controller settings on system performance is not discussed in this study. The exchange of power between the two storage systems and the load is provided by the three converters (CV_3 , CV_4 and CV_5) for the various operating modes according to a realistic driving cycle. However, the ARTEMIS cycle, recorded by INRETS, represents driving dynamics much closer to reality, like the WLTP cycle.

Using this type of cycle allows us to assess the dynamic response of the strategies developed. It should be noted that the ARTEMIS driving cycle is based on a statistical study carried out by the laboratory.

In the following sections, we present the practical implementation and comparison of the results

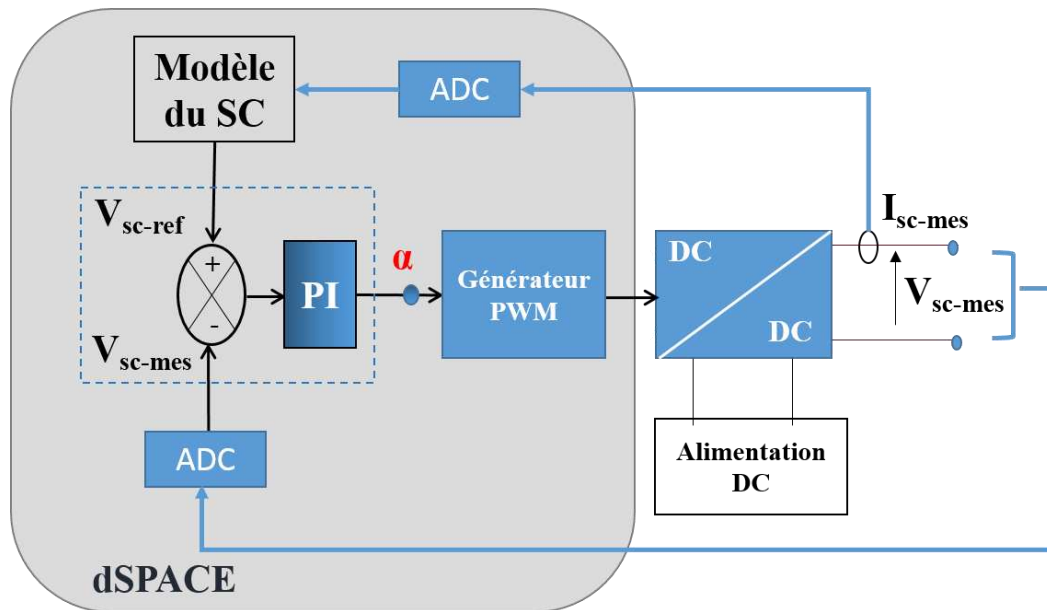


Figure 4.3: Principle of Supercapacitor emulation.

obtained with the different energy management strategies for the hybrid source composed of a pack of HE and a battery HP module. In our comparative study, we use the following two criteria:

- Maintain DC bus stability around the 110V reference value. The voltage stability at the input of the inverter is very important to ensure the continuity of service. In this case, it is necessary to stabilize the value of this voltage in permanent conditions with a minimum variation, except at power peaks. This is mainly due to the large ripple of the inductor current [? ?].
- Improvement in the lifespan of the storage system: using a hybrid source requires us to monitor the performance degradation of the two storage systems (battery HE and battery HP). With a very high power, the HP battery is much less stressed than its potential power. For this, in our work, we focus our objective on reducing the stress on the battery by placing more stress on the battery HP. This strategy allows a balance in the use of the two components, which will improve the life of the overall source. Two indicators will be evaluated to extract the image of aging:
 - The effective current left for the two storage systems.
 - The ampere-hours exchanged by the two storage systems during cycling.

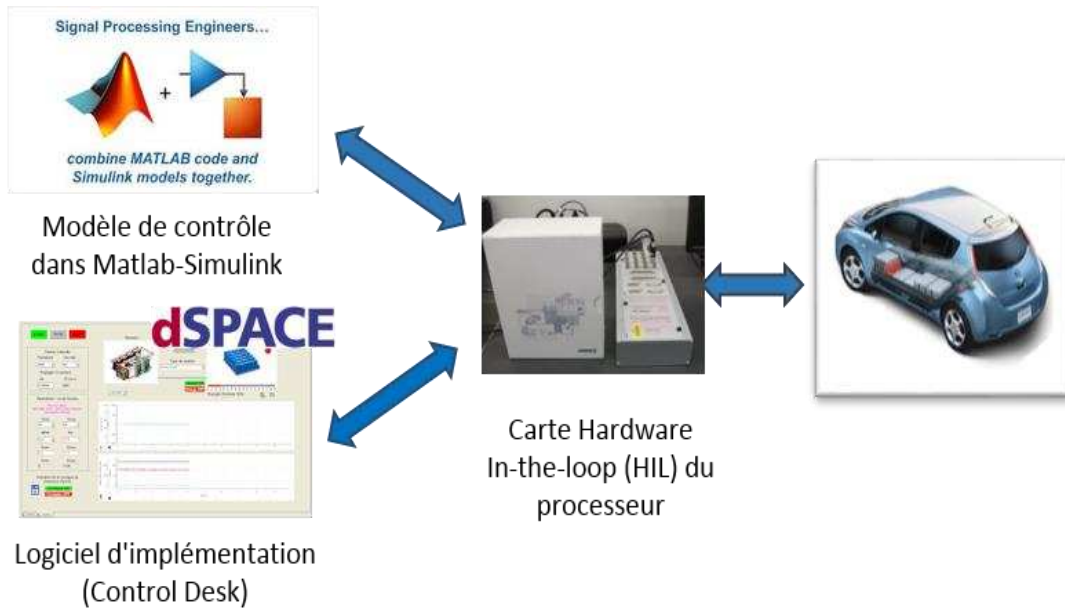


Figure 4.4: Matlab-dSPACE.

4.3 Validation of energy management strategies

4.3.1 Implementation of the strategy based on frequency separation

The principle of frequency separation-based energy management approach is based on the division of the power mission into several frequency channels to share this required power between the battery HE and battery HP in order to respect the dynamic of these sources and give a better lifetime to the battery HE. For this reason, each different band-pass channel will be sent to a specific power source. Thus, high-frequency demands will be produced by battery HP and those characterized by low frequencies will be given by the battery HE [157, 158].

This can be achieved using a low-pass filter characterized by a frequency of splitting (F_c : also called cut-off frequency) which obviously has a direct effect on the constraints applied to the battery. Indeed, a battery HE or UHE can produce a high energy level. However, it is unable to operate at high frequencies. On the other hand, the battery HP or UHP is able to operate at high frequencies but with a low level of energy. In the diagram shown in Figure 4.5, we distinguish two blocks; the first block rejects the negative signals. Later, the filter divides the positive signals into two frequency channels. The low-frequency powers will be provided by the battery HE. Finally, the difference between the two signals will be sent to the storage element [153].

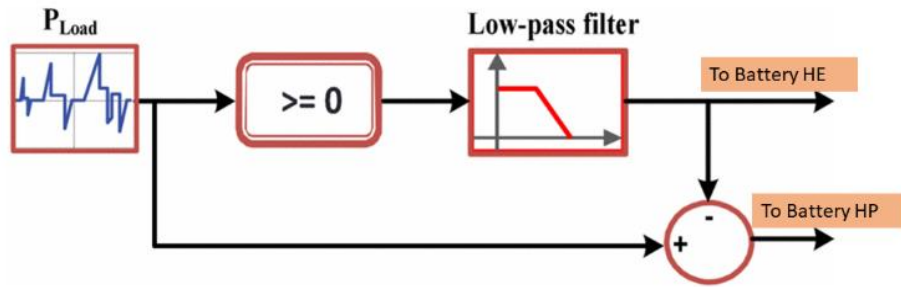


Figure 4.5: Principle of the frequency decoupling management strategy.

The frequency-separation-based energy management strategy for the case of power sources hybridization for an electric vehicle using a HE battery as the main power source and battery HP as the peak power unit was presented and tested on an experimental emulator test bench under standard driving cycle speed [154]. This simple control method of power sources based on a physical constraint of batteries, which is the low current response time, has shown its effectiveness.

4.3.2 Filtering Method

The frequency approach MF idea is based on the decomposition of the power demand into two components according to the dynamics of the storage components. SC_s , which are characterized by relatively high power and low energy capacity, suit better in the fast dynamics support. Here, the Li-ion battery will ensure moderate charge dynamics.

However, we aim to find the right value of the cutoff frequency τ_f to guarantee a suitable current I_{ch} sharing between the two sources while respecting the frequency domain specification of each source. I_n this part, we have implemented the MF strategy with five different τ_f (0.01s, 0.07s, 0.1s, 1s and 2s) in order to evaluate the time constant impact on the power-sharing between the Li-ion battery and the SC_s . The τ_f is considered constant along the ARTEMIS driving cycle. After the practical implementation, we show the monitoring of the evolution of the battery condition in Figure 4.6.

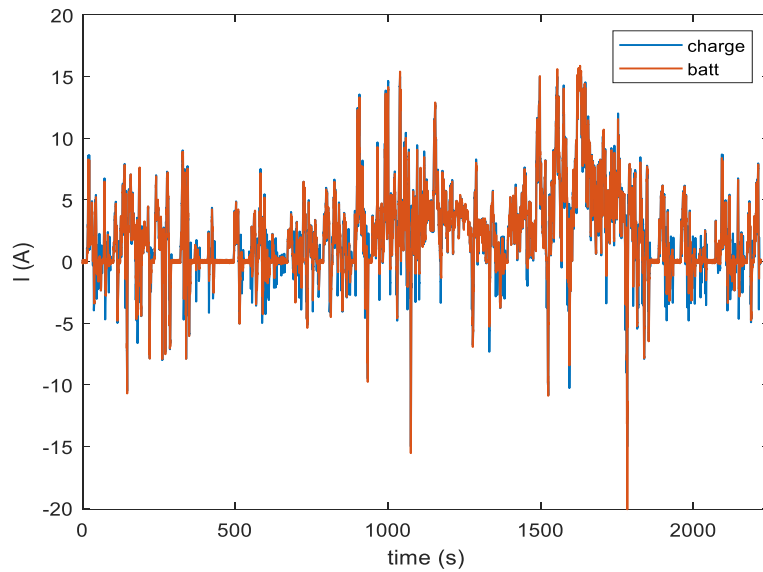


Figure 4.6: Charging and Li-ion battery currents.

The parameters of the Li-ion battery, super-capacity, and the converter used in experiments are given in Table 4.1.

Table 4.1: The used parameters in experiments

	PARAMETERS	VALUE
LI-ION BATTERY	Capacity	15Ah
	CELL IN SERIE CONNECTION NUMBER	16
	CELL IN PARALLEL CONNECTION NUMBER	1 branch
	VOLTAGE	95V
	CURRENT(MAX/MIN)	(15/30)A
SUPERCAPACITY	CELL IN SERIE CONNECTION NUMBER	34
	CAPACITY	1000F
	VOLTAGE	92V
	CURRENT(MAX/MIN)	(40/40)A
DC CONVERTER	MAXIMAL POWER	6.5KW
	VOLTAGE	200V
	CURRENT(MAX)	30A
	BRAKING LOAD	32A
	TRACTION LOAD	32A

4.3.3 Filtering method with power limitation

The frequency-sharing strategy can lead to a very interesting improvement in minimising the Li-ion battery's peak currents. This peak attenuation results in a reduction in the effective current seen by the battery. Unfortunately, this method does not deal with current limit exceedances of storage components. For this, associating a limitation block with the filtering block is essential for undesired peaks on the battery while ensuring more security of the onboard storage system in the electric vehicle. In this context, we have implemented the two scenarios LM [- 8A / 8A] + FM (1s) and LM [-10A / 10A] + FM (1s) for identical conditions (same parameters PI corrector, same battery and SC initial conditions, etc.) [159, 160].

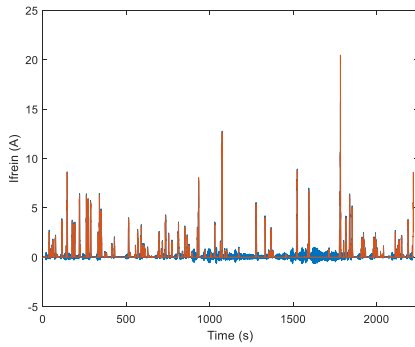
4.4 Single Source System Validation: Battery only powers the electric vehicle

The electric vehicle powered by a single source (Li-ion battery only) is the solution currently used by car manufacturers. To do this, we will study the performance of the onboard source in this type of vehicle, which represents a reference configuration for developing the management strategies dealt with in this research work. This part will present the different constraints applied to the battery [161].

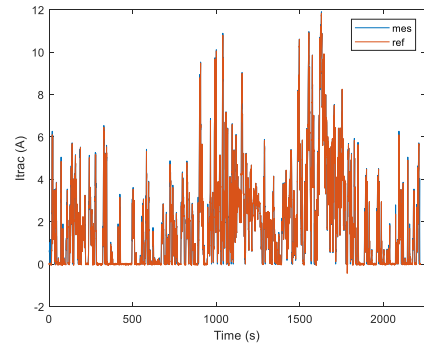
4.4.1 Charge currents

The load current is the sum of the braking current and the traction current, which are shown respectively in Figure 4.7a and Figure 4.7b. From these two figures, it is quite clear that the measured signals follow the reference signals due to the good operation of the PI controllers.

Figure 4.6 also presents the charge current and Li-ion battery current. This practical result shows that the battery current is almost identical to the charge current from which it is satisfied with the burden by this single source[162].



(a) Real current profiles and brake reference



(b) Real current profiles and traction reference

Figure 4.7: Brake and Traction Currents

4.4.2 Li-ion battery currents

Furthermore, Figure 4.6 shows the current demanded by the load and the current supplied by the Li-ion battery. This figure shows that the battery is indeed supplying the charge. The battery current is a little higher than the load current to compensate for the losses and the lower battery voltage compared to the DC bus. In this reference case, the effective current of the battery is 3.973A, and the ampere-hours exchanged by the battery is $1.67 C_{bat}$.

4.4.3 Li-ion battery charging status

The SOC load state is shown in Figure 4.8 while the initial state of the Li-ion battery is equal to 80%, with a DOD of almost 10% for a distance of 22km, consumption remains reasonable.

4.4.4 Continuous bus voltage

The continuous bus voltage shown in Figure 4.9 shows that this V_{bus} voltage is stable around the reference value 110 V. But for the sudden variations of the load, note that the bus voltage can reach 126V.

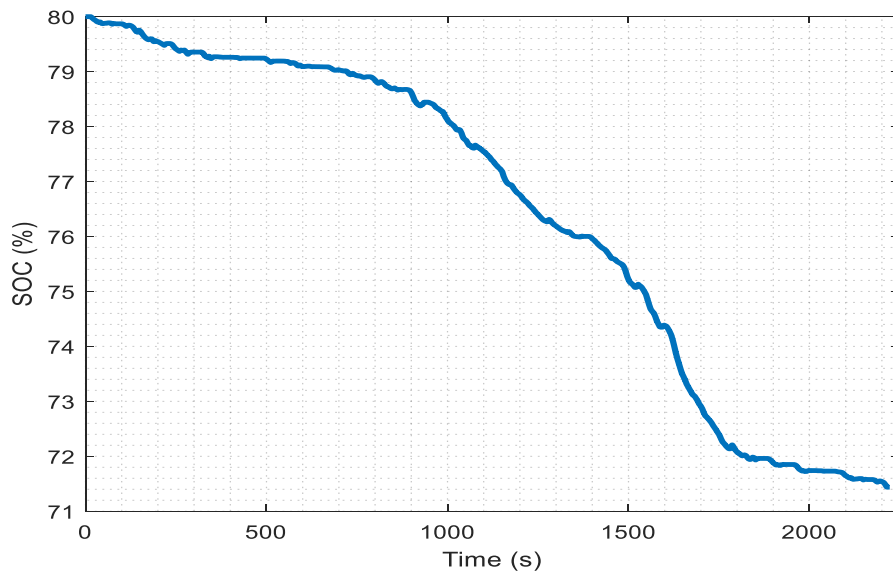


Figure 4.8: SOC battery state of charge during the cycle.

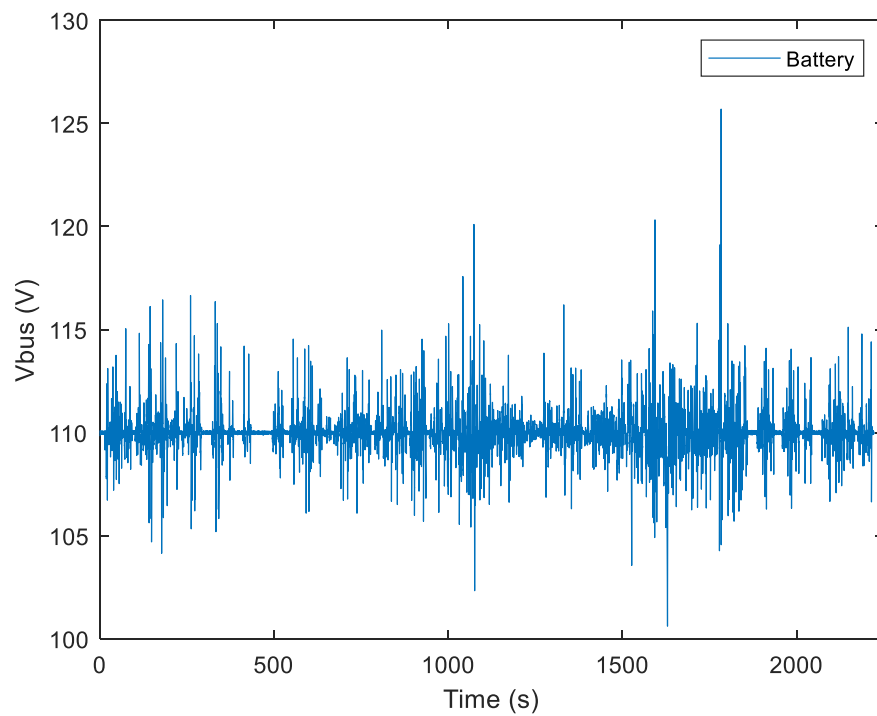


Figure 4.9: DC bus voltage during the cycle.

4.4.5 Hybrid System Validation HE Battery/HP Battery

For the ML, limiting the current amplitude keeps the current $I_{batt-ref}$ of the Li-ion battery in the interval $[Limit_{Inf} - Limit_{Sup}]$ as shown in Figure 4.10.

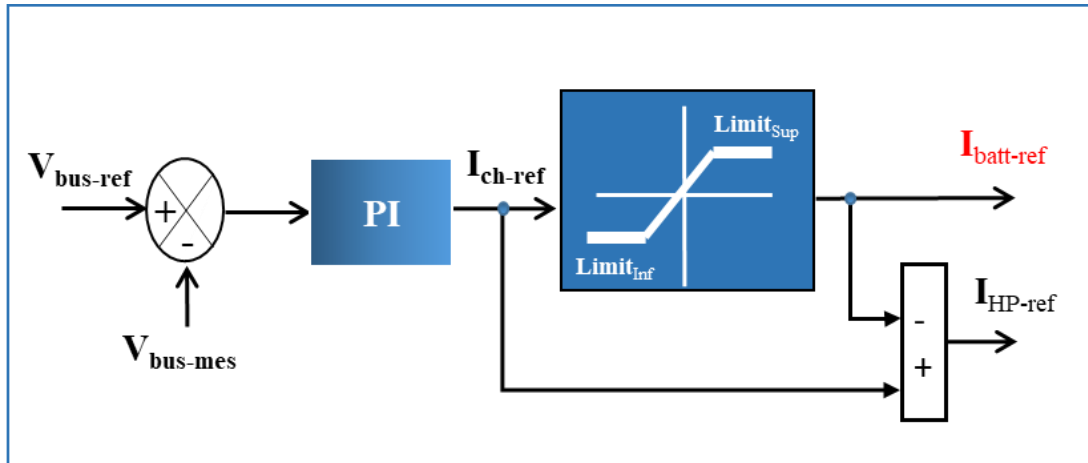


Figure 4.10: ML Working Principle without the SOC_{sc} Control.

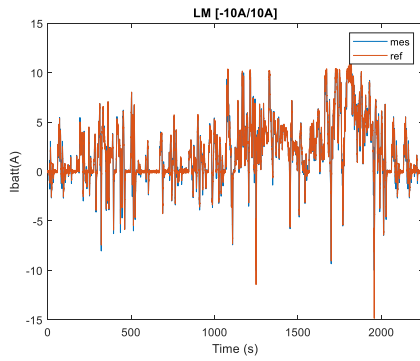
We impose a limitation band on the charge/discharge current regime of the Lion battery to respect the characteristics of the used cells and to avoid large currents during the usage of this main source. The difference between the reference current to ensure the load demand I_{chref} and the reference current of the $I_{battref}$ battery supplies the information of the reference current of the HP I_{HP-ref} .

In our case, we tested two values for the battery's current limitation. A first scenario with an 8A limitation (a method called ML [-8A / 8A]) and a second scenario with 10A as a limitation for the reference current (a method called ML [-10A / 10A]). The figures from Figure 4.11 until Figure 4.16 show the results of the practical implementation of these two scenarios. The analysis of these experimental results allowed us to observe the following remarks:

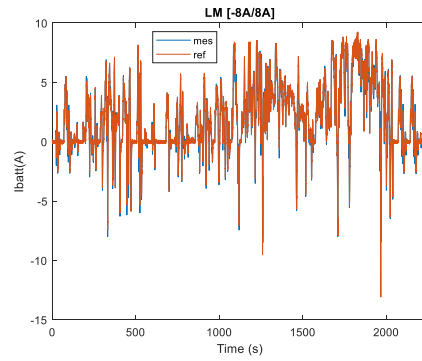
- We notice that the measured values follow well those generated by the Limitation strategy. Hence the robustness of the control of the two methods (ML [-8A / 8A] and ML [-10A / 10A]).
- The $I_{batt-mes}$ and $I_{batt-ref}$ currents presented in Figure 4.11b show that the main source

current is always within the limit band imposed by the PMS. The Rms current of the battery decreases with the reduction of the limiting current (3.66A for ML[-10A / 10A] and 3.51A for ML [-8A / 8A]).

- The I_{HP-mes} and I_{HP-ref} currents of the HP presented in Figure 4.11 show the transient dynamics of the secondary source during the cycle. We can also notice that the super-capacitor current is very low. This *rms* current increases with the reduction of the limiting current (0.53A for ML [-10A / 10A] and 1.12A for ML [-8A / 8A]).
- From Figure 4.11a, the V_{HP} voltage drop of the ML method [- 8A / 8A] is greater than the one of the ML method [-10A / 10A]. this tendency is confirmed by a greater decrease in SOC_{HP} in the ML's case method [-8A / 8A] (Figure 4.12).
- Figure 4.14 shows the evolution of the battery's SOC_{HE} state of charge for the two scenarios. Indeed, the stress on the Li-ion battery decreases with the reduction of limit currents.
- The bus voltage stability is well verified, as shown in Figure 4.15.

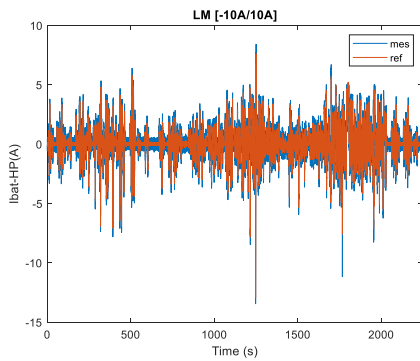


(a) Limitation to 10A

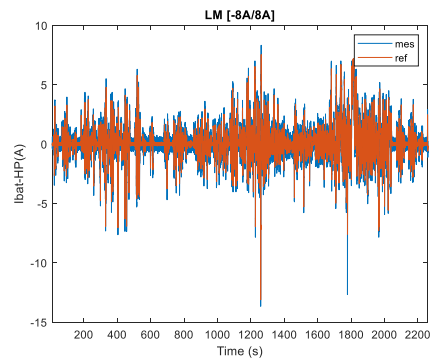


(b) Limitation to 8A

Figure 4.11: Real current profiles and Li-ion HE battery reference



(a) Limitation to 10A



(b) Limitation to 8A

Figure 4.12: Real and reference currents profiles of HP battery

Figure 4.17 shows the HP SOC regulation for the two methods. However, with this method we keep the secondary source charged at the end of the driving cycle in order to have it ready each time the vehicle is started. This regulation also generates more fluctuation on the current of the two storage systems with an efficacy value of the battery current which reaches 4.332A in the case of a limitation at 10A and 4.23A for a limitation to 8A (Figure 4.19 and 4.20).

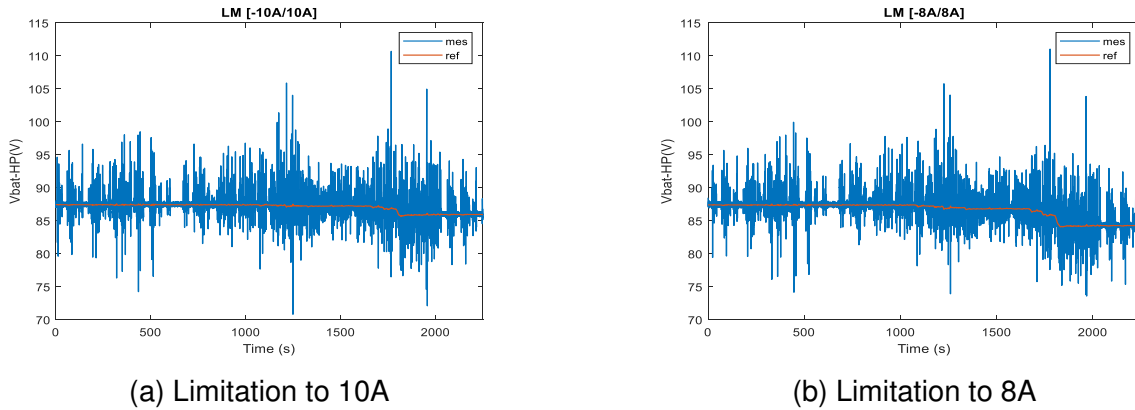


Figure 4.13: Real and reference voltages profiles of HP battery

To verify the correct operation, we have presented the experimental results of the ML [-10A / 10A] + MF (1s) + Control SOCHP in the following figures 4.16.

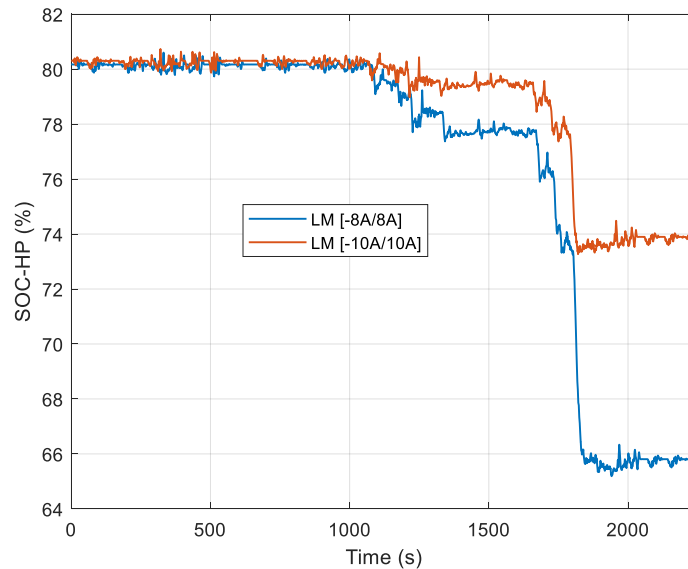


Figure 4.14: Real SOC of Battery HP for the two LMs.

4.5 Filtering Method with Power Limitation and SOC regulation of the HP battery

Despite an improvement in the constraints on the battery, the methods presented in the previous parts do not ensure the battery state of charge regulation 'SOCHP'. For that, we will introduce in this part of the thesis an extra regulation stage for the battery HP stage as shown in Figure 4.19.

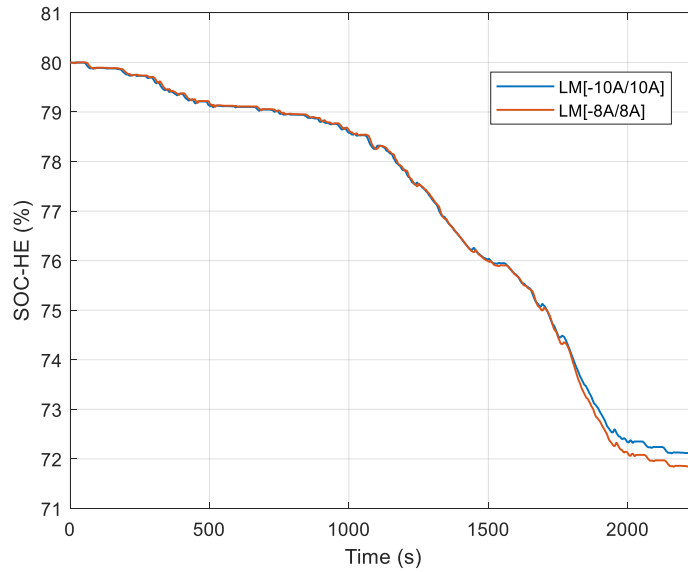


Figure 4.15: Real SOC of Battery HE for the two LMs.

Indeed, we will associate this regulation with the frequency method for different battery current limitations at 8A and at 10A.

Figure 4.18 shows the HP SOC regulation for the two methods. However, with this method, we keep the secondary source charged at the end of the driving cycle in order to have it ready each time the vehicle is started. This regulation also generates more fluctuation on the current of the two storage systems with an efficacy value of the battery current which reaches $4.332A$ in the case of a limitation at $10A$ and $4.23A$ for a limitation to $8A$ (Figure 4.18 and 4.19). To verify the correct operation, we have presented the experimental results of the ML $[-10A/10A]$ + MF $(1s)$ + Control SOC_{HP} in the following figures.

4.5.1 Continuous regulation with dynamic limitation of the battery power

In order to reduce the stress on the battery, we introduced a variation on the limitation of the battery current according to the state of charge of the SC. In our case, we used a linear function between the SOCHP and the maximum discharge current of the battery. At the same time, the battery will not charge while driving in order to reduce the stresses on this component and to be able to recharge the supercapacitor (Figure 4.18).

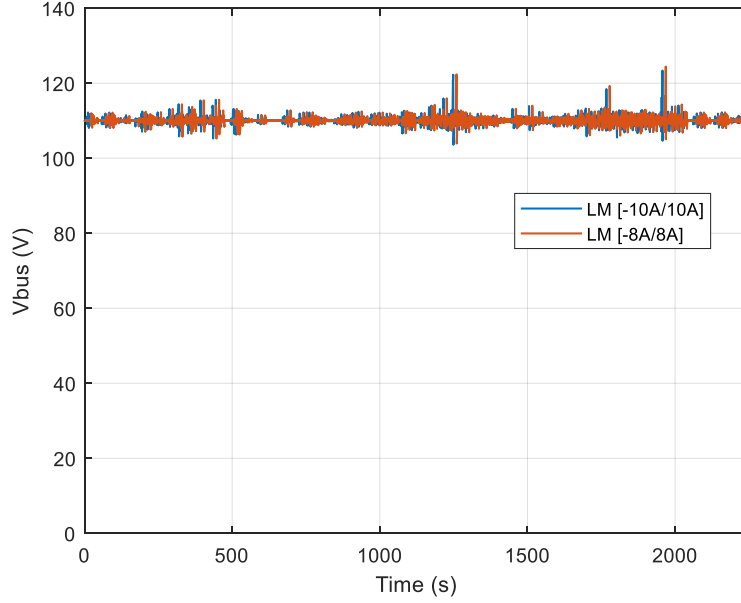
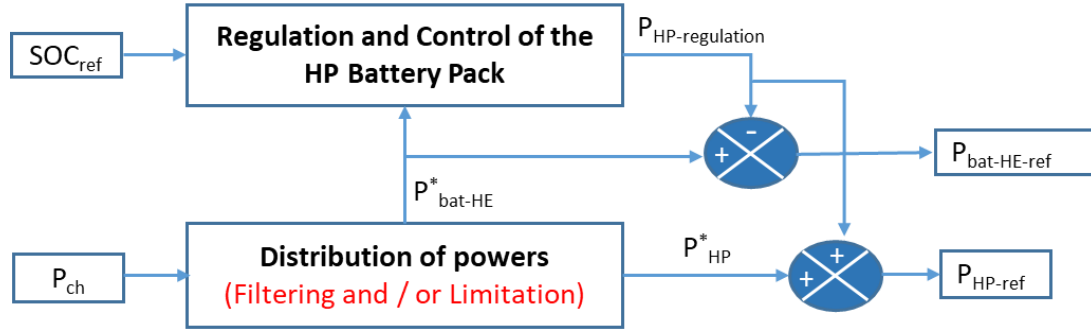


Figure 4.16: DC bus voltage for the two methods of limitation.


 Figure 4.17: Principle of energy management with continuous regulation of the SOC_{HP} .

The two limiting levels of $I_{batt-disch-limit}$ are defined by the following equation:

$$I_{batt-disch-limit} = \begin{cases} I_{disch} - Sup_2 & \text{if } SOC_{HP} < SOC_{HP} - ref \\ I_{disch} - Sup_1 & \text{if } SOC_{HP} \geq SOC_{HP} - ref \end{cases} \quad (4.1)$$

However, this LM [0 / Sup1 / Sup2] strategy only allows Li-ion battery operation in discharge mode. In this part, we have studied two variants for the battery current limitation:

- Limitation of the battery discharge current between 5A and 10A: The Sup1 limit of this first scenario is equal to 5A, on the other hand, its Sup2 limit is 10A.

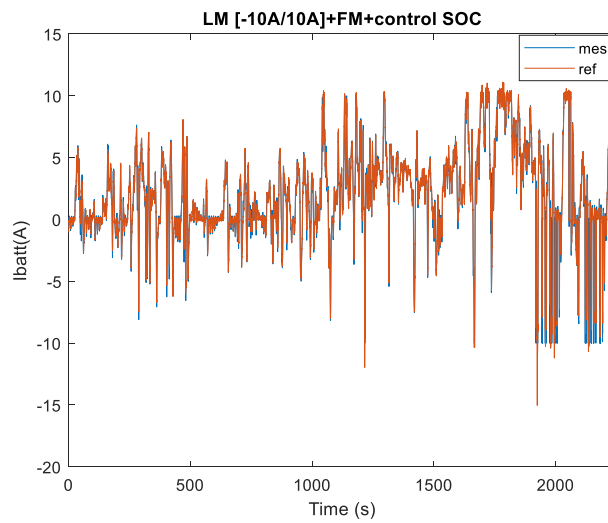


Figure 4.18: Real current profiles and Li-ion HE battery reference.

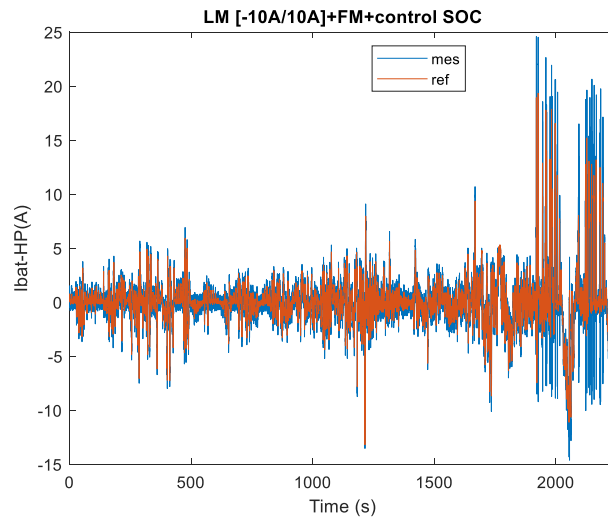


Figure 4.19: Real current profiles and Li-ion HP battery reference

- Battery discharge current Limitation between 3A and 10A: In this second test, we kept the same Sup2 limit, but the Sup1 limit was modified to 3A.

The results obtained with this method show an important improvement in the battery current with less fluctuation. The rms battery current in the Sup1 5A limitation case is less than 2.9A and 2.85A (Figure 4.20) for a limitation Sup1 to 3A. This fluctuation decrease is also observed in the current of the HP (Figure 2.8c). Figure 2.8c shows good SOC regulation of the HP in the two limiting cases. This regulation implies the same final energy state for both methods (Figure 2.8c), with good stabilization of the DC bus voltage (Figure 2.8c).

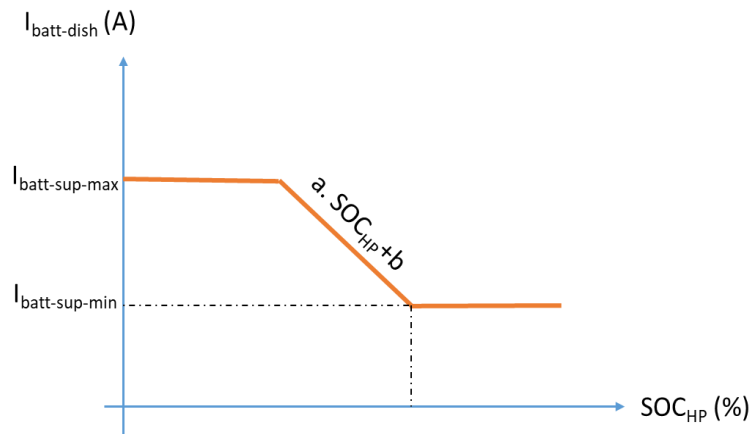


Figure 4.20: Real current profiles and Li-ion HP battery reference

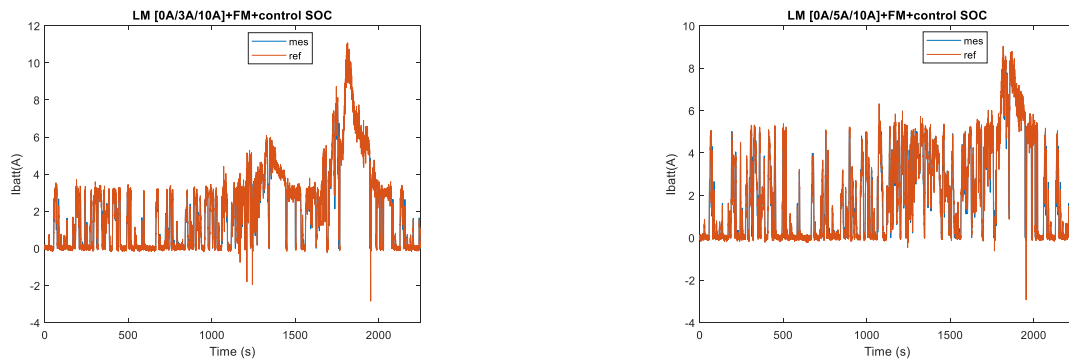


Figure 4.21: Real current profiles and Li-ion HE battery reference

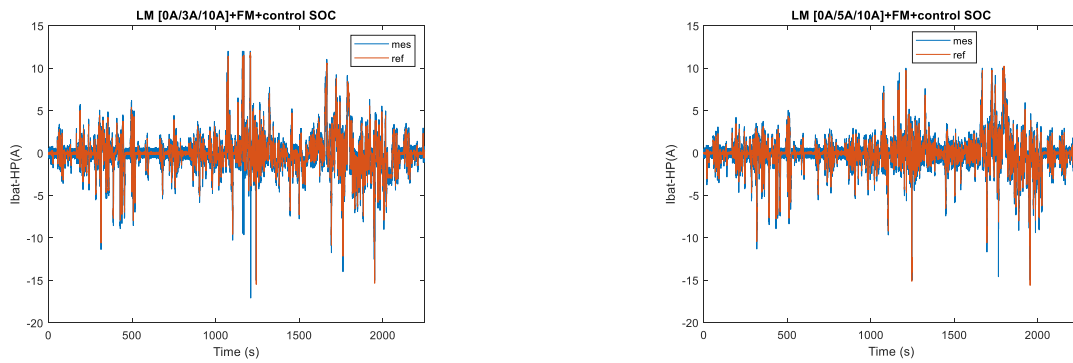


Figure 4.22: Real current profiles and Li-ion HP battery reference

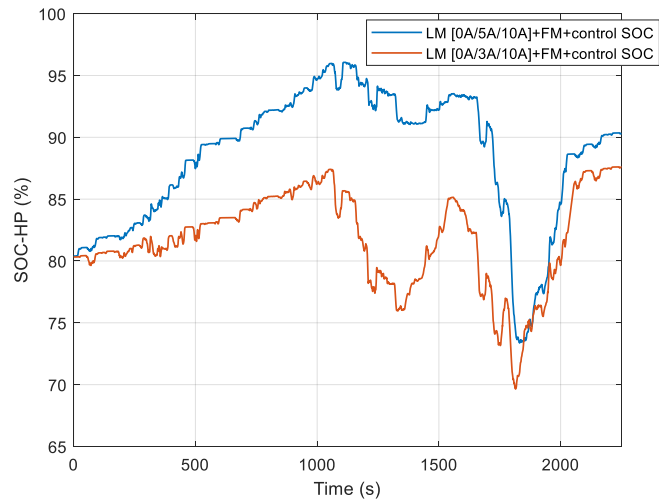


Figure 4.23: Real SOC of Battery HP for the two methods

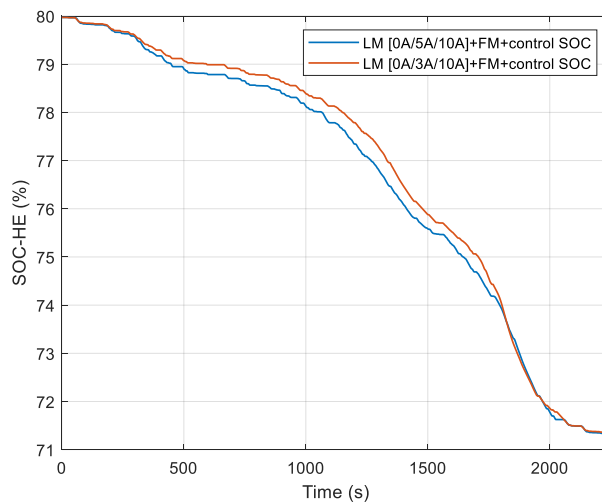


Figure 4.24: Real SOC of Battery HE for the two methods

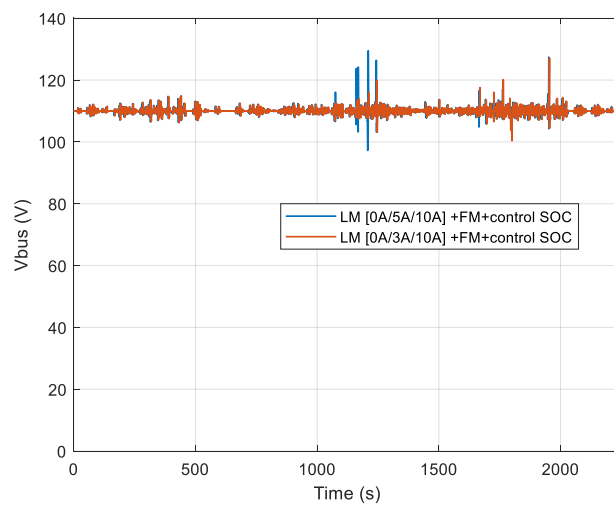


Figure 4.25: DC bus voltage for the two methods of variable limitation

4.5.2 Global assessment

In this chapter of the thesis, we presented the experimental results of the implementation of different existing methods in the literature and the comparison of these results. Results with the performances of a method developed in the laboratory. All the results obtained allow us to draw the following interpretations and conclusions:

- For all the validated management strategies, the measured signals follow the references imposed by the different regulatory loops.
- There are maximum stresses applied to the battery in the case of a single source (no hybridization), and the current in this case can reach 4.09A (Table 4.2).

Table 4.2: Courants Efficaces.

Valeur efficace	Bat HE	Bat HP	stress on Bat HP (%)	stress on Bat HE(%)
<i>Battery only</i>	3.973	0	0	100.00
<i>FM</i>	3.723	1.252	25.17	74.83
<i>LFM 10/10</i>	3.538	1.309	27.01	72.99
<i>LFM 8/8</i>	3.352	1.422	29.79	70.21
<i>LM -10A/10A control SOC</i>	4.332	2.346	35.13	64.87
<i>LM 0A/05A/10A + SOC variable</i>	3.02	1.938	39.09	60.91
<i>LM 0A/03A/10A + SOC variable</i>	3.029	2.11	41.06	58.94

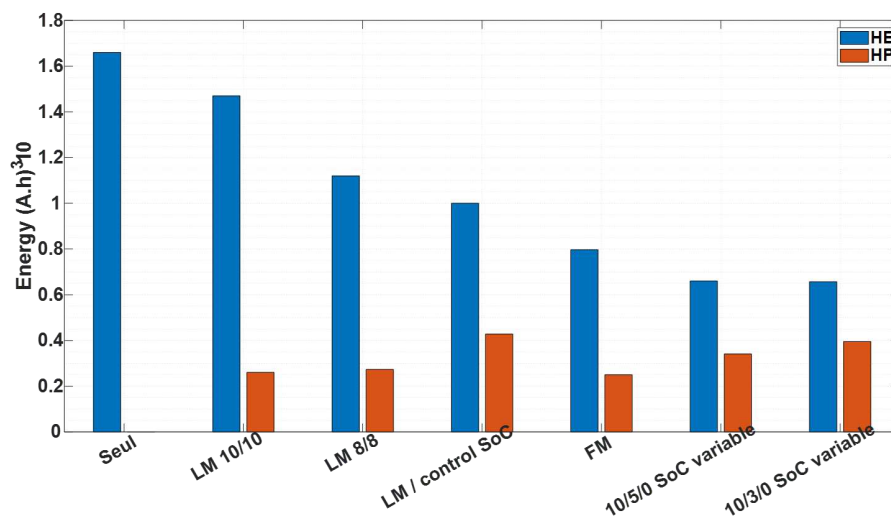


Figure 4.26: Comparative Analysis: Impact of Management Strategies on Battery Energy Exchange in Hybrid vs. Single-Source Configurations

- The frequency method usage with power limitation makes it possible to ensure a reduction of the stresses on the battery, but these methods do not ensure regulation of the state of charge of the HP battery, which can cause a complete discharge of this component.
- There is an optimal cut-off frequency of the low-pass filter to obtain a maximum reduction of the stresses on the battery (a time constant of 1s in our case).
- The regulation method ensures a return to the initial state of the HP battery SOC, on the other hand, it amplifies the fluctuations of the battery current, which causes an increase in the rms current of this component.
- The use of the variable regulation method ensures minimum stresses on the battery (Table 4.2), with a 30.18% reduction in stresses applied on the battery compared to the single-source case. This method also imposes a return of the state of charge to the reference value.
- The results of Figure 4.26 show a gain of 27.44% on the energy (in Ah) exchanged by the battery in the case of the SOCHP regulation method with variable limits on battery power, which allows for extended battery life.

4.6 Conclusion

This chapter presents an active hybrid energy storage system that mainly comprises a rechargeable high-energy Li-ion battery, high-power HP, and DC / DC power converters in order to control these two SSEs and the load within a VEH.

The Li-ion battery and the HP battery can be charged or discharged simultaneously, with the current or power suitably distributed between them according to a management strategy. The method of Limiting, Filtering, and the hybridization of these two methods are the heart of PMS. On the other hand, a SOCHP controller block is used if there is a vision towards the monitoring of the state of the secondary source. However, two main management strategies Management strategy without/with Control SOCHP have been developed to ensure energy sharing between sources and load. These management and control strategies are verified and compared to each other under certain operating conditions using Matlab-dSPACE equipment.

The experimental results show that the Management Strategy with Control SOCHP keeps the HP battery quasi-loaded at the end of each driving cycle as long as the management methods without control of the SOCHP parameter cannot guarantee that this secondary source is full at the start of each VEH start-up, in addition, there is a risk of having a deep HP discharge of for these strategies without control. On the other hand, the practical results show that the Management strategy with control SOCHP.

CHAPTER 5

INFLUENCE OF THE ENERGY MANAGEMENT METHOD ON THE AGEING OF THE HYBRID SOURCE

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4.6	Conclusion	126

5.1 Introduction

This chapter delves into the impact of energy management strategy and hybrid system topology on the sizing of key components, particularly batteries, in electric vehicles (EVs). We explore how these choices affect the constraints placed on energy storage technologies and, consequently, battery ageing. With a primary focus on the critical role of batteries in EVs, we analyze the implications of different energy management strategies and topologies on their dimensions. Moreover, we investigate how these factors influence battery ageing, a pivotal aspect for the overall performance and longevity of EVs. By placing batteries under the microscope, we aim to shed light on the trade-offs introduced by varying energy management strategies and hybrid system topologies regarding their dimension and subsequent performance implications. This chapter lays the groundwork for a comprehensive comparison between two hybrid source topologies, providing practical recommendations for designing more efficient and durable energy storage systems in EVs. The results of this study show that the choice of energy management strategy and hybrid system topology can have a significant impact on battery sizing and ageing. In general, strategies that minimize the depth of discharge of batteries lead to smaller batteries and slower aging. However, these strategies may also reduce the overall performance of the EV.

5.2 Case 1: The power module does not act as an energy source

In the scenario where the power module does not contribute as an energy source, its role is confined to managing power fluctuations, ensuring an average power of zero. This unique configuration diminishes the power module's size, as its primary function is to modulate power rather than store or supply energy. Conversely, the energy module assumes a significantly larger size to accommodate the entirety of the energy supply needed for the vehicle. In this setup, autonomy is solely reliant on the energy module, which becomes the exclusive source of power for the vehicle's propulsion.

A distinctive feature of this configuration is the increased number of cycles experienced by the power module. With its role restricted to power modulation and devoid of energy supply responsibilities, the power module undergoes more frequent cycling. This heightened cycling frequency necessitates a robust design for the power module to endure the increased mechanical stress associated with cycling. While the power module experiences more cycles, its reduced size is a compensatory factor, aligning with the system's overall emphasis on power modulation rather than energy supply [163].

This configuration choice reflects a deliberate trade-off between the sizes of the power and energy modules, optimizing the system for specific operational characteristics. The increased cycling capability of the power module contributes to its durability, aligning with the intended design parameters of this particular vehicular hybrid system.

5.2.1 Sizing a hybrid source for case 1

The algorithm (Figure 5.1) devised for sizing the hybrid source in Case 1 delineates a strategic approach tailored to optimize the dimensions of the power and energy modules. The primary focus of this algorithm lies in harnessing the power module's capacity to manage power fluctuations without contributing as an energy source. Initialization involves defining the vehicle's power and energy requisites and specifying the targeted autonomy. Subsequently, the algorithm calculates the power module's requirements, considering its duty cycle and cycling frequency. It then proceeds to size the power module, emphasizing a delicate equilibrium between physical dimensions and cycling capabilities. Simultaneously, the algorithm calculates the energy module's requirements for the entire vehicle autonomy, taking into account the absence of the power module as an energy source. The energy module is sized accordingly to meet these specifications. The final step involves validating that the combined dimensions of the power and energy modules align with the vehicle's spatial and weight constraints, ensuring that the autonomy target is achievable. The iterative nature of the algorithm allows for adjustments and refinements based on real-world testing, culminating in a hybrid source tailored to the distinctive operational demands of Case 1.

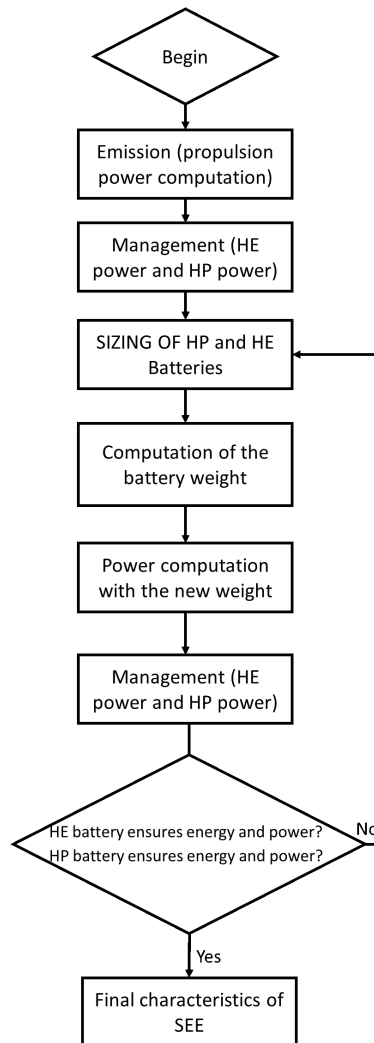
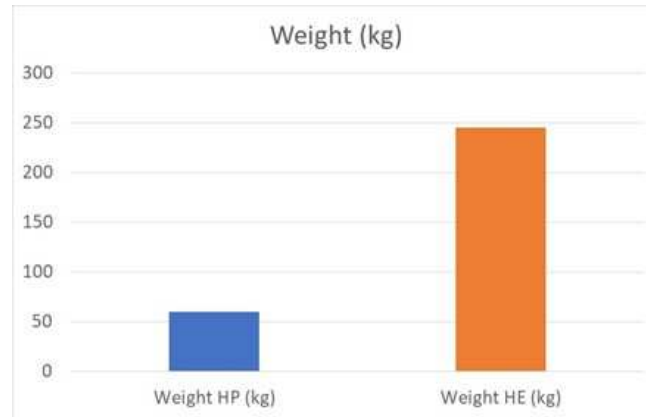
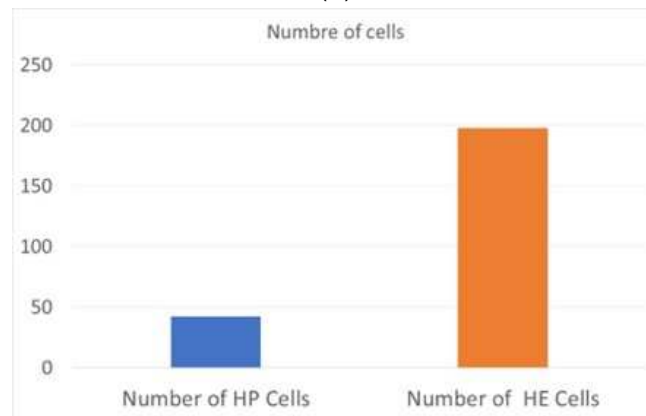


Figure 5.1: Sizing Algorithm for Hybrid Source in Case 1- Frequency Management.[4]

The presented figure 5.2 provides a comprehensive insight into the design trade-offs between the hybrid system's High-Energy (HE) and High-Power (HP) modules. The most prominent observation is the substantial weight difference, where the High-Energy module (HE) outweighs the High-Power module (HP) by a significant margin ($250kg$ compared to $50kg$). This weight variance underscores the inherent compromise between energy storage and power delivery capacities. The HE module, designed for high energy density, requires a more substantial structure, while the HP module, optimized for power output, maintains a more compact and lightweight profile. Simultaneously, the second histogram accentuates the contrasting approach in terms of cell count. The High-Energy module (HE) integrates a larger number of cells, totaling 180, compared to the



(a)



(b)

Figure 5.2: Sizing of Hybrid Power Source A - Number of Cells B – Weight

High-Power module (HP), which utilizes only 40 cells. This discrepancy in cell count reflects the focus on energy storage efficiency in the HE module, ensuring a greater capacity for prolonged energy supply. On the other hand, the HP module, tailored for quick power delivery, opts for fewer but potentially larger cells to enhance power density. This analysis's interplay between weight and cell count underscores the delicate balance required in hybrid system design. Designers must navigate the complex trade-offs to meet the specific demands of the application, whether prioritizing energy storage, power delivery, or finding a compromise that aligns with the operational requirements of the hybrid system. This figure 5.2 serves as a key reference for designers and engineers, offering valuable insights into the multifaceted considerations influencing the design of HE and HP modules in hybrid vehicles.

5.2.2 Evaluation of electrical constraints seen by the cells of the two HE and HP batteries

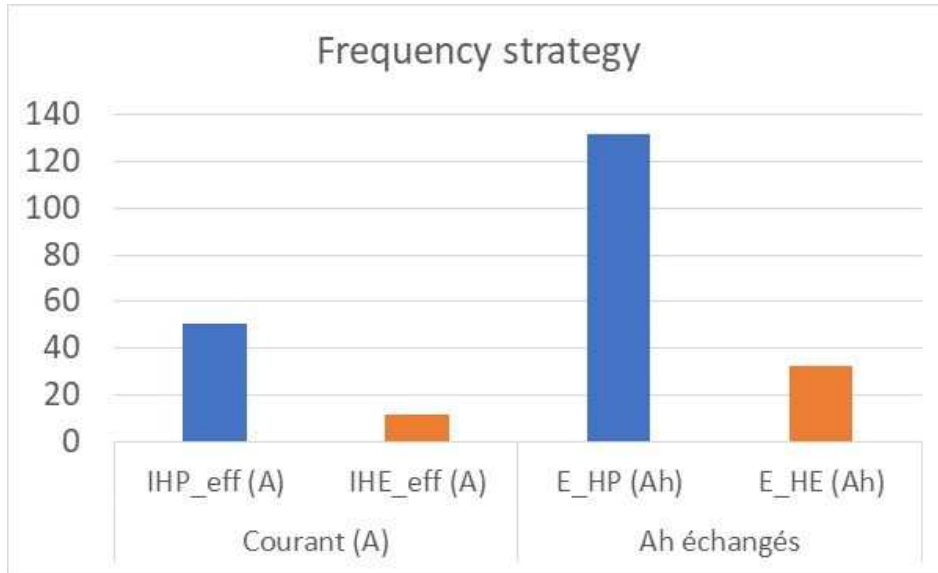


Figure 5.3: Constraints on HE and HP Batteries for Frequency Management.

In this depiction of the frequency management scenario within Case 1, the figure 5.3 delineates the constraints imposed on High-Energy (HE) and High-Power (HP) batteries. Two critical parameters, energy (E) and effective current (I_{eff}), are contrasted between the two sources. The effective current (I_{eff}) for the High-Power battery (HP) significantly exceeds that of the High-Energy battery (HE), marked by the inequality $I_{HP_{eff}} > I_{HE_{eff}}$. This divergence underscores the inherent disparity in the power delivery capabilities of the two batteries, with the HP battery designed to handle higher effective currents efficiently. Moreover, the energy supplied by the High-Power battery (E_{HP}) surpasses that of the High-Energy battery (E_{HE}). This significant difference in energy supply aligns with the intended functionalities of each battery type within the context of frequency management. The HP battery, optimized for rapid power delivery, provides energy under high-frequency demands. The constraints illustrated in this figure 5.3 emphasize the distinct roles and limitations of HE and HP batteries in managing frequency fluctuations. The HP battery, tailored for high-power applications, excels in handling elevated effective currents and supplying energy efficiently, while the HE battery prioritizes sustained energy delivery with a

focus on energy density. This figure 5.3 serves as a valuable reference for understanding the operational constraints on HE and HP batteries in the context of frequency management, providing insights crucial for optimizing hybrid system performance under varying frequency conditions.

5.2.3 Aging assessment for both HP and HE battery technologies

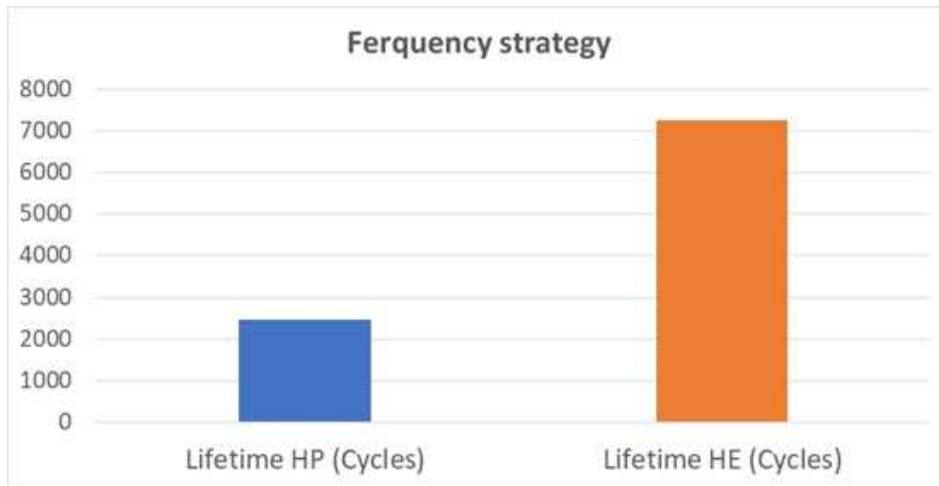


Figure 5.4: Aging of High Efficiency (HE) and High Power (HP) for Frequency Management Method.

This figure 5.4 illuminates the ageing characteristics of High Efficiency (HE) and High Power (HP) batteries within the context of the frequency management method. The ageing trajectories reveal a notable difference between the two battery types. Specifically, the High Efficiency (HE) battery exhibits a significantly higher cycle count, enduring approximately 7000 cycles. In contrast, the High Power (HP) battery undergoes fewer cycles, around 2500 cycles. This discrepancy in ageing signifies that the frequency management method places comparatively higher stress on the HE battery, necessitating a more extensive cycling regime. The HP battery, designed for quick and intense power delivery, experiences fewer cycles but potentially higher stress levels during each cycle. The observed ageing patterns underscore the distinct trade-offs associated with frequency management in hybrid systems. The HE battery, optimized for energy efficiency and sustained power delivery, demonstrates resilience in enduring a higher number of cycles. Meanwhile, the HP battery, emphasising rapid power delivery, showcases a lower cycle count

but may undergo more strenuous cycling conditions. This figure 5.4 is instrumental in understanding the impact of frequency management on the longevity and performance of HE and HP batteries. It provides valuable insights for system designers and engineers in optimizing battery selection and management strategies based on the specific requirements of frequency-sensitive applications.

5.3 Case 2: The power module acts as an energy source - energy splitting -.

In this second scenario, the power module plays a dual role as an energy source and manages power fluctuations. In this context, the power module provides the entire power needed for the vehicle's operation. However, to maintain an iso-energy balance with the energy module, it is periodically recharged by the latter. This intricate approach ensures optimal use of stored energy, minimizing losses and maintaining consistency between the two modules. Opting for the power module to participate as an energy source involves a specific design to keep both modules nearly identical in size. This dimensional symmetry aims to optimize the integration of both components within the hybrid system, avoiding excessive disparities that could lead to space and thermal management complications. Thus, this dimensional uniformity contributes to a more efficient use of space in the vehicle, ensuring a balanced distribution of responsibilities between the modules. The vehicle's autonomy in this scenario relies on close collaboration between the two modules. The energy module stores the energy needed for daily travel, while the power module intervenes to provide instantaneous power and is recharged by the energy module to maintain iso-energy. This synergy between the two modules offers a balanced solution, where each contributes complementary to the overall autonomy of the vehicle. The integrated design of these two modules optimizes the vehicle's energy efficiency while ensuring satisfactory autonomy for the driver. This scenario presents an integrated and balanced approach to energy utilization in a hybrid vehicle, highlighting the collaboration between the power and energy modules to ensure optimal performance.

5.3.1 Sizing a hybrid source for case 2

In developing hybrid vehicles, the power module sizing algorithm as an energy source is crucial in maximizing efficiency and range. This algorithm aims to determine the size, capacity, and key parameters of the power module, ensuring an optimal balance between power and energy for the vehicle.

The algorithm considers the typical driving profile, including variations in speed, accelerations, decelerations, and idle times. The driving profile derives power requirements for rapid accelerations, overtaking, and hill-climbing.

The algorithm establishes an energy management strategy for the power module as an energy source, determining when it should deliver power and when it should recharge. The algorithm optimizes (figure..) the balance between instantaneous power delivery and recharging of the power module to maintain available energy. The power module sizing algorithm as an energy source is essential to achieve an optimal balance between power, range, and efficiency in hybrid vehicles.

Within the framework of Case 2, where the power module assumes all power responsibilities and is recharged by the energy module to maintain iso-energy with the power module, specific details about the High Energy (HE) and High Power (HP) sources provide additional insights. The nearly identical mass of both HE and HP modules suggests a balanced design where the energy density of each is optimized for its specific functions. While the total mass is similar, differences in the specific characteristics of each source can be examined to understand their respective roles better. The assurance of autonomy by both modules underscores a redundant design that ensures the operational continuity of the system. This provides increased safety, as in the event of a failure in one module, the other can take over, preserving the overall autonomy of the electric vehicle. The analysis of powers involved in the recharging process, highlighting the very low power required by the energy module to recharge the power module, emphasizes the system's efficiency. This low recharge power indicates a judicious optimization of energy management, minimizing losses during recharging and enhancing the system's overall efficiency. In conclusion, within the context of Case 2, specific details about the HE and HP sources reveal a

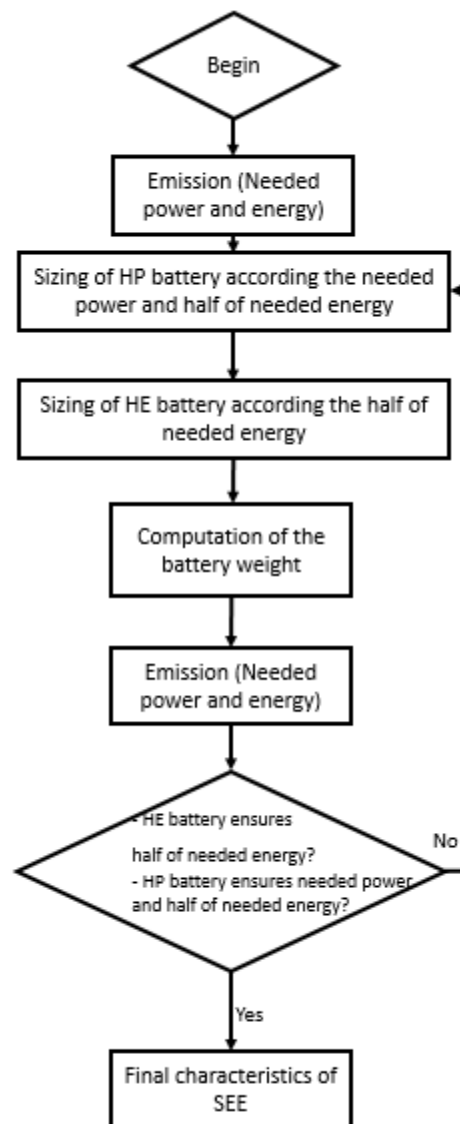


Figure 5.5: Sizing Algorithm for Hybrid Source in Case 2- Splitting Energy

carefully balanced design, where each component plays a distinct role in ensuring the power and autonomy of the electric vehicle. This approach underscores the importance of source-specific considerations to optimize the overall system performance.

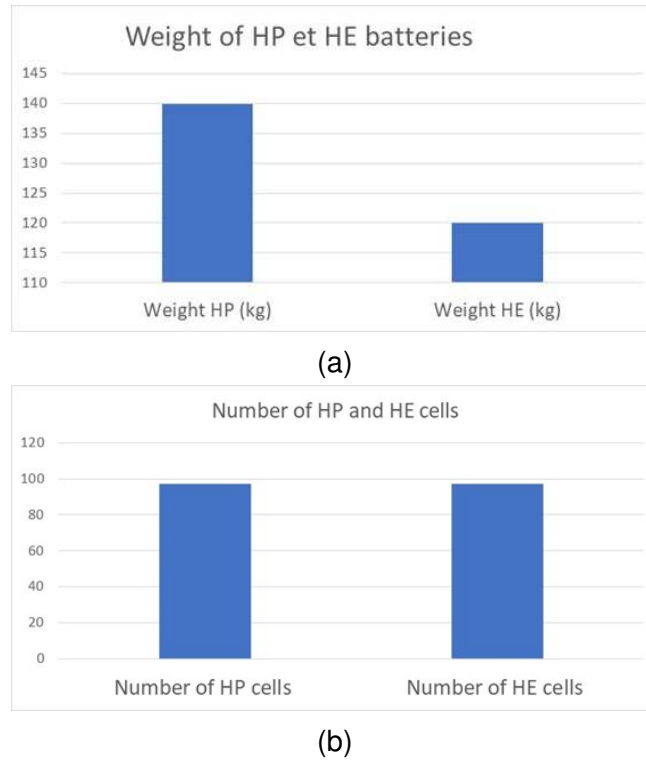


Figure 5.6: Sizing of Hybrid Power Source A - Number of Cells B – Weight for energy splitting method

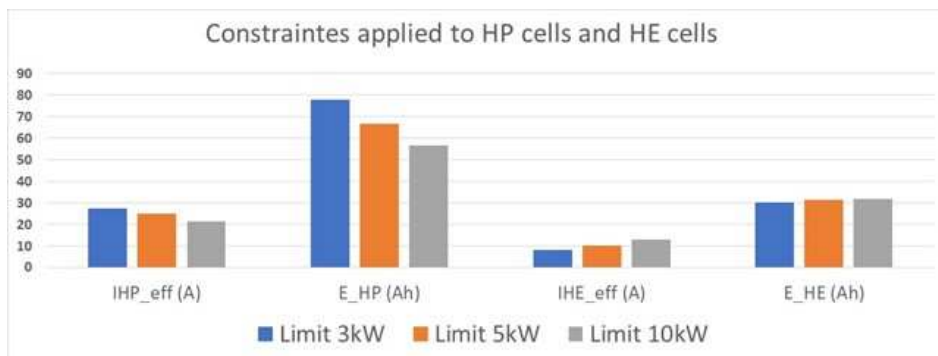


Figure 5.7: Constraints on HE and HP Batteries for energy splitting method.

5.3.2 Evaluation of electrical constraints seen by the cells of the two HE and HP batteries

The in-depth analysis of the high-power (HP) and high-energy (HE) battery performances under various power limitations has revealed significant trends. The energy histograms indicated remarkable stability for the high-energy battery (HE), with bars remaining nearly constant across diverse power limitations (3kW, 5kW, 10kW). This stability suggests that the HE battery can

sustain consistent energy performance regardless of imposed power requirements. In contrast, high-power battery (HP) results unveiled substantial variation in supplied energy based on power limitations. Specifically, the histogram showed that the energy at $3kW$ was significantly higher than that at $5kW$ and $10kW$. This observation underscores the sensitivity of the HP battery to changes in power conditions, indicating an increased ability to respond to lower power requirements optimally. Simultaneously, the analysis of battery stress revealed distinct dynamics. The HP battery exhibited a decrease in stress as power limitations increased, suggesting a positive adaptation to higher power demands. Conversely, the HE battery showed an opposite trend, with increased stress in response to rising power limitations. This observation raises important considerations regarding stress management for high-energy batteries in scenarios of higher power, highlighting the need for careful management. These results emphasize the diversity in performance between HP and HE batteries under variable power limitation conditions, providing valuable insights for the design and optimization of hybrid vehicle systems

5.3.3 Aging assessment for both HP and HE battery technologies

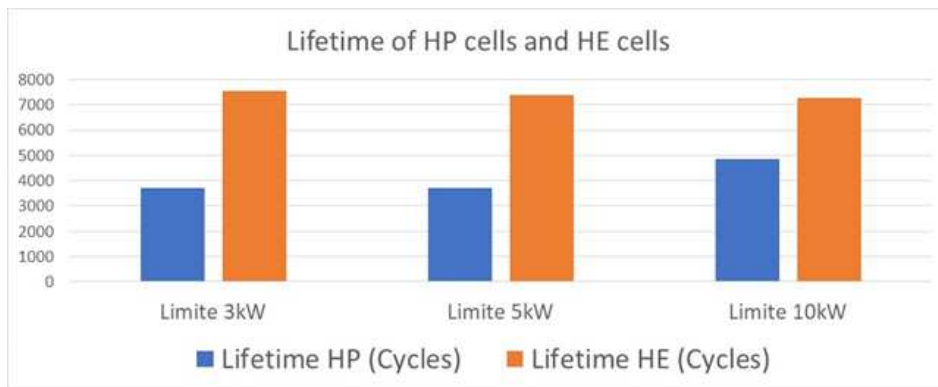


Figure 5.8: Aging of High Efficiency (HE) and High Power (HP) for energy splitting method.

The investigation into the ageing characteristics of high-power (HP) and high-energy (HE) batteries is depicted in Figure 2.8c, where distinct ageing patterns have emerged under varying power limitations. Notably, the ageing behaviour of the high-energy (HE) battery remains consistent across all three power limitations, indicating an unaltered rate of capacity degradation

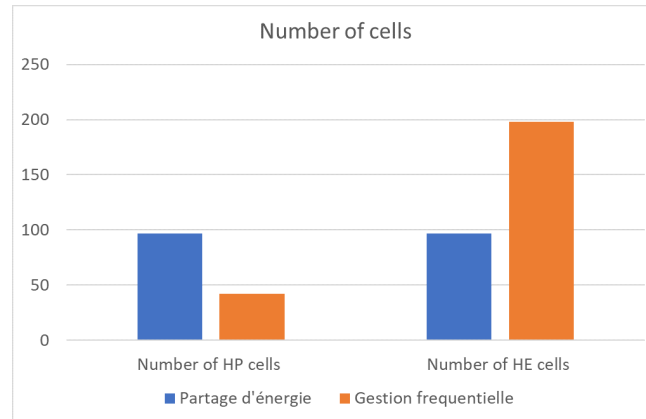
over the observed cycles. Surprisingly, the number of cycles for HE remains nearly identical across the 3 kW, 5 kW, and 10 kW limitations, suggesting that the ageing process in the HE battery is resilient and unaffected by changes in power limitation methodologies. Conversely, the ageing trajectory of the high-power (HP) battery is notably influenced by the power limitations imposed. For the kW and 5 kW limitations, the HP battery exhibits a comparable number of cycles, approximately cycles. However, under the kW limitation, the ageing process accelerates, with the battery enduring almost cycles before reaching a similar level of degradation. This discrepancy indicates a sensitivity of the high-power battery to the specific power limitation, with higher power demands evidently accelerating the ageing process. These findings underscore the divergent ageing responses of HP and HE batteries, with the former exhibiting sensitivity to power limitations, especially at higher power levels. The consistent ageing behaviour in the HE battery, irrespective of power limitations, implies a more stable and predictable ageing profile. Such insights are invaluable for devising tailored strategies in battery management to enhance the longevity and performance of hybrid electric vehicles.

5.4 Comparison of the results from both cases.

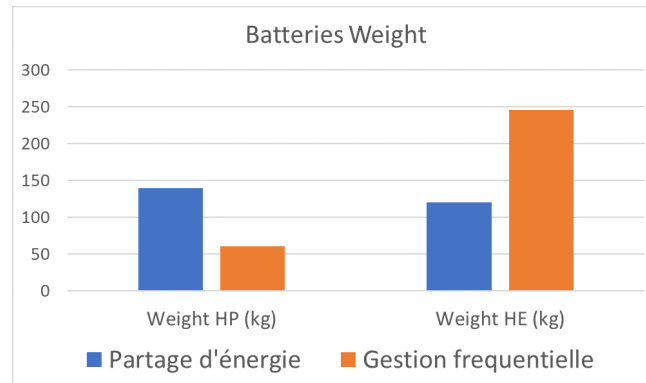
Examining the dimensions of a hybrid source in the two cases, frequency management and energy splitting, reveals significant disparities, highlighting fundamental differences between the two approaches.

5.4.1 Case 1: Frequency Management

In frequency management, the High Efficiency (HE) and High Power (HP) modules exhibit distinct differences in weight and the number of cells. As depicted in Figure 5.9, the High Power (HP) battery demonstrates significantly lower weight compared to the High Efficiency (HE) battery, while the number of cells varies substantially. This configuration arises from specific requirements associated with frequency management, where the High Power (HP) battery is optimized for higher power tasks, resulting in a lighter and more compact design.



(a)



(b)

Figure 5.9: Sizing of Hybrid Power Source a - Number of Cells b – Weight for 02 cases

5.4.2 Case 2: Energy Splitting

Conversely, the energy splitting approach is characterized by nearly equivalent weights for High Efficiency (HE) and High Power (HP) modules, as shown in Figure 5.9. This similarity results from the sizing algorithm seeking to balance power and energy for each module, leading to more homogeneous weights between the two. Overall, the sum of module weights in the energy splitting method proves to be less than that in frequency management, underscoring advantages in terms of overall weight in this approach.

5.4.3 Overall Analysis:

The dimensional comparison between the two cases reveals fundamentally different design choices. Frequency management prioritizes optimization specific to each battery's function, re-

sulting in substantial differences in weight and the number of cells. In contrast, energy splitting aims for an overall balance between power and energy, resulting in more uniform dimensions and reduced total weight. This dimensional analysis is crucial for engineering decision-making, providing essential insights into the optimal design of hybrid sources based on the specific requirements of the system.

5.4.4 Comparison of electrical constraints seen by the modules

In comparing the electrical constraints for both cases, distinct patterns emerge for High Efficiency (HE) and High Power (HP) modules.

- **High Efficiency (HE) Constraints:** For the High Efficiency (HE) module, there is minimal variation in both energy (E_{HE}) and effective current ($I_{HE_{eff}}$) between the two cases. This consistency suggests that the chosen methods and limitations have a relatively similar impact on the electrical constraints of the HE module.
- **High Power (HP) Constraints:** In contrast, the High Power (HP) module exhibits significant differences in electrical constraints between the two cases. Notably, the method of energy splitting with a 10 kW limitation imposes the least constraint on the HP module. This finding indicates that changing the method and introducing limitations has a substantial influence on the electrical constraints experienced by the HP module.
- **Global Impact of Method and Limitation Changes:** The observed variations in HP constraints underscore the sensitivity of the module to alterations in the chosen methodology and limitations. Particularly, the energy splitting method with a 10 kW limitation appears to be the least restrictive for the HP module. This global change in method and limitation significantly influences the electrical constraints experienced by the High Power module.

This comparative analysis sheds light on the nuanced impact of method and limitation choices on the electrical constraints for high-efficiency and high-power modules. It serves as valuable insight for optimizing hybrid systems' design and constraints management based on specific performance requirements.

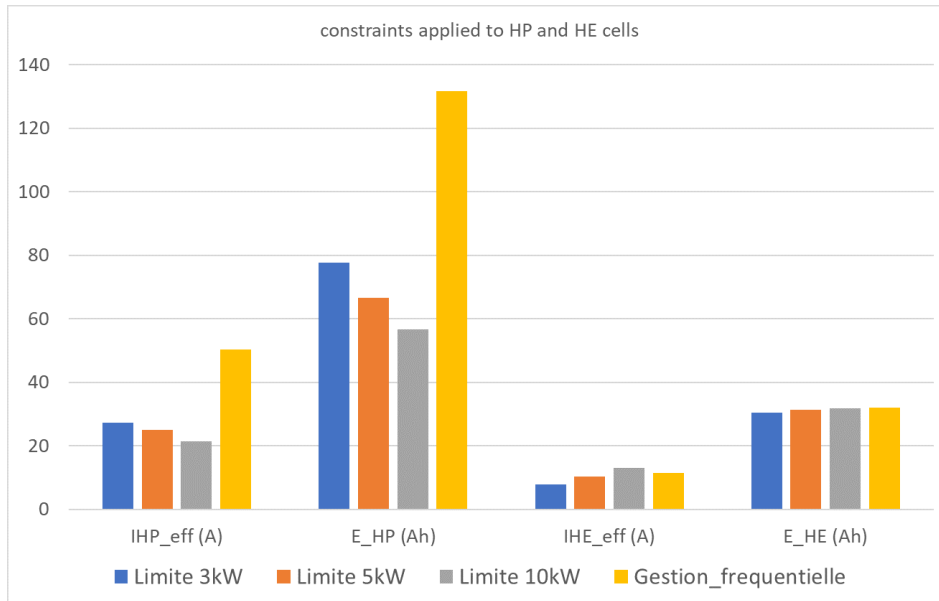


Figure 5.10: Constraints on HE and HP Batteries for 02 cases.

5.4.5 Comparison of ageing for the two modules

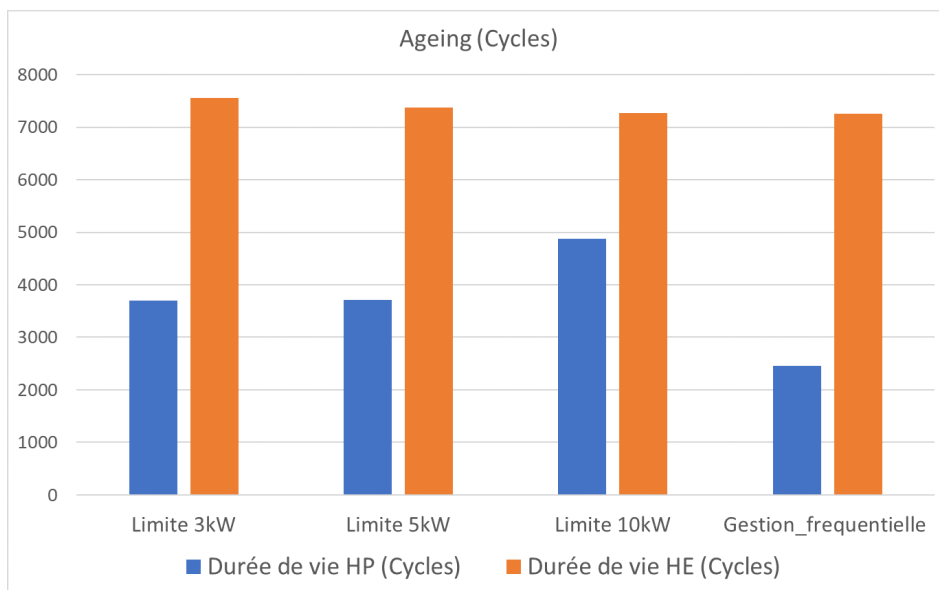


Figure 5.11: Aging of High Efficiency (HE) and High Power (HP) for 02 cases.

In evaluating the ageing characteristics for both High Efficiency (HE) and High Power (HP) modules across different limitations and methods, distinct patterns emerge.

- **High Efficiency (HE) Aging:** Remarkably, the aging behavior for the High Efficiency (HE)

module remains consistent across the two cases and various limitations. This uniform ageing pattern suggests that the HE module exhibits similar ageing trajectories, regardless of changes in the methodology or limitations applied.

- **High Power (HP) Aging:** In contrast, the ageing performance of the High Power (HP) module varies significantly across different methods and limitations. The ageing is notably better in the energy splitting method with a 10 kW limitation. This finding implies that the choice of method and limitation can substantially impact the HP module's ageing characteristics.
- **Global Impact of Method and Limitation Changes:** The observed differences in ageing, particularly the improved ageing in the energy splitting method with a 10 kW limitation for the HP module, underline the sensitivity of ageing to alterations in the chosen methodology and limitations. This global change in method and limitation significantly influences the ageing patterns experienced by the High Power module.

This comparative analysis provides crucial insights into the nuanced impact of method and limitation choices on the ageing characteristics of both high-efficiency and high-power modules. Understanding these dynamics is essential for optimizing the design and longevity of hybrid systems based on specific performance and ageing considerations.

5.5 Conclusion

In this chapter dedicated to the in-depth exploration of the influence of energy management methods on the ageing of the hybrid source, our goal was to unravel the specific implications of energy management choices on the lifespan of key components, with a particular emphasis on High Efficiency (HE) and High Power (HP) modules. The chapter began with a detailed presentation of two major energy management methods: frequency management and energy splitting. Each of these methods was scrutinized from various angles, from module sizing to managing electrical constraints, to understand their respective impact on the hybrid source's lifespan.

The analysis of HE and HP module dimensions revealed significant differences between the two methods. Frequency management generated more pronounced variations in weight and the number of cells, while energy splitting led to a more balanced approach, with more homogeneous dimensions between modules. Examining electrical constraints highlighted significant variations, especially for HP modules, between the two methods. The energy splitting method, particularly with a 10 kW limitation, demonstrated advantages in reducing electrical constraints for HP modules. Observing module aging was a focal point, revealing notable differences between methods. While the aging of HE modules remained relatively constant, the aging of HP modules significantly improved in the context of energy splitting with a 10 kW limitation. This chapter opens significant perspectives to guide future research in hybrid system design. The conclusions drawn from this in-depth analysis provide a solid foundation for more informed energy management choices, aiming to optimize the lifespan of hybrid sources. The results of this chapter also underscore the crucial importance of choosing energy management methods tailored to the specific characteristics of HE and HP modules to maximize the efficiency and longevity of hybrid systems.

CONCLUSION

The objective of this thesis was to enhance the performance and characteristics of energy storage systems, thereby facilitating the integration of Electric Vehicles (EVs) into the automobile market. Our study revolved around the comparison of a conventional Li-ion battery single-source with a hybrid source comprising High Energy (HE) Li-ion batteries as the primary source and High Power (HP) Li-ion batteries as the secondary source.

One of the key aspects of our research was to investigate the impact of management strategies on the lifespan of the energy storage system. Our aim was to extend the system's lifetime without compromising its mass and volume efficiency. This was achieved through the development of novel management methods based on criteria related to the aging of the two utilized technologies.

The sizing approach we proposed primarily relied on manufacturer-provided data. The expressions developed for sizing battery packs depended on factors such as energy density, charge-discharge rates, voltage, and internal resistance of battery cells.

Our results demonstrated that for EVs with less than 300 km of autonomy, the hybridization of HE and HP batteries led to significant improvements in system mass, volume, and cost. Notably, HE batteries showed reductions of up to 50% in mass, volume, and cost compared to using batteries alone.

This study also highlighted the potential benefits of Ultra High Power (UHP) Li-ion batteries

for hybridization, providing encouraging results. While information on UHP battery lifespan is scarce in the literature, their performance in terms of mass, volume, and cost proved favorable when compared to supercapacitors.

We dedicated a substantial portion of our research to energy management strategies, presenting various online methods for hybrid systems. Through numerical simulations, we evaluated these strategies against a commonly used frequency-based method. The results indicated that the proposed strategy could reduce the size of high-energy batteries.

Additionally, we conducted experimental validation on a 1 KW test bench to assess the influence of battery technologies on hybrid source performance, confirming that UHP batteries are the most suitable for enhancing ESS lifespan.

Furthermore, a pivotal aspect explored in this thesis was the impact of energy management strategies on the aging of the hybrid source. We delved into the dynamic world of online energy management methods, examining their potential for extending the life of hybrid energy storage systems. Through comprehensive numerical simulations and comparisons with a conventional frequency-based method, we shed light on the potential of these strategies to minimize ageing effects and improve the longevity of energy storage. This facet of our research reaffirms the integral role that energy management plays in enhancing the overall performance and durability of hybrid sources for electric vehicles.

In conclusion, this work opens the door to several promising avenues of further research. One such path involves refining power management strategies with a focus on battery lifespan. Another direction could be an extension of the test protocol to explore additional parameters, such as temperature, to gain deeper insights into their interactions with battery aging. These future endeavors promise to enhance further the efficiency and reliability of Storage Energy Hybrids (SEHs).

Perspectives

The hybridization of energy storage sources holds promising prospects in the energy field. By integrating different storage technologies, such as high-energy (HE) and high-power (HP) batteries, with advanced management methods, hybrid systems can provide optimal synergy between instantaneous power and long-term storage capacity. This opens up opportunities for diverse applications, ranging from electric vehicles to renewable energy storage systems.

From the perspective of battery lifespan, hybridization can play a crucial role in extending operational cycle life. By optimizing energy flow management, reducing stresses on batteries, and judiciously balancing charge-discharge cycles, hybrid systems can help minimize the effects of premature aging. Ongoing advancements in storage technologies and management algorithms can also positively impact battery sustainability within the context of hybridization.

Future outlooks include the development of more advanced management methods, leveraging artificial intelligence and machine learning for real-time adaptation to variable operating conditions. This could maximize energy efficiency while optimizing battery lifespan. Additionally, exploring new combinations of storage technologies and integrating innovations such as solid-state batteries could open novel pathways for improved performance and increased lifespan.

In brief, the hybridization of energy storage sources offers exciting prospects for optimizing energy performance and extending battery lifespan, paving the way for more sustainable and high-performing systems in an ever-evolving energy landscape.

Exploring the direct integration of ageing as a parameter in online power management is an innovative research area. This approach could enhance the ability to anticipate and compensate for ageing effects in both single-source and hybrid configurations. It requires the development of advanced algorithms capable of dynamically considering the ageing state to optimize power in real-time.

Extending the obtained results to new chemistries, particularly Nickel-Manganese-Cobalt (NMC) batteries, is a crucial avenue. This involves adapting existing models and energy management algorithms to account for the specificities of these new chemistries. This extension

allows the exploration of performance and constraints unique to these emerging technologies.

Exploring new technologies, such as sodium-ion batteries or solid-state batteries, represents an exciting research direction. This requires adapting ageing models and energy management strategies to accommodate the unique characteristics of these emerging technologies. The integration of sodium-ion batteries, for example, could offer advantages in terms of cost and durability, while solid-state batteries could enhance safety and energy efficiency.

In summary, these perspectives offer a comprehensive approach to broaden the impact of the thesis, from online power management considering ageing to exploring new NMC chemistries and integrating emerging energy storage technologies. These research directions will contribute to strengthening the understanding of energy storage systems and opening new opportunities for their application in diverse contexts.

RÉSUMÉ LONG DE LA THÈSE EN FRANÇAIS

Titre : Dimensionnement et gestion de l'énergie d'une source hybride pour un véhicule électrique

Introduction

L'impératif de relever les défis écologiques et économiques se profile avec acuité dans le paysage contemporain. L'appel à l'action, souvent formulé comme la "transition énergétique et écologique," marque un tournant profond dans notre approche de toutes les activités humaines. Ce qui était autrefois une considération stratégique est désormais devenu une nécessité incontournable. Cette transformation est catalysée par la croissance dynamique des économies et des populations en Asie et en Afrique, des régions qui sont passées de participants passifs à acteurs centraux dans la transition énergétique et écologique mondiale.

Au cœur de cette transition se trouve la reconnaissance que le modèle de transport traditionnel a atteint les limites de sa durabilité. Les dynamiques mondiales ont subi un changement sismique, entraîné par l'essor de nouvelles puissances économiques et des tendances démographiques croissantes, combiné à l'épuisement des réserves de combustibles fossiles conventionnels. Il ne s'agit plus de savoir 'si' le modèle de transport traditionnel sera remplacé,

mais plutôt 'quand' il cédera la place à un paradigme en évolution.

Le secteur des transports, responsable d'environ 25% des émissions mondiales de CO₂, joue un rôle central dans le défi du changement climatique. En conséquence, l'électrification des véhicules a émergé comme une solution convaincante pour réduire notre dépendance aux combustibles fossiles. Atteindre l'objectif de l'électrification des véhicules nécessite un examen minutieux de ses composants constitutifs. Parmi ceux-ci, la batterie se présente comme un déterminant principal du coût et des performances d'un véhicule électrique. Les batteries sont connues pour subir une dégradation de performance au fil du temps en raison du processus de vieillissement, entraînant une réduction de la capacité de stockage d'énergie et une augmentation des pertes de conversion d'énergie. Cette dégradation se manifeste sous la forme d'une diminution de l'autonomie et d'un compromis de l'efficacité énergétique. La viabilité économique et écologique des véhicules électriques est intimement liée à la rentabilité et à la longévité de leurs batteries. Alors que les technologies avancées de stockage d'énergie offrent la promesse d'une densité énergétique et d'une efficacité plus élevées, des gains immédiats peuvent être réalisés par l'optimisation des technologies de batterie lithium-ion existantes.

C'est dans ce contexte que cette recherche se déroule, adoptant une perspective centrée sur l'utilisateur pour étudier les implications des applications des véhicules électriques sur le vieillissement des systèmes de stockage d'énergie. De plus, elle explore des stratégies pour maximiser le potentiel des batteries lithium-ion, en particulier en prolongeant leur durée de vie. Le cœur de cette exploration est centré sur le concept d'hybridation des sources d'énergie. Cette approche tire parti des forces de deux technologies distinctes – l'une caractérisée par une énergie spécifique élevée et l'autre par une densité de puissance significative – pour améliorer les performances des systèmes de stockage d'énergie embarqués, avec un accent particulier sur le vieillissement, le poids, les coûts et l'efficacité.

Cette étude s'inscrit dans un contexte plus large, mettant en évidence l'importance de la transition énergétique et écologique et la nécessité cruciale de relever les défis des applications des véhicules électriques et du stockage d'énergie. Elle contribue à la poursuite mondiale d'un avenir énergétique plus propre et plus durable, offrant des perspectives sur des stratégies

visant à améliorer la longévité et l'efficacité des systèmes de stockage d'énergie des véhicules électriques. Les chapitres suivants aborderont les méthodologies, les résultats et les implications du dimensionnement et de la gestion de l'énergie d'une source hybride pour les véhicules électriques, éclairant le chemin vers un avenir des transports plus durable et plus efficace.

Notamment, les limitations du stockage d'énergie à source unique sont cruciales dans cette discussion. Les solutions de stockage d'énergie monolithiques échouent souvent à répondre aux diverses exigences et contraintes des applications des véhicules électriques. Ces limitations englobent une densité énergétique réduite, une puissance de sortie restreinte et une susceptibilité au vieillissement. La nécessité critique de pallier ces limitations a conduit à l'innovation vers des solutions de stockage d'énergie hybrides qui combinent les forces de plusieurs technologies de stockage d'énergie. Ces systèmes synergiques offrent la perspective d'améliorer la densité énergétique, la puissance de sortie et la longévité globale du système. En tant que tel, cette recherche sert de phare d'espoir et de progrès, s'efforçant de transcender les limites des systèmes de stockage d'énergie actuels, assurant un avenir des véhicules électriques plus durable et plus efficace.

L'hybridation des sources de stockage d'énergie émerge comme une solution innovante pour surmonter les défis associés aux limitations et contraintes des ressources dans l'électrification des véhicules électriques (VE). En combinant différentes technologies de stockage d'énergie, telles que les batteries lithium-ion et les supercondensateurs, l'hybridation offre l'opportunité d'optimiser les performances des systèmes de stockage d'énergie. Cette approche augmente non seulement la densité énergétique, prolongeant ainsi l'autonomie des VE, mais elle répond également aux besoins de puissance instantanée grâce à l'utilisation de supercondensateurs ou de batteries à haute puissance. De plus, elle contribue à atténuer les problèmes liés à la charge et à la décharge rapides des batteries, prolongeant ainsi leur durée de vie. L'hybridation des sources de stockage d'énergie représente une étape prometteuse vers l'amélioration continue des performances des VE tout en répondant aux contraintes inhérentes à leur électrification. Cela contribue à une transition vers une mobilité électrique plus durable et plus efficace.

Chapitre 1 : Fondamentaux des Sources de Stockage d'Énergie

Dans ce chapitre, nous examinerons les bases des technologies de batteries, les diverses sources de stockage d'énergie disponibles et les formes existantes d'hybridation. Nous fournirons une vue d'ensemble complète des options actuelles et des raisons pour lesquelles certaines combinaisons sont préférées dans des contextes spécifiques. Alors que nous nous aventurons dans ce premier chapitre, nous nous immergeons dans le domaine dynamique des systèmes de stockage d'énergie (ESS) dédiés aux véhicules électriques. Le paysage des transports électriques évolue rapidement, nécessitant des solutions sophistiquées pour améliorer l'efficacité, l'autonomie et la performance globale. Ce chapitre sert d'exploration panoramique des technologies et méthodologies de pointe dans le domaine des ESS. Notre voyage commence par une analyse approfondie des technologies de stockage d'énergie de pointe, y compris, mais sans s'y limiter, les batteries lithium-ion, les supercondensateurs et les innovations émergentes. Nous analysons leurs forces, leurs limitations et les défis uniques posés par l'électrification des transports. En explorant les recherches et avancées récentes, nous visons à dévoiler le rôle crucial joué par les ESS dans la formation de l'avenir de la mobilité électrique. De plus, ce chapitre éclaire les complexités de l'intégration des systèmes de stockage d'énergie dans les véhicules électriques, en abordant des considérations clés telles que le poids, la taille et l'évolutivité. En obtenant des informations sur le paysage actuel, nous posons les bases des discussions ultérieures sur le dimensionnement et la gestion de l'énergie des sources hybrides. Rejoignez-nous pour découvrir le monde multifacette des ESS, où l'innovation et l'exploration convergent pour conduire l'avenir des transports durables. En conclusion, ce chapitre a mis en lumière le paysage énergétique du secteur des transports et a souligné l'impératif d'une transition énergétique. Alors que la demande de véhicules propres et sans émissions s'intensifie, l'intégration de solutions innovantes devient primordiale. Bien que les véhicules hybrides et électriques émergent comme des alternatives prometteuses à long terme, il est évident que les offres actuelles du marché ne parviennent pas à égaler les performances des voitures à moteur à combustion interne traditionnelles.

Pour favoriser l'adoption généralisée des véhicules électriques, il est crucial de relever les contraintes auxquelles sont confrontés à la fois les consommateurs et les fabricants. Les consommateurs sont préoccupés par des aspects tels que l'autonomie limitée, les temps de charge prolongés et les coûts initiaux élevés associés à l'achat de véhicules électriques. Parallèlement, les fabricants font face à des défis liés à l'optimisation de la consommation d'énergie des véhicules et à l'amélioration des niveaux de récupération d'énergie. C'est dans ce contexte que l'importance de l'hybridation se révèle.

L'intégration des technologies hybrides dans les systèmes de stockage d'énergie offre une solution convaincante pour combler l'écart de performance entre les véhicules électriques et les véhicules conventionnels. En combinant différentes technologies de stockage, telles que les batteries et les supercondensateurs, l'hybridation offre la possibilité d'augmenter l'autonomie, de réduire les temps de charge et d'améliorer l'efficacité globale. Cela répond non seulement aux préoccupations des consommateurs, mais s'aligne également avec les objectifs des fabricants visant à améliorer la consommation et la récupération d'énergie. Les prochains chapitres approfondiront les principes et les applications des systèmes de stockage d'énergie, en mettant particulièrement l'accent sur le rôle de l'hybridation dans l'avancement des capacités des véhicules électriques.

Chapitre 2 : modélisation multiphysique des batteries pour les véhicules électriques

Ce chapitre se concentrera sur la science fondamentale derrière les batteries, incluant les modèles mathématiques utilisés pour comprendre leur comportement, les méthodes de caractérisation pour évaluer leurs performances et les études de vieillissement pour anticiper leur évolution au fil du temps.

L'objectif de la modélisation est de prédire le comportement des batteries en termes de caractéristiques électriques, thermiques, puis de vieillissement. Ces trois modèles formeront ensemble le modèle multiphysique de la batterie, qui sera utilisé dans cette thèse. Le modèle

de vieillissement sera composé de deux parties : un modèle de vieillissement calendaire et un modèle de vieillissement cyclique. Les deux types de vieillissement sont additionnés pour former le modèle global de vieillissement.

Ce chapitre commence par expliquer les caractéristiques et paramètres essentiels des batteries, fournissant ainsi une base pour comprendre leur comportement et leurs performances. Nous explorerons des facteurs clés tels que la capacité, la tension, la résistance interne et l'efficacité, en mettant en lumière la manière dont ces propriétés influencent les performances de la batterie dans différentes applications. De plus, le chapitre approfondit le rôle crucial de la modélisation pour simuler le comportement des batteries, optimiser leur utilisation et élaborer des stratégies innovantes pour leur amélioration.

Dans les sections suivantes, nous aborderons la modélisation des batteries en traitant des aspects électriques, thermiques et de vieillissement. La modélisation du comportement électrique inclut la compréhension des réponses dynamiques des batteries à différents profils de charge et conditions de fonctionnement. Sur le plan thermique, nous explorerons les systèmes de gestion thermique complexes essentiels pour maintenir la santé et la sécurité des batteries. De plus, le vieillissement des batteries, une considération critique dans les applications pratiques, sera abordé, car il impacte directement la longévité et les performances globales d'une batterie.

Après une présentation du contexte, de la problématique et du produit étudié, ce deuxième chapitre présente la modélisation et l'identification de la batterie. La modélisation de la batterie est réalisée sous la forme d'un modèle multiphysique afin de prendre en compte les caractéristiques électriques, thermiques et de vieillissement de la cellule. Alors que les modèles électriques et thermiques sont basés sur la théorie des circuits équivalents, le modèle de vieillissement est élaboré de manière empirique à partir de la littérature des travaux antérieurs et d'une campagne de tests de caractérisation du composant de stockage d'énergie utilisé.

Cette étude a choisi de distinguer le vieillissement calendaire et le vieillissement cyclique pour identifier la dégradation de la batterie due à la conduite et à la charge par rapport au vieillissement calendaire. Chaque modèle a été paramétré par identification avec les résultats des tests sur le véhicule et le composant batterie afin de garantir la cohérence du modèle avec

le cas d'étude.

Les résultats des tests et la modélisation du vieillissement ont permis une meilleure compréhension des facteurs en jeu. Le vieillissement calendaire est fortement atténué par les basses températures et, dans une moindre mesure, par un faible niveau de charge. En ce qui concerne le vieillissement cyclique, les courants élevés accélèrent le vieillissement, et ce encore plus lorsque le cyclage est couplé à des températures basses proches de 0°.

Chapitre 3 : Dimensionnement et Gestion de l'Énergie des source de stockage

Dans ce chapitre, nous aborderons les aspects pratiques du dimensionnement des batteries en tenant compte des besoins spécifiques des applications. Nous passerons en revue les méthodes de gestion de l'énergie conventionnelles et les approches innovantes développées pour optimiser l'utilisation des batteries.

Le véhicule hybride électrique (VHE) représente une solution stratégique à l'un des défis les plus significatifs de nos besoins énergétiques futurs. Néanmoins, de nombreux indicateurs affectent la performance de ce type de véhicule, notamment en termes de conception, du type de chaîne de traction, de la configuration des composants, de la masse du véhicule et surtout de la masse de chaque système de stockage, ainsi que de la précision dans l'estimation de leur état de fonctionnement à chaque instant. De plus, la réalisation d'un groupe motopropulseur économe en énergie nécessite de relever des objectifs complexes tels que le type de conduite, la minimisation des pertes de conduction, le poids des sources et, surtout, la stratégie de gestion de l'énergie (PMS) choisie pour le partage de la puissance de charge entre les systèmes de stockage d'énergie (SSE).

Dans ce travail, la vision était orientée vers des stratégies et des contrôleurs suffisamment simples et rapides à exécuter en temps réel. En effet, la méthode de limitation et la méthode de fréquence basées sur des règles déterministes ont été introduites dans cette étude pour gérer la répartition de la demande d'énergie du véhicule entre les batteries HE et HP Li-ion dans une

topologie parallèle. Au-delà de cela, nous distinguons deux principales catégories de gestion à la lumière d'un indicateur de contrôleur qui est le paramètre SOCHP.

Dans ce chapitre, après avoir comparé les différentes stratégies de gestion de l'énergie pour une source de stockage hybride, les différents éléments (batteries HE et HP) ont été dimensionnés pour répondre aux exigences de la puissance de propulsion et de la récupération totale d'énergie lors du freinage du véhicule. Les résultats du dimensionnement de la source hybride avec différentes stratégies de gestion ont montré l'intérêt de l'hybridation et l'importance du choix de la méthode de gestion pour l'optimisation de la source d'énergie.

Il a ensuite été démontré la valeur d'une nouvelle approche de gestion de l'énergie basée sur la variation du partage de la puissance en fonction de l'état de charge de la batterie HP. Les stratégies de gestion de l'énergie pour la source de stockage hybride ont été présentées et comparées avec une méthode de référence issue de la littérature concernant les contraintes physiques observées par les composants des batteries HE et HP. La comparaison a montré que les contraintes d'une puissance efficace et de la quantité d'énergie échangée, telles que perçues par les batteries, peuvent être réduites avec les méthodes de gestion proposées en sollicitant davantage les batteries HP. Cette légère augmentation est loin d'empêcher les batteries HP de répondre aux demandes de puissance imposées par le véhicule.

Chapitre 4 : Validation expérimentale

Nous présenterons ici les expériences menées au sein du laboratoire ESTACA'Lab, les résultats obtenus et les leçons tirées de ces essais. Cette partie permettra de faire le lien entre la théorie et la pratique, en validant les hypothèses et les modèles développés précédemment.

La complexité des études sur les véhicules hybrides électriques (VHE) réside dans l'association de deux systèmes de stockage avec une architecture parallèle, nécessitant un contrôle en temps réel des gestionnaires pour répondre à la demande de charge tout en respectant les diverses contraintes liées aux caractéristiques des sources et à la sécurité du système. En d'autres termes, la clé de notre travail réside dans le développement de lois de contrôle robustes et efficaces

pour la gestion de l'énergie du groupe motopropulseur. Cependant, la présente étude vise à améliorer les stratégies de contrôle des méthodes (LM, FM, LFM) pour minimiser les contraintes sur la batterie par rapport aux contraintes d'un véhicule alimenté par une seule source. De plus, cette étude vise également à intégrer la stratégie de contrôle SOC pour réguler l'intervention de la batterie pendant le cycle de roulage, avec de meilleures performances globales. Ces lois ont été implémentées et validées sur un prototype réel, en tenant compte de contraintes supplémentaires telles que l'agressivité de la conduite, la sécurité opérationnelle, etc.

Ce chapitre commence par une brève description du banc d'essai développé au sein du laboratoire ESTACA afin de valider les approches de gestion proposées. Dans tous les travaux pratiques réalisés dans notre thèse, nous considérons que la température ambiante est en moyenne égale à 25°C, ce qui est négligeable pour un VHE, à condition que la température soit comprise entre 10°C et 30°C. Cependant, à des températures très élevées ou très basses, un modèle thermique précis est nécessaire pour la batterie Li-ion. Ce problème ne sera pas pris en compte car il ne constitue pas l'un des principaux objectifs de ce sujet. La présentation des principaux résultats expérimentaux a conduit à une étude comparative entre les stratégies énergétiques proposées. Enfin, nous présenterons les principaux résultats expérimentaux permettant de juger des performances des deux stratégies de gestion de l'énergie et de leur influence sur le système de stockage d'énergie (SSE) en termes de masse, de volume et de contraintes observées par les composants de stockage.

Ce chapitre présente un système de stockage d'énergie hybride actif qui comprend principalement une batterie Li-ion rechargeable à haute énergie, une batterie HP haute puissance, et des convertisseurs de puissance DC / DC pour contrôler ces deux sources de stockage d'énergie (SSE) ainsi que la charge au sein d'un véhicule électrique hybride (VEH).

La batterie Li-ion et la batterie HP peuvent être chargées ou déchargées simultanément, avec le courant ou la puissance répartis de manière adéquate entre elles selon une stratégie de gestion. La méthode de limitation, de filtrage, et l'hybridation de ces deux méthodes constituent le cœur du système de gestion de l'énergie (PMS). Par ailleurs, un bloc contrôleur SOCHP est utilisé pour surveiller l'état de charge de la source secondaire. Deux principales

stratégies de gestion, avec et sans contrôle du SOCHP, ont été développées pour assurer le partage de l'énergie entre les sources et la charge. Ces stratégies de gestion et de contrôle ont été vérifiées et comparées sous certaines conditions de fonctionnement à l'aide d'équipements Matlab-dSPACE.

Les résultats expérimentaux montrent que la stratégie de gestion avec contrôle SOCHP maintient la batterie HP quasi-chargée à la fin de chaque cycle de conduite, alors que les méthodes de gestion sans contrôle du paramètre SOCHP ne peuvent garantir que cette source secondaire est pleine au début de chaque démarrage du VEH. De plus, il existe un risque de décharge profonde de la batterie HP avec ces stratégies sans contrôle. En revanche, les résultats pratiques montrent que la stratégie de gestion avec contrôle SOCHP améliore significativement les performances de la batterie HP.

Chapitre 5 : Impact des Méthodes de Gestion de l'Énergie sur le Vieillissement

Ce dernier chapitre analysera l'impact des différentes stratégies de gestion de l'énergie sur le vieillissement des sources hybrides. Nous examinerons comment ces stratégies influencent la durabilité et les performances des systèmes de stockage hybride dans le contexte des véhicules électriques.

Ce chapitre explore l'impact des stratégies de gestion de l'énergie et de la topologie des systèmes hybrides sur le dimensionnement des composants clés, notamment les batteries, dans les véhicules électriques (VE). Nous étudions comment ces choix affectent les contraintes imposées aux technologies de stockage d'énergie et, par conséquent, le vieillissement des batteries. En mettant l'accent sur le rôle crucial des batteries dans les VE, nous analysons les implications des différentes stratégies de gestion de l'énergie et topologies sur leurs dimensions.

De plus, nous examinons comment ces facteurs influencent le vieillissement des batteries, un aspect fondamental pour la performance et la longévité des VE. En analysant les batteries en détail, nous visons à éclairer les compromis introduits par les différentes stratégies de gestion

de l'énergie et topologies des systèmes hybrides en termes de dimensions et d'implications sur les performances.

Ce chapitre établit les bases d'une comparaison exhaustive entre deux topologies de sources hybrides, fournissant des recommandations pratiques pour la conception de systèmes de stockage d'énergie plus efficaces et durables dans les VE. Les résultats de cette étude montrent que le choix de la stratégie de gestion de l'énergie et de la topologie du système hybride peut avoir un impact significatif sur le dimensionnement et le vieillissement des batteries. En général, les stratégies qui minimisent la profondeur de décharge des batteries conduisent à des batteries plus petites et à un vieillissement plus lent. Cependant, ces stratégies peuvent également réduire les performances globales du VE.

Dans ce chapitre dédié à l'exploration approfondie de l'influence des méthodes de gestion de l'énergie sur le vieillissement de la source hybride, notre objectif était de démêler les implications spécifiques des choix de gestion de l'énergie sur la durée de vie des composants clés, en mettant un accent particulier sur les modules à Haute Efficacité (HE) et Haute Puissance (HP).

Le chapitre a commencé par une présentation détaillée de deux principales méthodes de gestion de l'énergie : la gestion par fréquence et le partage de l'énergie. Chacune de ces méthodes a été examinée sous différents angles, depuis le dimensionnement des modules jusqu'à la gestion des contraintes électriques, afin de comprendre leur impact respectif sur la durée de vie de la source hybride.

L'analyse des dimensions des modules HE et HP a révélé des différences significatives entre les deux méthodes. La gestion par fréquence a généré des variations plus marquées en termes de poids et du nombre de cellules, tandis que le partage de l'énergie a conduit à une approche plus équilibrée, avec des dimensions plus homogènes entre les modules.

L'examen des contraintes électriques a mis en évidence des variations importantes, surtout pour les modules HP, entre les deux méthodes. La méthode de partage de l'énergie, particulièrement avec une limitation de 10 kW, a montré des avantages en réduisant les contraintes électriques pour les modules HP.

L'observation du vieillissement des modules a été un point focal, révélant des différences

notables entre les méthodes. Alors que le vieillissement des modules HE est resté relativement constant, le vieillissement des modules HP s'est nettement amélioré dans le contexte du partage de l'énergie avec une limitation de 10 kW.

Ce chapitre ouvre des perspectives significatives pour orienter les futures recherches dans la conception des systèmes hybrides. Les conclusions tirées de cette analyse approfondie fournissent une base solide pour des choix de gestion de l'énergie plus informés, visant à optimiser la durée de vie des sources hybrides. Les résultats de ce chapitre soulignent également l'importance cruciale de choisir des méthodes de gestion de l'énergie adaptées aux caractéristiques spécifiques des modules HE et HP afin de maximiser l'efficacité et la longévité des systèmes hybrides.

Conclusion Générale

En conclusion, cette thèse vise à fournir une compréhension approfondie des défis et des opportunités liés à la gestion et au dimensionnement des systèmes de stockage d'énergie hybrides pour les véhicules électriques. Grâce à une approche combinant modélisation théorique, expérimentation pratique et analyse comparative, cette recherche apporte des contributions significatives à l'amélioration de la durabilité, de l'efficacité et de la viabilité économique des VE. La mise en œuvre des stratégies et des technologies étudiées dans cette thèse pourrait jouer un rôle crucial dans la transition vers une mobilité plus propre et plus durable.

APPENDIX A

SPECIFIC GAS DATA

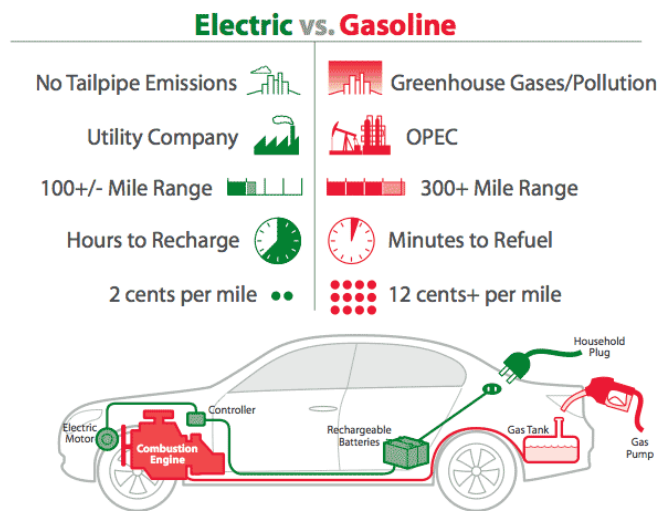


Figure A.1: Electrical Gasoline car comparison



Figure A.2: CO₂ emissions depending on the type of electric vehicle

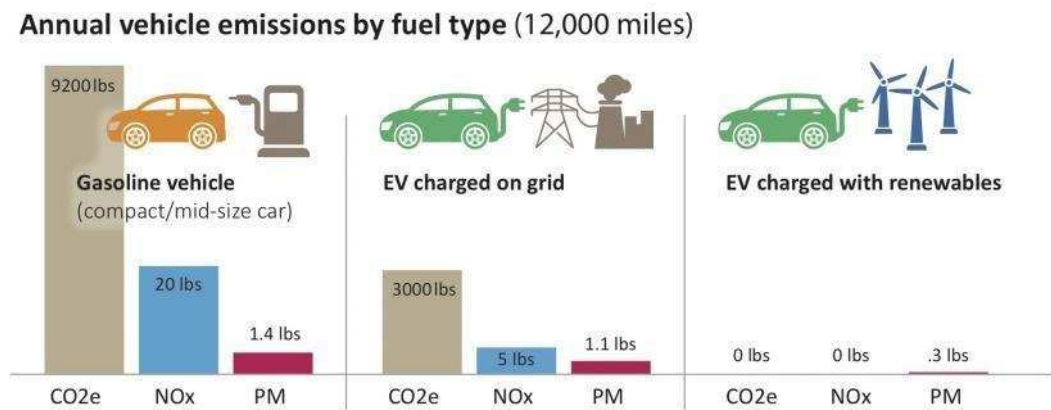


Figure A.3: Annual vehicle emissions by fuel type (19300 km)

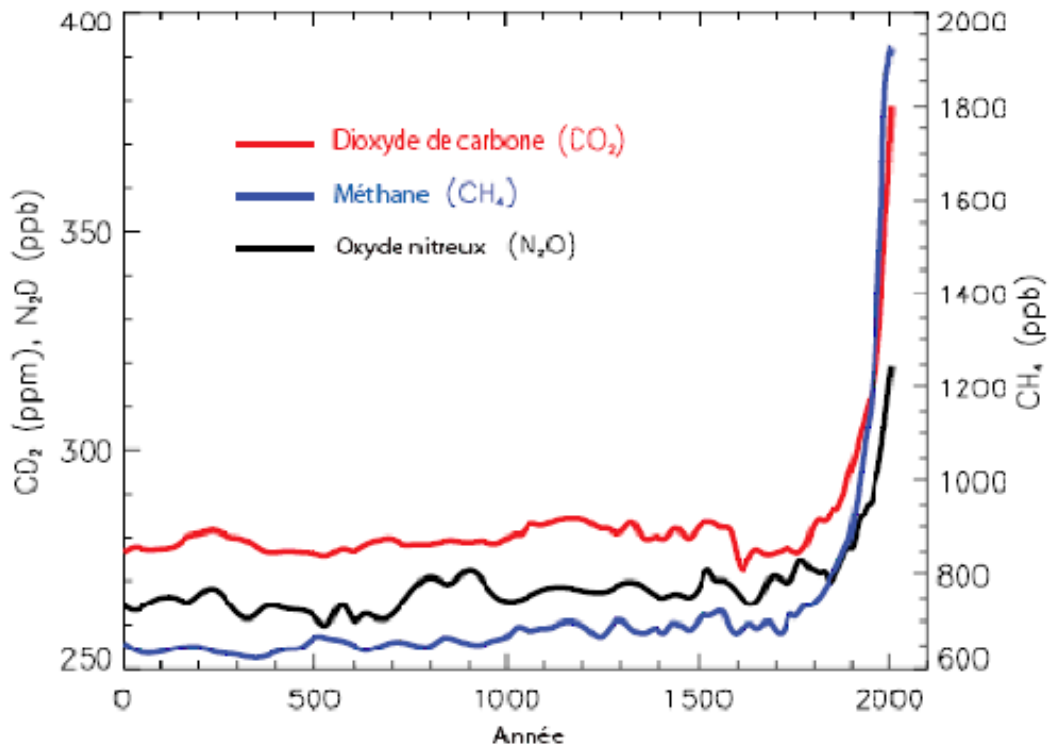


Figure A.4: CO₂, N₂O and CH₄ emissions

Les principaux gaz à effet de serre

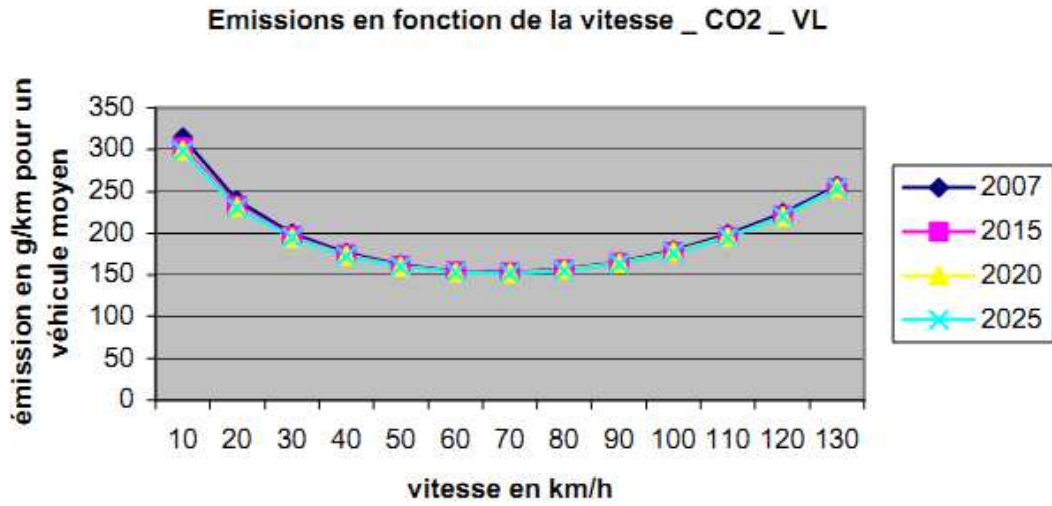
Gaz	Formule	Durée de vie	Formation du GES	PRG à 100 ans
Dioxyde de carbone	CO ₂	50 - 200 ans	-Combustion -Décarbonatation -Fermentation	1
Méthane	CH ₄	12 ans	(déchets, entérique) -Fuites (gaz, charbon)	23
Protoxyde d'azote	N ₂ O	114 ans	-Sols agricoles -Réactions chimiques	296
Gaz fluorés	HFC	HFC-23 : 260 ans	-Climatisation -Solvants	Moyenne 1 930
	PFC	CF ₄ : 50 000 ans	-Procédés industriels (en part. métallurgie)	Moyenne 7 200
	SF ₆	3 200 ans	-Procédés particuliers -Équipements électriques	22 200
Effet de serre additionnel -Quatre gaz à effet de serre indirect : SO ₂ , NO _x , COVNM, CO, +CFC (protocole de Montréal)				

Ozone 19%
Gaz halogénés 13%
N₂O 6%
CH₄ 18%
CO₂ 55%

Figure A.5: The main greenhouse gases

APPENDIX B

EMISSION ESTIMATES FOR THERMAL VEHICLES



htpb]

Figure B.1: CO₂ emission function of vehicle speed

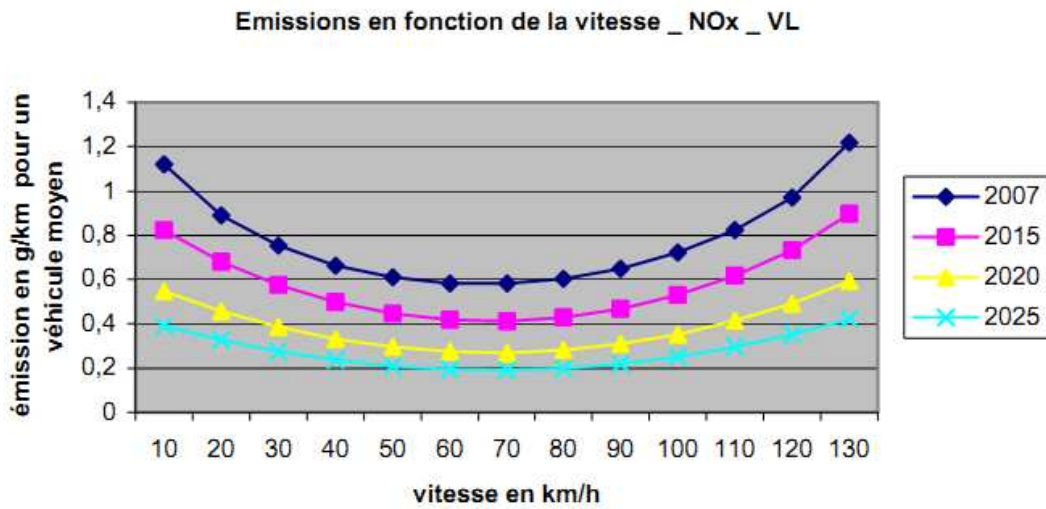


Figure B.2: NO_x emission function of vehicle speed

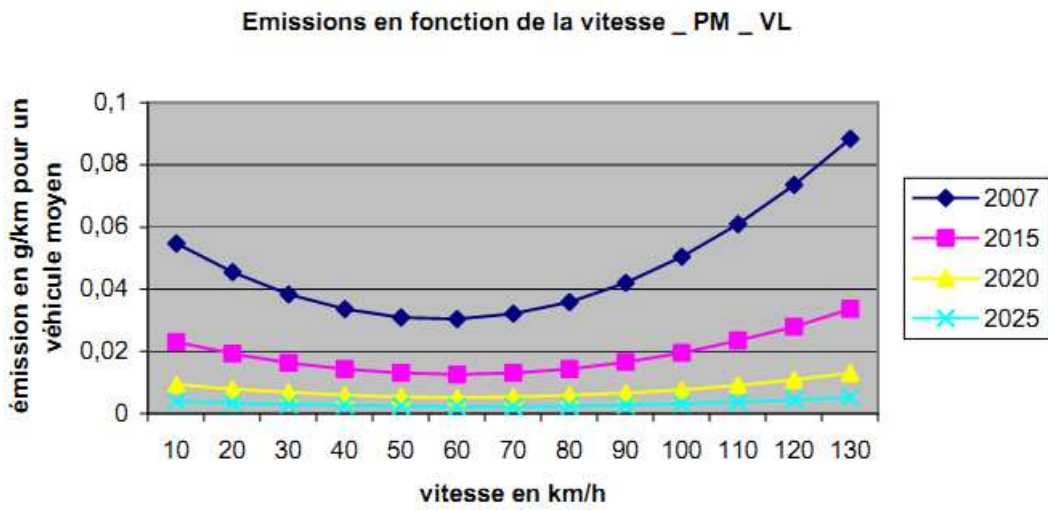



Figure B.3: *PM* emission function of vehicle speed

APPENDIX C

DATASHEETS

DATASHEET
BC ENERGY SERIES RADIAL D CELL 350F ULTRACAPACITOR



BCAP0350 E270 T11

FEATURES AND BENEFITS

- Round, radial mounting design for easy surface mount assembly
- Over 500,000 duty cycles
- 10 year life capability
- Ultra-low internal resistance

PRODUCT SPECIFICATIONS

CAPACITANCE	
Nominal capacitance	350 F
Capacitance tolerance	+20% / -0%
VOLTAGE	
Rated voltage	2.7 V DC
Surge voltage	2.85 V DC
Maximum operating voltage	2.7 V DC
Isolation voltage	N/A
RESISTANCE	
ESR, DC	3.2mΩ
Resistance tolerance	Max.
Thermal resistance (Rth)	10.9C/W
TEMPERATURE	
Operating temperature range	-40°C to +65°C
Storage temperature range	-40°C to +70°C
Temperature characteristics	
Capacitance change % at 25°C	± 5%
Internal resistance % at 25°C	± 150%
POWER	
Pd	4.300 W/kg
ENERGY	
E _{max}	5.62 Wh/kg
LIFESPAN	
Endurance After 1,000 hours application of rated voltage at 65°C	
Capacitance change	<20% decrease
Internal resistance	<25% increase
Life test At rated voltage and 25°C	10 years
Capacitance change	≤20% decrease
Internal resistance	≤100% increase
CYCLES	
Cycles - Capacitors cycles between specified voltage and half rated voltage under constant current at 25°C (500,000 cycles)	

APPLICATIONS

- Industrial power back up
- Portable power tools
- Renewable energy systems
- Short term UPS (uninterruptible power supply) and telecom applications

Capacitance change	20% decrease
Internal resistance	100% increase
CURRENT	
Leakage current After 72 hours at 25°C. Initial leakage current can be higher.	0.3 mA
Short circuit current (Isc) CAUTION: Current possible with short circuit from U _s . Do not use as an operating current.	840 A
Maximum continuous current	25 A
Maximum peak current, 1 sec	220 A
CONNECTION	
Terminal	Radial
SIZE	
Dimensions	See drawing
Volume	0.053 L
Mass	63g

MOUNTING RECOMMENDATIONS

Solder tabs to PCB. See application note for further information and slot spacing recommendations.

MARKINGS

Parts are marked with the following information: rated capacitance, rated voltage, product number, name of manufacturer, positive and negative terminal, warning marking, serial number.

ADDITIONAL TECHNICAL INFORMATION

Capacitance and ESR, DC measured per document no. 1007239, available at www.maxwell.com.

I_L = leakage current after 72 hours at 25°C

I_{sc} (short circuit current) = $\frac{V_{RATED}}{ESR}$

R_{th} = thermal resistance

$E_{max} = \frac{1}{2} CV^2$
 $= \frac{0.12V^2}{3,600 \times mass}$

$P_{max} = \frac{V^2}{4R(1kHz)}$
 $= \frac{V^2}{mass}$

$P_d = \frac{0.12V^2}{R(DC)}$
 $= \frac{0.12V^2}{mass}$

Figure C.1: Ultracapacitor Datasheets

APPENDIX D

HYBRID OPTIMIZATION ALGORITHM

(PSO/ NM)

The problems of optimization in electrotechnics present several related difficulties to the user's needs (search for a global solution, reliable solution, the variety of problems dealt with, reasonable calculation time, etc.), characteristics of the optimization problem (non-linearity, derivatives difficult to access, etc.) and time. Several optimisation methods are proposed to analyze or resolve these optimization problems. In this context, deterministic methods (e.g. gradient descent, Newton or Nelder-Mead NM) are based on the value of the objective function and constraints, as well as the value of their first derivatives and sometimes their second derivatives. These are iterative convergence methods towards a local minimum, and convergence towards a global optimum is not always assured. Deterministic methods are generally effective when assessing the objective function very fast or when its form is known a priori. Nevertheless, in optimisation problems in electrotechnics, one does not possess enough information on the objective function and its derivatives. To this end, the use of stochastic (also called metaheuristic), in general, avoids this problem and has a great ability to find the overall optimum of the problem. The stochastic methods more promising are the algorithms based on collective intelligence inspired by nature,

the most common are genetic algorithms and Particle Swarm Optimization (PSO).

For our study, we chose a hybrid optimization technique based on PSO stochastic method to perform a global search and a simplex algorithm of Nelder-Mead NM for a local search. The SE embedded system team developed This hybrid algorithm in our S2ET division of the ESTACA'LAB laboratory -Laval. We used to identify the parameters of the models (electrical, thermal and aging) of the Li-ion batteries tested. Due to the pronounced nonlinearity and high complexity of Li-ion batteries, analytical solutions of battery models are not easy to establish. Moreover, the number of parameters is large so parameter identification is very challenging using conventional approaches []. This paper uses a hybrid Particle Swarm–Nelder–Mead (PSO–NM) optimization algorithm to identify the optimal parameters of the battery model. The proposed algorithm is made-up of a modified particle swarm optimization algorithm (PSO) aimed at identifying the most promising areas and a Nelder–Mead simplex algorithm (NM) for performing local searches within these areas [46]. However, integrating the Nelder–Mead (NM) simplex method and particle swarm optimization (PSO) aims to combine their advantages and avoid disadvantages. The Nelder–Mead simplex search method is proposed by Nelder and Mead (1965), a non-derivative search method for multidimensional unconstrained. This method has been widely used in unconstrained optimization scenarios because it is easy to use and does not need the function's derivatives under exploration. The operations of NM method rescale the simplex based on the local behaviour of the function by using four basic procedures: reflection, expansion, contraction and shrinkage, which are described in detail in. Using these procedures, the simplex moves from the worst point towards the best point. However, a major drawback limits the applications of NM method in simulation optimization, which is that it is very sensitive to the choice of initial points and not guaranteed to attain the global. Optimum. Particle swarm optimization (PSO) is one of the most powerful optimization techniques developed by Eberhart and Kennedy in 1995. The development of this method was based on the simulation of simplified social behavior of animals, such as fish schooling and bird flocking. In this context, PSO method optimizes a problem by placing a swarm of candidate solutions, namely the particles, in the problem's search space, and moving these particles around in the search space according to the positions and velocities

of the particles [34]. Thereafter, it finds the global best solution by simply adjusting the trajectory of each individual towards its own best location (Local Position, LP) and the best particle of the entire swarm (Global Position, GP). It should be noted that the major difference between the PSO and other population-based optimization methods are their memory regarding the inertia weight and social exchange information. As a result, the PSO method is becoming very popular for optimising various continuous nonlinear problems due to its simplicity and efficiency. Despite the advantages discussed above, the practical use of an evolutionary computation technique in solving complex optimization problems is severely limited by the high computational cost of the slow convergence rate. In this context, the convergence rate of PSO method is also typically slower than those of local direct search techniques such as NM simplex method. For that, a hybrid approach incorporating the PSO and an NM simplex search method is used in our study for effectively solving battery parameters optimization problems. The proposed optimization algorithm can further improve the convergence and accuracy in obtaining optimal solutions over existing methods. Figure D.1 shows the flow charts of the hybrid PSO–NM optimization algorithm composed of a PSO followed by a NM algorithm.

To identify the parameters for the battery model depicted in Fig. 1, by hybrid PSO–NM optimization algorithm, the objective function must be defined. In this way, the simulated data of the battery model should provide a best fit to the experimental data. So, both the Sum of Squares Error (SSE) and absolute error value between the experimental voltage data and the model-based simulation data should be minimal. The mathematical formulation of objective the function is as follows:

$$\begin{cases} \text{Min}_X \{F(X)\} \\ X_{\min} \leq X \leq X_{\max} \end{cases} \quad (\text{D.1})$$

Where $X = \{x_1, x_2, \dots, x_N\}$ are the parameter bounds of research space. The combined objective function of battery model identification is given by:

$$F(X) = \sum_{i=1}^n (\hat{V}_{bat} - V_{bat})^2 + \sum_{i=1}^n |\hat{V}_{bat} - V_{bat}|^2 \quad (\text{D.2})$$

Where, \hat{V}_{bat} is the model output terminal voltage, V_{bat} the battery terminal voltage, and n is the number of data points. The advantage of combined objective functions, including Euclidean norms (SSE) and absolute value is the ability to cover both the large and small errors in the proposed model of Li-ion battery.

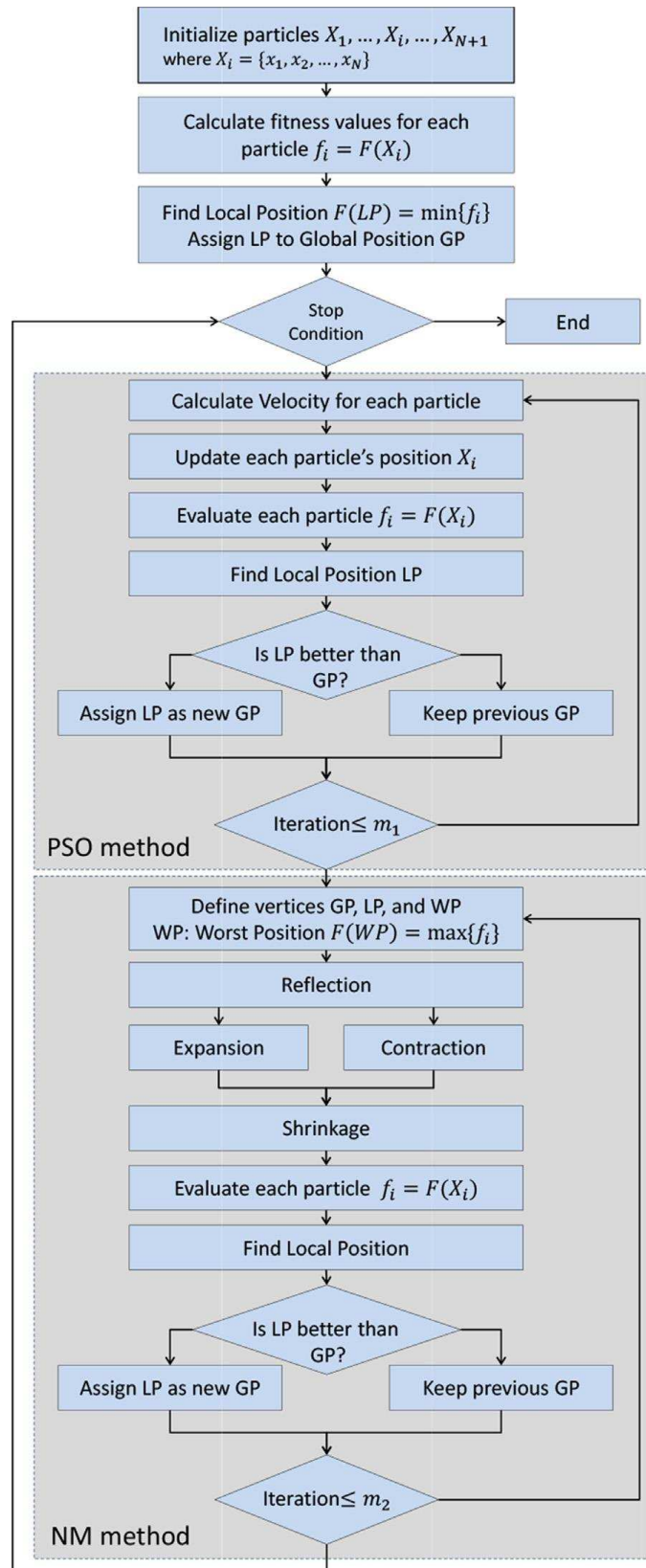


Figure D.1: PSO-NM algorithm

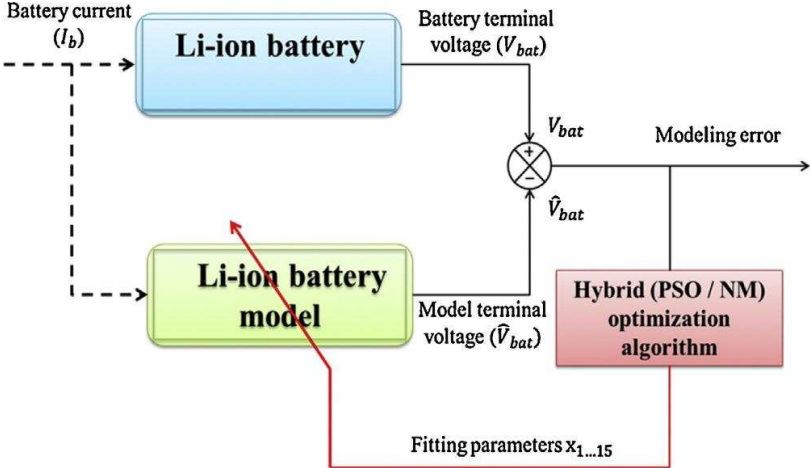


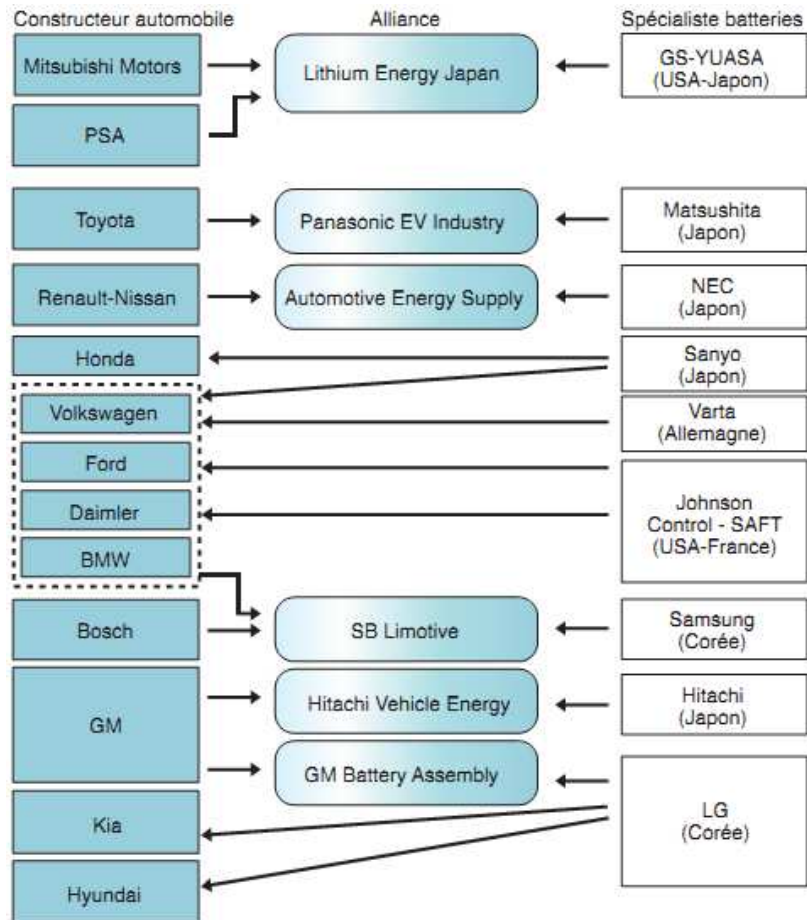
Figure D.2: Block-diagram of parameters identification system

APPENDIX E

EXAMPLES OF CURRENT REALIZATIONS OF ELECTRIC VEHICLES

Véhicule Electrique				
	Renault- Fluence ZE	Bolloré-BlueCar	Mercedes -Smart	Toyota FT-EV
Puissance Moteur (kW)	70	50	30	45
Batterie	Li-ion (20kWh)	LMP (30kWh)-300kg	Li-ion (14kWh)-140kg	Li-ion
Recharge	8h (220V) 20min (bornes)	6h (220V)	8h (220V)	2h30 (220V)
Poids	1600	1120	890	-
Autonomie	160	150	115	90
Prix d'achat (€) (Batterie)	20900 (82€/møe)	330€/mois	23680 (4770)	-

Figure E.1: Electrical vehicles



Source : IFP Energies nouvelles

Figure E.2: Alliances and cooperation policies between battery manufacturers and car manufacturers

APPENDIX F

MATLAB - SIMULINK INTERFACE

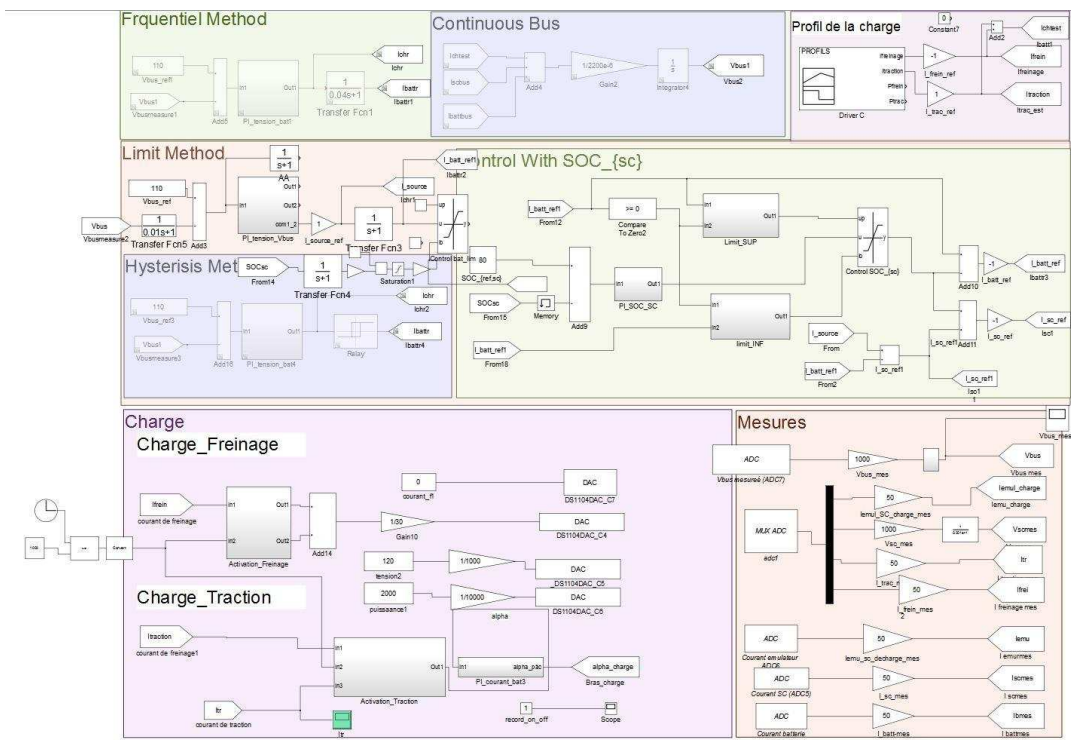


Figure F.1: Simulink Interface

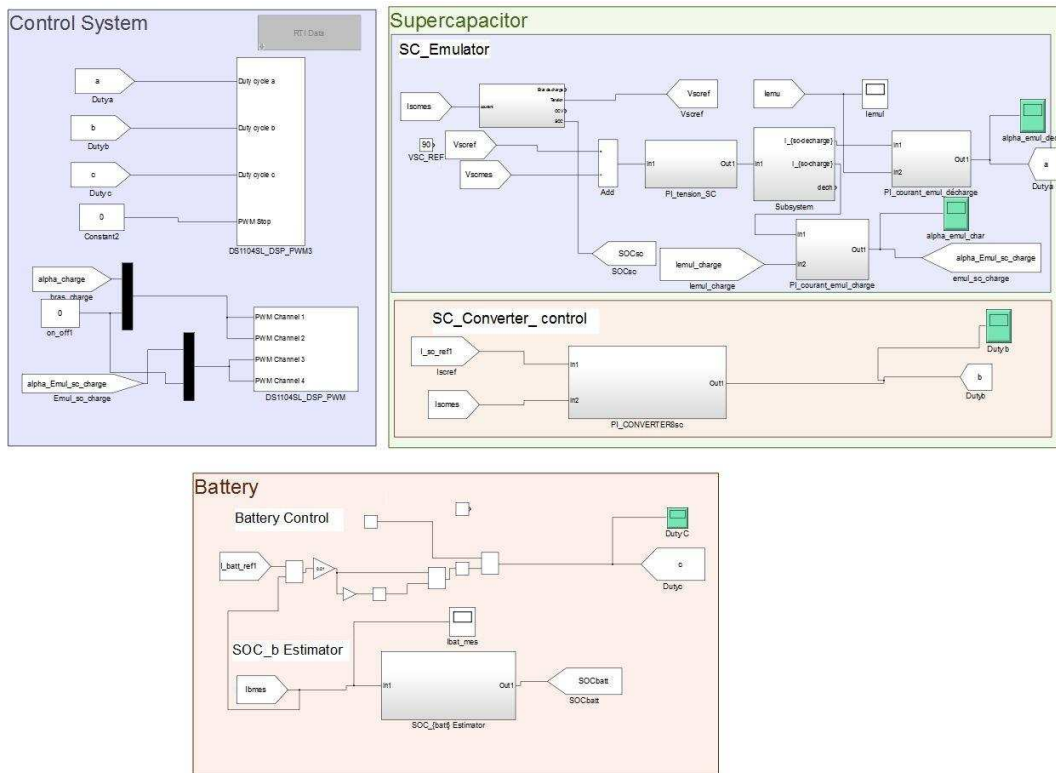


Figure F.2: Battery and supercapacitor models (Simulink-Matlab)

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