Politecnico di Torino

Master's degree in mechatronics engineering

Academic year 2020/2021

July 2021

High-Performance passenger HEV modelling and simulation:

IGBT and SiC inverters comparison

Mentor:

Prof. Tonoli Andrea

Ing. Serena Alberto

Ing. Gaviani Giovanni Maria

Candidate:

Manildo Lodovico

To my beloved, Margot.
August 15th, 2008 – November 27th, 2020

To my beloved grandma, Pierina.
March 4th, 1929 – March 23rd, 2021

To my beloved grandpa, Antonio.
July 13rd , 1930 – June 24th 2021

ACKNOWLEDGEMENTS

These years flew away so fast, I still cannot believe that my university career is over. I hope that all the sacrifices I have done will not have been in vain.

I would like to thank all the people who have belief in me, all my friends that I have found and, also lost, during these years.

The things that I will surely miss are: the strange feelings I felt while entering into an examination room, the trembling of the knees while reading exams' results and hope that these have gone well.

I will carry this period, this city and these people in my heart forever. There were ups and downs, moments of hate and love, great emotions in winning the Varano de 'Melegari Formula SAE event.

I would specially thank Margherita, my beloved girlfriend, you have always been close to me, you have given me the strength to keep pushing even when I was disheartened, you are the compass that gives me the route. I love you.

A special thank goes to Mr. Vianello, Ing. Gaviani, Ing. Serena and Dott. Caberlotto for the opportunity given to me, the patience and professionalism with which I was welcomed into the company.

To all my friends, who has helped, supported, endured and with whom I experienced beautiful and unique emotions.

To Gallina's family who have always treated me like a son which made my stay in Turin much sweeter.

Last but not least, to my parents Francesco, Francesca, Niccolò, Matilde who have always given me the chance to be myself and have never been oppressive. To my beloved grandma "Nonna Toi", who always makes me feel special, to my grandpa "Nonno Cesare", who has passed away too young and inspired me to become a man of honor and sound principles. To my grandpa "Nonno Toni" who has always been a reference in the family, to my grandma "Nonna Peia" who taught me what kindness and goodness are. To my great uncles Mario, Daniela, Elisa Clara who are milestones.

RIASSUNTO

La situazione climatica mondiale è critica, l'industria automobilistica ha gli occhi puntati addosso, le autorità di competenza hanno obiettivi ambiziosi da raggiungere e hanno stabilito tempistiche strette. Nel concreto, l'Unione Europea ha stabilito che l'intero sistema automobilistico diventi "CO_2 neutral" entro il 2050, obiettivo difficile da realizzare utilizzando piattaforme tradizionali a combustibili fossili, è inevitabile quindi una evoluzione tecnologica che combini l'utilizzo di più fonti propulsive o più ecologiche, come per esempio, l'utilizzo di motori a idrogeno o l'implementazione di sistemi propulsivi ibridi, nei quali il motore a combustione interna è abbinato ad uno o più motori elettrici. Il veicolo ibrido ha una storia lunga cento anni, tuttavia a seguito dell'arretratezza tecnologica di quegli anni, l'implementazione di questa architettura non ha avuto particolare successo, infatti le batterie e i motori elettrici erano di dimensioni notevoli, gravando sul peso dell'intero veicolo e sullo spazio occupato. L'efficienza totale bassa e i costi elevati hanno portato i costruttori a investire sulle tecnologie tradizionali fino al 1990, quando i giapponesi della Toyota hanno studiato e implementato l'architettura ibrida più diffusa al mondo. Gli anni successivi sono stati decisivi, gli altri costruttori mondiali guardavano con ammirazione la perfezione dell'architettura giapponese e nel 2017, dopo il noto scandalo mondiale chiamato "Diesel Gate", nel quale le centraline motore sono state dotate di un software capace di modificare le emissioni del veicolo durante i cicli di omologazione. La bufera mediatica ha generato un inevitabile controllo a tutte le case automobilistiche e molti veicoli si sono confermati essere più inquinanti rispetto a quanto rilevato durante il ciclo di omologazione, di conseguenza il ciclo è stato sostituito e sono state aggiunte delle prove su strada per rilevare le emissioni in ambienti reali.

Le restrizioni si sono inasprite, l'evoluzione tecnologica sull'elettronica di potenza ha permesso di aumentare l'utilizzo dell'architettura ibrida o totalmente elettrica e al giorno d'oggi, gran parte delle case automobilistiche hanno a listino almeno un modello ibrido o elettrico. L'elettronica di potenza, in particolare l'inverter, è in continua evoluzione e la ricerca sta portando i produttori di elettronica all'utilizzo di materiali e leghe speciali in grado di essere molto efficienti, sia dal punto di vista termico che energetico, capaci di diminuire peso e dimensioni di inverter. Nel caso degli inverter SiC, il sistema di raffreddamento può essere notevolmente ridotto in dimensioni, essendo una lega capace di dissipare molto meglio il calore rispetto agli inverter IGBT. Anche il pacco batterie ha subito un'evoluzione a livello di componentistica e materiali, tale da potersi ricaricare in tempi brevi e di immagazzinare molta energia.

L'obiettivo ambizioso dell'Unione Europea è quindi raggiungibile solo adottando queste tecnologie, nella seguente tesi è stato sviluppato un modello 0-dimensionale della modalità elettrica di un veicolo ibrido ad alte prestazioni. Il tutto è stato sviluppato in ambiente Matlab/Simulink™ ed è utile a comprendere i miglioramenti nell'adozione di inverter a tecnologia SiC rispetto a inverter IGBT.

Il modello funziona partendo da un ciclo WLTP classe 3 dal quale vengono ottenuti due segnali, velocità longitudinale e accelerazione, successivamente i segnali vengono convertiti in richiesta di coppia e velocità rotazionale dei due motori presenti nell'asse anteriore del veicolo. Queste richieste vengono immesse in due mappe di efficienza relative ai due motori elettrici a flusso assiale prodotti da Texa S.p.a. e agli inverter abbinati ai motori, ogni tipologia ha la propria mappa. Una percentuale di efficienza totale del sistema è ottenuta e quindi, calcolate le perdite di potenza, tali perdite solo poi sommate alla potenza richiesta al sistema propulsivo per muovere il veicolo e la corrente totale richiesta alla batteria viene ottenuta. Il ciclo viene ripetuto all'infinito fino a quando la carica della batteria arriva al 5% e i risultati, in termini di elettricità consumata e chilometri percorsi con una carica di batteria vengono quindi valutati e confrontate le due tipologie di inverter, SiC e IGBT.

ABSTRACT

The world climate situation is critical, the automotive industry has its eyes on it, the competent authorities have ambitious goals to achieve and have set tight deadlines.
The European Union (EU) has established that the entire automotive system will become "CO2 neutral" by 2050, a difficult goal to achieve using traditional fossil fuel platforms, therefore a technological evolution that combines the use of multiple propulsive sources, or more ecological, is inevitable. For example, the use of hydrogen engines or the implementation of hybrid propulsion systems, in which the internal combustion engine is combined with one or more electric motors.
The hybrid vehicle has a history of one hundred years, however, following the technological backwardness of those years, the implementation of this architecture was not particularly successful, in fact the batteries and electric motors were of considerable size, weighing on the weight of the entire vehicle and occupied space. The low total efficiency and high costs led manufacturers to invest in traditional technologies until 1990, when the Japanese of Toyota company have studied and implemented the most widespread hybrid architecture in the world. The following years were decisive, the other world manufacturers looked with admiration at the perfection of Japanese technology and in 2017, after the well-known worldwide scandal called "Diesel Gate", in which the engine control units were equipped with software capable of modifying the vehicle emissions during type-approval cycles. The media storm generated an inevitable check on all car manufacturers and many vehicles were confirmed to be more polluting than what was detected during the homologation cycle, consequently the cycle was replaced and road tests were added to detect emissions in real environments.
The restrictions have tightened, the technological evolution on power electronics has made it possible to increase the use of hybrid or all-electric architecture and nowadays, most car manufacturers have at least one hybrid or electric model on the list. Power electronics, in particular inverters, are constantly evolving and research is leading electronics manufacturers to use special materials and alloys capable of being very efficient, both from a thermal and energy point of view, capable of reducing the weight and overall dimensions of the inverter. In the case of Silicon Carbide (SiC) inverters, the cooling system can be significantly reduced in size, being an alloy capable of dissipating heat much better than insulated-gate bipolar transistor (IGBT) inverters.
The battery pack has also undergone an evolution in terms of components and materials, such that it can be recharged quickly and stores a lot of energy.
The ambitious goal of the EU is therefore achievable only by adopting these technologies. In the following thesis a 0-dimensional model of the electric mode of a high-performance hybrid vehicle is developed. The model is developed in the Matlab/Simulink ™ environment and is useful for understanding the improvements in the adoption of SiC technology inverters compared to IGBT inverters. The model works starting from a class 3 WLTP cycle from which two signals are obtained, longitudinal speed and acceleration, then are converted into torque demands and rotational speeds of the two motors present in the front axle of the vehicle. These requests enter in two efficiency maps relating to the two axial flux electric motors produced by Texa S.p.a. and to the inverters associated, each type has its own map. A percentage of the total efficiency of the system is obtained and then, the power losses are calculated and added to the power required by the propulsion system to move the vehicle and the total current required by the battery is obtained. The cycle is repeated indefinitely until the battery charge reaches 5% and the results, in terms of electricity consumed and kilometers traveled with a battery charge, are then evaluated and compared between the two types of inverters, SiC and IGBT.

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Introduction

The focus on this work will be to design and simulate a high-performance hybrid vehicle. The vehicle would be a passenger car with a P2/P4 architecture combined with a V12 engine.

In the first chapter, it will be presented a history review, starting from the first hybrid vehicle designed before the First World War, moving from examples of passenger cars of the post Second World War period and ending with today's motorsports technologies.

The second chapter will be a focus on different architectures and classifications, related to electric motor positioning with respect to gasoline engine and nominal powers.

In the third chapter, the global warming issue will be presented, giving a brief introduction of the Kyoto Protocol, moving from the Paris Agreement and finally reaching today's European norms which regulate the market of new vehicles.

Moving deeper in the thesis' core, a focus will be held related to batteries topologies and fundamental concepts in chapter four.

In the fifth chapter, IGBT (Insulated Gate Bipolar Transistor), SiC (*Silicon Carbide)* and GaN (*Gallium Nitride*) inverter typologies are presented.

In the sixth chapter, different electric motors will be presented and a comparison will be held.

The seventh and eighth chapters are related to the electric mode of the hybrid powertrain of an high performance HEV that will be modelled in MATLAB/Simulink™ environment in order to evaluate performance improvements comparing different in vehicle inverters.

The last chapter, number nine, results will be presented and a discussion on different inverters technology to be applied in order to achieve the best performance-cost trade off will be held.

1. HYBRID VEHICLES

1.1 History of HEV

The first passenger car model dates back to the late 18th century. Despite poor documentation related to vehicles of those years, a Parisian engineer and coach builder in Paris called Charles Jeantaud, was probably the first to seriously devote himself to the vehicle production since 1881, five years before Karl Benz with his Patent Motorwagen.

The essential elements needed to build and let an electric car to be driven were already available:

- the DC electric motor was patented by Thomas Davenport in 1834;
- lead-acid rechargeable batteries by Gaston Planté in 1859;
- the system for the production and distribution of DC electricity by Thomas Edison was patented in 1880;

Jeantaud's choice was certainly motivated by the simplicity of construction of a vehicle, in fact the search for energy saving or reduction of pollution, which is the goal of this technology of today, were not relevant for that time.

The electric car was less complex than the internal combustion one and, for its use, it was not necessary to start the motor with the starting handle, push the clutch and change gears.

The use of these three devices was considered by many to be a significant impediment to the spread of the automobile with an internal combustion engine.

Figure 1.1 Charles Jeantaud driving, probably, the first ever electric vehicle built.

The first electric vehicles were initially introduced to replace the square carriages, the taxis of the time and some electric engines were used to transform the existing carriages, as interchangeable groups with their front axle.

Charles Jeantaud also built the first cat to set a land speed record of 39.24 mph, the electric motor was able to provide 35 Hp, which is more than 3 times the power that a combustion engine was able to generate at that time. In 1899 the same record was beaten from another electric car, this time manufactured by Compagnie Internationale des Transports Automobiles de Paris, it has reached the impressive speed of 100 mph thanks to a double motor configuration that was able to guarantee a power of 68 Hp.

However, first drawbacks came out, the energy supply was a 650 kg lead-acid battery, which range at top speed was just enough to cover the few kilometers of the road used to homologate the record.

In the meanwhile a manufacturer of coaches and suppliers of the Austrian imperial house, Lohner, also decided to build electric touring cars. Chassis and bodies came from his factory, while electrical equipment was supplied by Béla Hegger, where Ferdinand Porsche worked as technical director. [1]

A patent dates back to 1897 which credits the invention of the hybrid system to a young Austrian engineer called Ferdinand Porsche.

Porsche studied a particular engine, suitable for being integrated into the front wheels. The Lohner Electric Phaeton, presented in Paris in 1900, had 5 Hp, which can be increased to 14 for short periods, being able to reach a cruising speed of 37 km / h or a maximum speed of 60 km / h. The range was about 50 km with 400 kg of batteries. Weight and autonomy were evidently its weak points., so the next Lohner Semper Vivus, still designed by Porsche, set out to do away with them. The propulsion system was modified, adding two small generators, with 3.5 Hp De Dion-Bouton petrol engines, which could recharge a smaller and lighter battery.

Figure 1.2: 1900, Porsche-Lohner first hybrid vehicle.

So, the first hybrid car was therefore born exclusively to grasp the advantages of electric traction, limiting the penalties imposed by the low battery capacity.

However, as everything in a prototype phase, also this passenger car had economical and functional drawbacks. The DC motor sliding brushes were subjected to rapid wear, motor windings were expensive and unreliable due to bad electrical insulation. Another problem was present during the starting procedure, in fact, due to the high current draw of the DC motors for the early first period of time, in order to avoid overheating was mandatory to temporarily reduce the voltage by mean of costly and complicated combinational switches, what nowadays are called inverters.

While the electric car in Europe was a social status sign, in the USA it was truly the comfort and the ease of use of the car that let it be so widespread. It’s true that was not something that everyone could have afforded but over 4000 cars produced at that time, 1600 were electric.

The most sold one was for sure the 1905 Rauch & Lang Brougham.

Figure 1.3: 1905, Rauch & Lang Brougham

However, the electric car began to disappear when customers accepted the driving difficulties of thermal engines and the performance of the latter exceeded that of electric motors, thanks to the semi-automatic transmissions developed by Ford and Oldsmobile and it’s commonly believed that the coup de grace was given by the introduction of the starter in 1916.
The fatal blow was struck by Henry Ford who “adjusted” the existing petrol car reducing noises, gas exhaust smells and vibrations, in addition the Ford assembly line was just introduced, able to provide cheap cars.

Figure 1.4: Ford’s production line

In the following years, the electric car was almost forgotten since the Second World War, where fuels were monopolized by military uses, while electricity, at that time produced in many countries by water, seemed to be abundant and inexhaustible. Different cars were born for individual use like the Peugeot VLV produced in 400 units within the two-year period from 1941 to 1943.

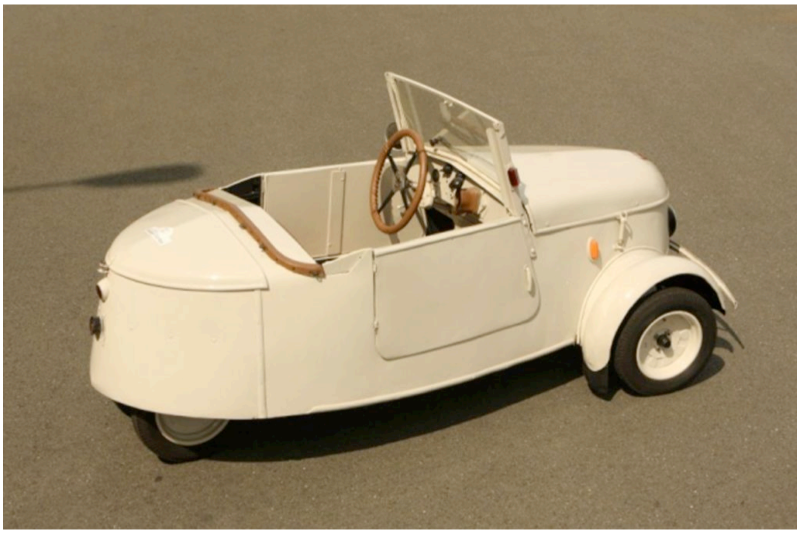

Figure 1.5: 1941, Peugeot VLV

More pervasive was the presence of electric transport vehicles, used by municipal services and deliveries. The technology used in these creations was still fundamentally the same costly technology as in the first cars: lead batteries, DC motors, contact controllers.

Few years later, in the 1970's the energy crisis took place, petrol price was incredibly raised due to the OPEC *(Organization of the Petroleum Exporting Countries)* embargo following the war of Kippur, in which Israel state decided to invade Egypt and Syria. The embargo lasted in 5 months but, however the needs of find an alternative to petrol cars prompted many to invest money and resources. At the same time, emission limits for cars are being introduced in the USA, confirming the trend. [2]

Figure 1.6: 1974, SebringVanguard CitiCar

The best-known example of an electric car produced in small series is provided by the American SebringVanguard CitiCar, built in approximately 3,500 units between 1974 and 1976 and sold at a price of approximately $4,500. It had a fiberglass body, built in derogation of the safety standards which led the car weights only 570 kg. A 2.5 Hp DC motor, powered by six 6V lead-acid batteries, through a contact controller, could make them reach 60 km/h and a range of about 60 km. At that time, technological progress already made it possible to build electronic DC voltage regulators, the choppers, which would be better for cost and reliability than contact controllers. The voltage was regulated by interrupting the power supply for short intervals of variable duration.

Figure 1.7: 1972, FIAT X1/23

FIAT also followed this world trend with the X1/23 revealing the car in the 1972 car show. FIAT's car was able to accommodate two passengers in really small dimensions. The front axle electric motor delivered 10 kW, capable of offering a maximum speed of 75 km/h. With 166 kg of lead-acid batteries, it was possible to achieve a range of 70 km, barely sufficient for urban use.
The impossibility to achievable better range with batteries alone led to the resumption of the Lohner Semper Vivus scheme, adapting it to the times and conforming it to the new technologies available.

In 1974, one of Motorola's founders, Russell Feldman, commissioned Victor Wouk (1919 - 2005), considered the father of American electric vehicles, to participate in the program.
He founded Petro-Electric Motors where he developed a prototype derived from the Buick Skylark, the first example of a hybrid electric car conceived to reduce consumption and emissions of the internal combustion engine.

Figure 1.8: Buick Hybrid

It was renamed "Buick Hybrid" for that occasion, an intermittent Wankel engine was installed to drive a 20 kW generator, used to recharge the batteries.

The prototype exceeded 100 km/h, demonstrating the possibility of halving the consumption of the original car and reducing emissions by approximately 90%, albeit with lower performance. Other manufacturers also tried this route, using conventional internal combustion engines.

In 1978, Fiat hybrid 131 born. The original gearbox was replaced with a 24 kW DC motor, capable of rotating at the same speed as the heat engine. A combined power of 65 Hp was guaranteed adding a derived engine from the Fiat 127. An electronic regulation system was able to implement what nowadays is called "KERS" (*Kinetic Energy Recovery System*). The recharging of the batteries during braking and the adding of electrical power onto the transmission during acceleration, was possible thanks to a digital microprocessor and a chopper, controlled by the brake and accelerator pedals.

Figure 1.9: Fiat 131 hybrid

The performance was similar to the Fiat 131 equipped with the 1300cm^3 4 cylinder petrol engine but with a huge improvement in fuel consumption near 25%. [3]

Although the interesting results obtained due to the costs and the small size of the boot, half of the trunk was occupied by the 180kg lead-acid batteries, the practical applications were put aside.

In the following period, almost all the manufacturers continued to carry out research in this sector, bringing substantial technological improvements to hybrid electric cars, above all thanks to the constantly increasing performance of electronic microprocessors, and to the availability of improved NiMH batteries and, later, to the Li-ion.

While the USA invested billions to improve the battery efficiency with the USABC (*US Advanced Battery Consortium*) and in collaboration with the PNGV (*Partnership for a New Generation of Vehicles*), research program promoted by Bill Clinton which had the aim of reduce vehicle consumption up to 2,9 l/100km within the year 2003, in Asia, Toyota was secretly studying this technology since the 1960s.
They built two concepts based on Toyota Crown and Toyota Sport 800, however these concepts remained so due to the gas turbine that was used instead of a classic petrol engine as generator for battery recharging. After 30 years of study, in the nearly 90s, the G21 project was born. The aim was to build a reliable, affordable and fuel saving hybrid vehicle.
Few engineers and designers were involved in the project, starting from a blank sheet. The question they would been able to answer was " What is a car for the 21th century?", their thoughts were strictly related to global warming, air pollution, energy and safety. So the key words were "environment" and "resources".

Their attention was focused on a new hybrid system able to double the fuel efficiency. "We studied various systems for about six months from the end of 1994, before deciding that the two-motor type was the best option because of the high fuel efficiency potential. We assumed that power electronics (semiconductors and electronic circuits used to efficiently control power) would make leaps in the near future. There was a lot of promise here. The conventional transmission could be completely eliminated. And yet, the technological hurdles remained high.", Toyota managing officer Satoshi Ogiso said. [4]

They were right, in fact, the 11th December 1997 the Kyoto Protocol was officially published. The objectives of this international treaty were to prevent global warming, reducing the CO_2 emissions, and promote the so called "green" energy consumption.

The adopted system in the concept car presented at the Tokyo Motor Show was called "Toyota energy management system" (EMS). It was featured with a single electric motor, a petrol engine, a CVT transmission, a capacitor. It was able to have a fuel consumption of 30 km/l which was quite impressive.

Figure 1.10: Toyota Prius first concept

The EMS evolution is what would come to be known as "Toyota Hybrid System" (THS).

Toyota brought the hybrid technology on another level and its competitors were not able to follow the trend investing resources on other technologies, such as petrol and diesel engines.

The introduction of Lithium-ion technology has made it possible to reduce the weight of the battery to one third, compared to Lead ones. This new battery was very promising due to its good weight performance ratio.

Lithium-ion batteries, in combination with more restrictive rules, that were undersigned from over 180 countries all over the world in the Tokyo protocol, allowed the development and continuous improvement of hybrid and full electric vehicles, considered the future way of transport system.

1.2 HEV Technology in Motorsport

In the 2000s everything was moving to that direction, also race cars gave a huge thrust to this technology.

Figure 1.11: Kimi Raikkonen, Jerez GP. 2009

In 2009 F1 constructors were allowed to use KERS. The recovered energy can either be stored as mechanical energy or as electrical energy with a maximum power of 81 Hp. Although this system added a boost while the car was under hard accelerations, the car tight space available and the difficulties related to the batteries let this system disappear for the following season.

Meanwhile, also in WEC championship, there were LMP1 cars that were hybrid. The most winning and discussed one was the Audi R18 TDI hybrid.

Figure 1.12: Audi R18 TDI hybrid

This race car was equipped with a V6 TDI (*Turbo Diesel Injection*) engine matched with an electric motor. The diesel engine produced 510 Hp on the rear axle, while the electric motor fed torque to the front axle. Thanks to this 4-wheels drive configuration, dominated the championship beating Porsche and Toyota from 2012 up to 2016. The so called, Diesel Gate scandal, signs the end of WEC competitions for Audi sooner and for Porsche later, in 2018.

Coming back to F1 the 2014 was a year of change, FIA (*Federation International de l'Automobile*) edited the rules, allowing teams to use kinetic and heat recovery systems, only 100 kg of race fuel were allowed and so the turbos. Due to this fuel restrictions all the teams were almost forced to swap the naturally aspirated engines to turbo ones.
KERS were now renamed an MGU-K (*Motor Generator Unit – Kinetic*) and the heat recovery system as MGU-H (*Motor Generator Unit – Heat*) and the so called " Hybrid era" took place.

Figure 1.13: Lewis Hamilton, Singapore GP. 2014

1.3 Motorsport technology applied to Hybrid Supercars

Since sports competitions are a good place to test new technologies that can be introduced to the market, some car constructors like BMW, McLaren, Porsche, Ferrari, etc. decided to bring this new hybrid concept within sports car. They were not looking for the best fuel economy from the system that let them achieve better performance.

The first car maker to reveal a hybrid supercar was BMW with the i8 model, in 2011 at Frankfurt motor show. The i8 was a plug-in marketing tool, able to show how hybrid technology can produce fast, good looking and exciting cars.

Figure 1.14: BMW i8

The car is equipped with a 3-cylinders 1500 cm^3 engine able to provide 231 Hp on the rear axle, matched with a 131 Hp electric motor on the front axle. [5] The propulsion system is stored within a high tech extremely light mixed aluminum and carbon chassis. The battery is located in the middle, in order to balance the weight distribution perfectly.

Figure 1.15: Bmw i8, internal structure

This plug-in hybrid vehicle is able to guarantee a declared 0-100 km/h within 4.4 seconds, almost 40km in full electric drive and a combined consumption of 2,1 l/100km. It's impossible to achieve these performance, in term of fuel consumption and acceleration, without an hybrid/full electric vehicle configuration.

Whenever Porsche, Ferrari, McLaren and, later, Mercedes, came into play, the traditional "Supercar" moved by astonishing V12 or bi-turbos V8 masterpieces have been replaced by the so called "Hypercars". Extremely fast supercars with hybrid plug-in powertrains.

Figure 1.16: a) Porsche 918 b)Ferrari LaFerrari c)Mercedes Project one d)McLaren P1

2. HYBRID ARCHITECTURES

2.1 Micro, mild, full and plug-in hybrid electric vehicles (HEV)

The HEV propulsion system has at least two sources of power: the internal combustion engine (ICE) and an electric motor (EM). The powertrain is then quite complex because it contains all the components of an ICE vehicle plus components of a pure electric vehicle (EV) like converters, high voltage batteries and inverters. It needs two energy sources, the fuel tank for the engine and a battery for the electric machine so distinctions have to be done in order to classify HEV due to different levels of hybridization.
Although few disadvantages related to more complex electrical structure, building difficulties and more weighting vehicles, a lot of pros in terms of efficiency and performance are present. In fact, EM have very high efficiency and provide instant high torque even at low speeds.
If the objective function of the system is strictly related to fuel economy, the ICE can be downsized thanks to the EM assistance and the gear ratio can be lowered. On contrary, if the aim is to improve performance in term of driving excitement and power delivery, the EM can be matched with a high performance V6,V8 or, even, V12 ICE. The EM bridges the typical torque gap at low rpm (*rounds per minute*) of a naturally aspirated engine or avoids the turbo lag in a turbo engine.
So, related to the grade of hybridization, HEV can perform at least one of the following functions:

- Start/stop the engine while is idle;
- Electric torque assistance;
- Regenerative braking;
- Battery charging while driving or/and when parked;
- Pure electric driving;

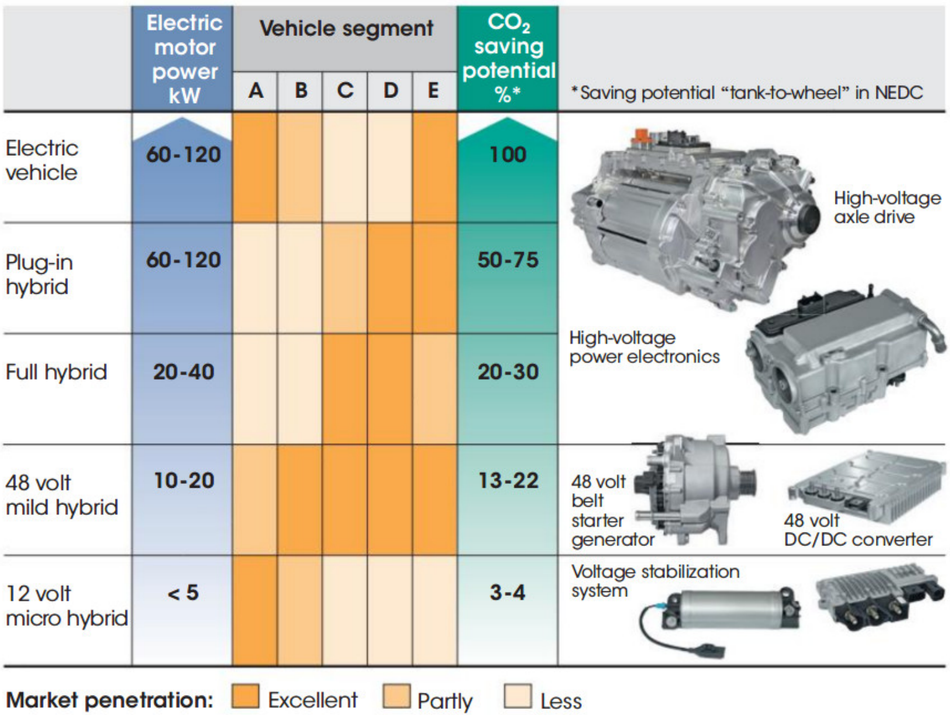

Figure 2.1: Hybrid vehicles definitions, where vehicle segments are:
A – Subcompact; B – Compact; C – Medium; D – Large; E – Premium cars;

2.1.1 Micro HEV

In this configuration the key components are:

- ICE;
- 12 V batteries;
- EM as a starter.

In micro HEV, the electric motor used as starter/generator cannot supply additional torque to the ICE and can perform the most basics feature from the above list:

- Start/stop the ICE while is idle;
- Regenerative braking;

The first function switches off the ICE and restart it whenever is needed without driver intervention. In a driving scenario, while the car is stopped in front of a traffic lights, if neutral gear is engaged (in case of manual gearbox) or the brake is pressed and the vehicle in idle (in case of automatic gearbox) the ICE is shut down in order to reduce fuel consumption and air pollutants up to 8%. When the system acquires the driver wish to restart the car, while pushing the clutch or taking of the foot from the brake pedal, it asks electricity from a special designed 12 V battery equipped on the vehicle, able to withstand hard duty cycles, and that electricity flows up to the starter.
Few conditions have to be met in order to let the system work correctly:

- Battery state of charge (SOC) has to be over a certain voltage range;
- ICE has to be at its own working temperature

Most of micro HEV vehicles are also equipped with a sort of energy management function (EMF). Thanks to EMF the fuel consumption can be optimized, the 12 V battery energy is managed in a way that alternator is not always under loading condition, avoiding energy waste due to the impossibility to store it. Further energy recovery is done thanks to regenerative braking, the heat produced due to friction between the pad and the brake disc is converted in electricity and stored in the low voltage battery. Most of today's ICE vehicles are examples of micro HEV. [7]

2.1.2 Mild HEV (MHEV)

In this configuration the key components are:

- ICE;
- 48 V or 160 V EM;
- 48 V batteries;
- Inverters;
- DC/DC converters.

The EM can provide additional torque to the ICE propulsion system; the torque assistance can be of two different types: torque fill and/or torque boost.

Torque fill can be explained considering the transient behavior of an ICE while accelerating. In this case the ICE, especially turbo ones, has some physical delays that cannot be avoided

due the mechanical inertia of the moving components and of the air flowing inside manifolds. This leads to the so called “turbo-lag” which is a gap, always located on the lower rpm side of the ICE map, that has to be filled in order to have instant torque response.
While, Torque boost is the capability of the EM to overcome physical ICE limits in term of maximum torque available leading on a positive torque offset. The EM positioning choice while designing the vehicle can lead to different mild HEV topologies from P0 to P5, so the grade of complexity, costs and performance varies between different topologies:

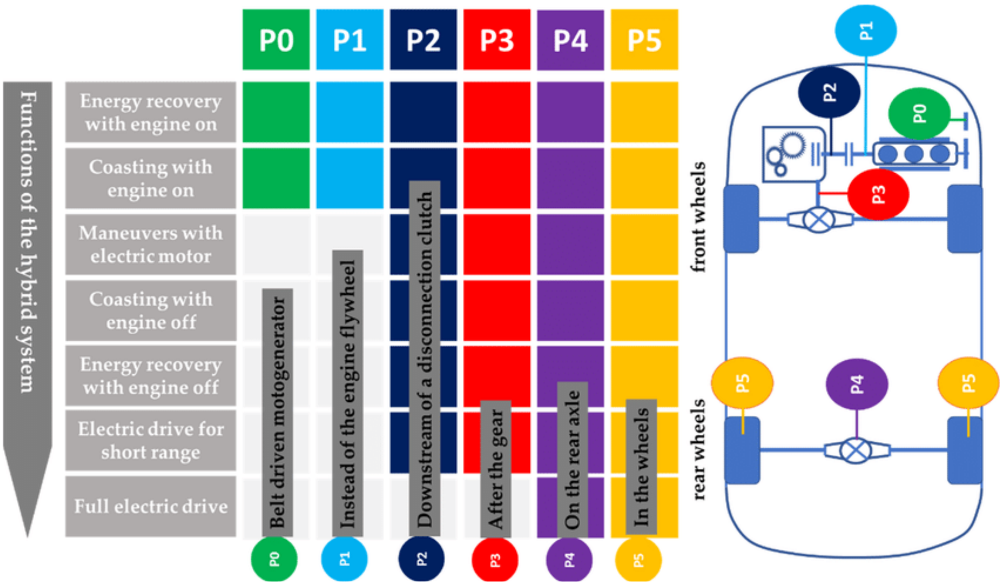

Figure 2.2: Different topologies of HEV

Table 2.1 Different topologies of HEV explanations.

P0	**the EM is connected to ICE by mean of a belt – BiSG**
P1	the EM is connected directly with the ICE crankshaft
P2	the EM is side-attached through a belt or integrated between ICE and the transmission
P3	The EM is decoupled from the ICE while connected through a gear mesh with the transmission
P4	The EM is decoupled from the ICE while connected through a gear mesh on the rear axle
P5	The EM is integrated within the wheel-hub, depending on ICE position can be on front or rear hubs

The **P0** topology, also known as BiSG (*Belt integrated Starter* Gene*rator*) configuration can be “easily” integrated on existing ICE types with few modifications, that leads to relatively low upgrading costs.

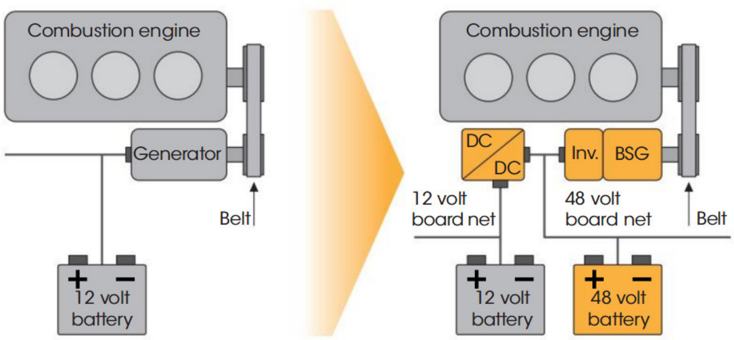

Figure 2.3: ICE conversion to BiSG HEV type.

In this configuration a decoupling of EM and ICE cannot be possible because of they are mechanically linked though the belt, leading to friction losses while the EM is providing boost torque or in regenerating energy. In addition, the whole belt system (belt, tensioner, bearings, etc) has to be redesigned in order to withstand higher torque and more engine on/off cycles.

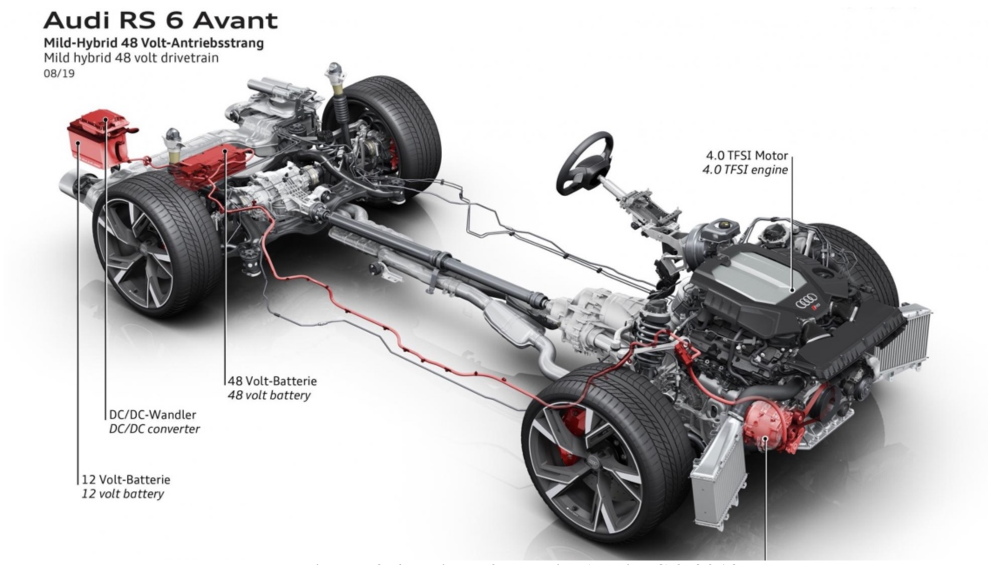

Figure 2.4: Mild P0 hybrid Audi RS6, 2019

The **P1** topology is similar to the P0 one, with the difference that the EM is connected directly to the ICE crankshaft. The EM can provide extra-torque directly to the crankshaft without the limitations given by the belt, assisting the ICE while accelerating and regenerate energy while the vehicle is decelerating. The belt removal leads to efficiency advantages because a source of losses is eliminated, and the torque provided by the EM can be higher with respect to the P0 configuration.

However, the components integration in P0 and P1 topologies is really complex and the trade-off between cost-performance is not effective, leading most of the manufactures to not invest in these topologies anymore. [7]

2.1.3 Full HEV (FHEV)

The **P2,P3,P4,P5** topologies are better in terms of performance improvement and energy flow efficiency thanks to the EM positioning.

In the **P2** configuration the EM is positioned on the transmission input shaft after the clutch, so the two power sources can be completely be decoupled through the control system, leading to higher energy recuperation potential and the possibility to drive exclusively with the EM, for a short range in this case. The EM can be connected to the transmission through a belt, if outside the gearbox, or a gear mesh, if positioned within.
One example is the Porsche Panamera E-hybrid system which is capable to achieve extremely high performance, around 460 Hp and 700 Nm, thanks to the 100 kW electric and 2900 cm^3 V6 twin-turbo gasoline engines combination while containing the CO_2 emissions up to 56 g/km according to the NEDC (*New European Driving Cycle*).

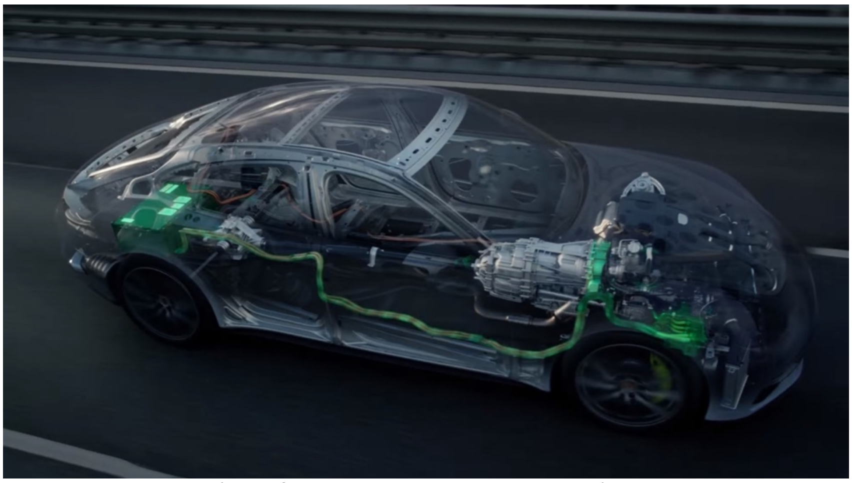

Figure 2.5: Porsche Panamera E-Hybrid system

The **P3** is really close to the P2 one, the bigger difference is that in this case the EM is mounted on the output shaft instead of the input shaft of the transmission. Also in this case the decoupling can be performed in order to let the vehicle be able to move with the combination of the two different power source motors or one out of two only. This configuration has the highest energy recuperation potential, due to no losses related to engine and transmission when the driveline is disconnected.
Ferrari LaFerrari is an example of this architecture.

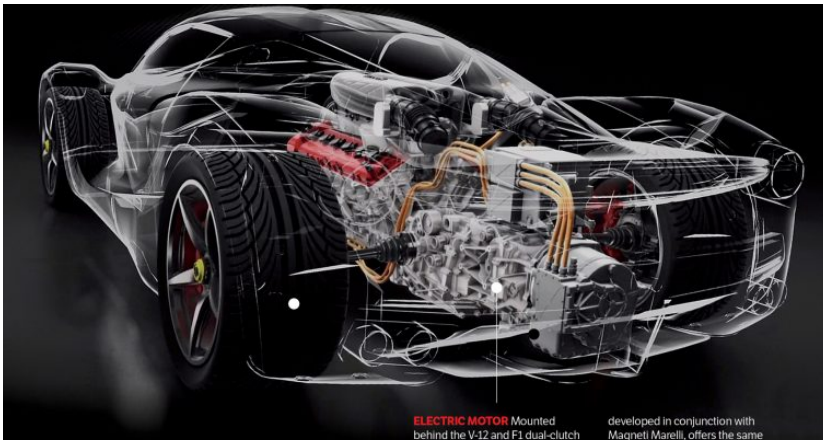

Figure 2.6: Ferrari LaFerrari hybrid architecture

The V12 Ferrari ICE is paired with a DCT (*dual clutch transmission*) and an EM able to add 120 kW to the already high power engine. Different driving mods can be obtained as well, a complex control system has been designed in order to have a smooth power delivery while combining the two power units by mean of two inverters and two DC-DC converters. [7]

2.1.4 Plug-in HEV (PHEV)

The **P4** and **P5** are often combined with **P3** one, in fact most today hyper-cars have 2 EM: one is paired with an ICE above the transmission and the other one is located on the opposite axle.
Due to weight distribution, the most common choice is to locate the ICE in the middle position, with batteries and transmission that it develops backward and the other EM in the opposite axis. This choice is the most effective one, because it leads to optimal weight distribution and the possibility to have a 4-wheel drive vehicle while both engines work

together. The LMP1 WEC cars were the first car motorsport vehicles that were equipped with this kind of powertrain. Porsche was one of the main players in WEC, thanks to the knowledge achieved, they were able to build their first hybrid masterpiece, the Porsche 918 E-Hybrid. [7]

Figure 2.7: Porsche 918 E-Hybrid

2.1.5 Electric Vehicles (EV)

Although, pure **P4** and **P5** topologies can be found within pure electric vehicles, avoiding many mechanical components like transmission and differential gearboxes that are sources of friction losses. The control system can provide awesome dynamical characteristics implementing the so called "Torque vectoring". It splits the torque dynamically between the four different wheels, it improves the cornering grip working in different driving conditions. It works with few parameters: yaw rate, steering wheel angle and vehicle speed. The four electric motors, in case of P5 architecture, or two in case of P4 architecture, works independently with fast response thanks to no delays related to mechanical components. Rimac is the most known car maker that uses this technology to improve driving excitement and performance on their full electric vehicles.

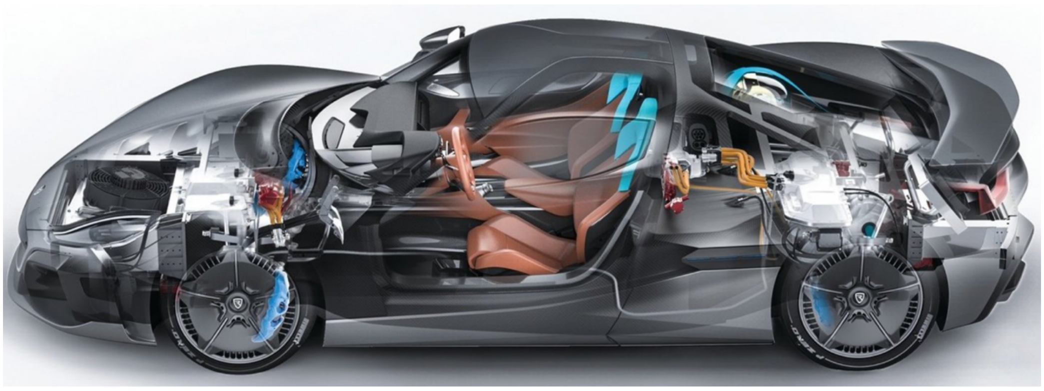

Figure 2.8: Rimac C-Two full electric architecture

A resume table then can be obtained:

Table 2.2: HEV resume table [8]

	MICRO HYBRID	MHEV	HEV	PHEV	EV
Electric Power [kW]	2-4	10-20	25-60	40-100	>60
Operating voltage [V]	12	48	150-350	<400	400-800
Torque fill	NO	YES	YES	YES	YES
Torque boost	NO	YES	YES	YES	YES
Coasting	NO	YES	YES	YES	YES
Energy recovery	OPTIONAL	YES	YES	YES	YES
Brake regeneration	NO	YES	YES	YES	YES
Electric driving	NO	NO	YES	YES	YES

2.2 Parallel, Series and Mixed HEV

Another way to classify HEV is related to the positioning of the EM with respect to ICE. This classification is similar to the previous one, but it’s less rigorous. The three topologies are: Parallel HEV, Series HEV and a combination of the two, Mixed HEV. [9]

2.2.1 Parallel HEV

The parallel hybrid is more closely linked to the concept of the traditional vehicle, in which the EM works in parallel with the ICE one, to cover the torque demand at low revs and allow braking energy recovery
This architecture is among the most used in hybrid cars. It is characterized by a mechanical power coupling node, whereby both motors supply torque to the wheels. The ICE can also be used to recharge the batteries if needed. The mechanical node position is fundamental to characterize different architectures within the propulsion system serve to distinguish pre-transmission (P2), post-transmission (P3) and post-wheels (P4 or P5). In most cases, for example, the ICE is the dominant part and the EM has the simple function of providing greater power if needed, mainly at start and in acceleration.
Most designs combine a large EM often located between the ICE and automatic gearbox transmission, replacing the flywheel.
Low gears are then avoidable, and so the consumption at stationary wheels or at slow pace is reduced. This configuration also allows to reduce the ICE sizes because it’s supported by the EM. This makes them suitable vehicles for city rhythms rather than long motorway journeys.

2.2.2 Series HEV

It is an HEV in which the power required for propulsion is provided exclusively by the EM. The series hybrid approaches the idea of the pure electric vehicle, where there’s the chance to recharge the battery on board thanks to the ICE used as generator, these kinds of vehicles are also denominated as “range extender”.

In this type the ICE is not connected to the wheels anymore, it has the task of generating the current to power the EM that transforms it into motion, while the overload of energy is stock inside the batteries. When a large amount of energy is required, it is drawn from both the ICE and the batteries. A complex transmission can be avoided, or reduced, since EM are capable of operating over a large range of rotation speeds. The ICE efficiency changes as the rpms varies, in this case, the rpms are set to always obtain maximum efficiency, since acceleration and deceleration are not strictly related to that engine. The ICE is usually strictly designed for that porpoise, since it doesn't need a big range of rpms as in traditional motion vehicles.
In some prototypes, small electric motors are installed for each wheel (P5). The considerable advantage of this configuration is to be able to control the power delivered to each wheel.

The major disadvantage of series HEV consists in the serious reduction in efficiency compared to thermal-only engines in conditions of high and constant speed. This is caused by the fact that in the thermal-electric-motion conversion part of the energy is lost while it would not happen with a direct transmission. This drawback is not present in parallel HEV.
So this architecture is the most suitable for vehicles that require continuous braking and restarting such as urban cars, buses and taxis.
An example of this architecture is the BMW i3:

Figure 2.9: Bmw i3

2.2.3 Mixed HEV

Mixed HEV are characterized by a mechanical joint, as in parallel HEV, and an electrical joint, as in series HEV. The construction method for making this double coupling can vary. The most widespread sample is given by the THS (*Toyota Hybrid* system) that Toyota Prius is equipped, which achieves the mechanical coupling between the ICE, two EMs and the final drive shaft through a specifically designed transmission which is constituted by a combination of a planetary gear and a reducer.

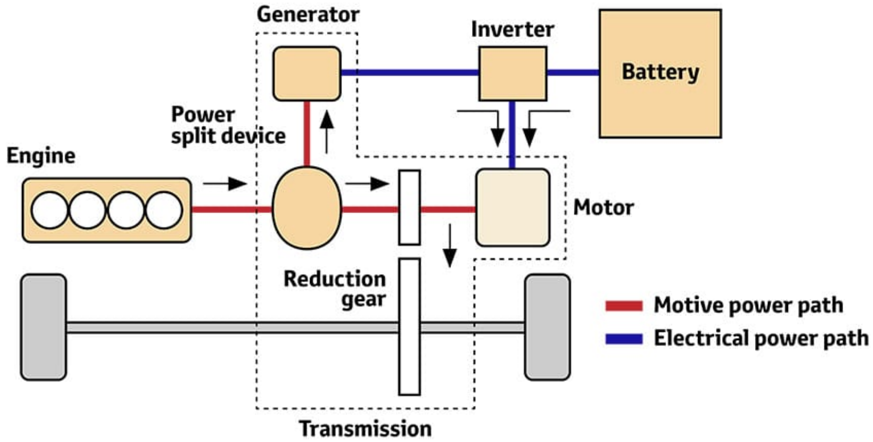

Figure 2.10: Toyota hybrid system (THS) scheme

The drive motor would boost engine output while acting as a generator during deceleration to charge the batteries. The second motor is used as starter and uses the drive power of the engine to generate electricity as well as control the transmission. A power split device with planetary gears would connect the two motors with the engine. The input shaft and output shaft are on the same plane to make the car more compact. The engine output is divided between driving the vehicle and power generation, and the continuously variable transmission (CVT) controls engine speed, to let it work on the more efficient range of the map. An inverter is needed to convert the current between the DC batteries and the AC synchronous motors. [8]

3. Global warming

3.1 Kyoto protocol

The 11th December 1997 the so called "Kyoto protocol" has been signed from most of the world's countries. The focal theme was the global warming caused by a clear anthropogenic responsibility. The aim of this international concordat was to reduce the quantitative emissions of greenhouse gasses of the Parties which are the most relevant cause of global warming. The baseline were the 1990 emission values. The main gasses which cause the global temperature increasing are listed below:

- CO_2 produced by the use of fossil fuels in all energy and industrial activities as well as in transport;
- CH_4 produced by waste landfills, livestock farms and rice crops;
- N_2O produced in the agricultural sector and in the chemical industries;
- HFCs used in the chemical and manufacturing industries;
- PFCs used in the chemical and manufacturing industries;
- SF_6 used in the chemical and manufacturing industries.

Each one of these gasses has its own GWP (*Global Warming Potential*) which represent the greenhouse potential of the gas with respect to a part of CO_2.

Table 3.1: Different gasses GWP

Gas	Atmospheric Lifetime	100-year GWP[a]	20-year GWP	500-year GWP
Carbon dioxide (CO_2)	50-200	1	1	1
Methane (CH_4)[b]	12±3	21	56	6.5
Nitrous oxide (N_2O)	120	310	280	170
HFC-23	264	11,700	9,100	9,800
HFC-125	32.6	2,800	4,600	920
HFC-134a	14.6	1,300	3,400	420
HFC-143a	48.3	3,800	5,000	1,400
HFC-152a	1.5	140	460	42
HFC-227ea	36.5	2,900	4,300	950
HFC-236fa	209	6,300	5,100	4,700
HFC-4310mee	17.1	1,300	3,000	400
CF_4	50,000	6,500	4,400	10,000
C_2F_6	10,000	9,200	6,200	14,000
C_4F_{10}	2,600	7,000	4,800	10,100
C_6F_{14}	3,200	7,400	5,000	10,700
SF_6	3,200	23,900	16,300	34,900

Source: IPCC (1996)

[a] GWPs used here are calculated over 100 year time horizon

[b] The methane GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.

Although CO_2 has the lower GWP with respect to the other gasses, it represents the cause of almost the 55% of the greenhouse effect. Sometimes also CO_2eq index is used, it represents the sum of GWP of all the gasses and the footprint of an object, the so called "Carbon assessment".

However, since the concordat should have been signed from at least a number of countries which produces at least >55% of greenhouse gasses, 8 years has been passed till Russia signed. Finally the 16th February 2005 the concordat become effective till 2012, from that day the signatory countries undertake to reduce their CO_2eq emissions by different percentages related to each country.

However, although the weak results obtained from the Tokyo protocol, it was a milestone for raising awareness in countries about global warming. [10]

3.2 Paris Agreement

From 2012 till 2015 the COP (*conference of Parties*) passed some years of troubles in finding a shared point of view, when finally at the end of 2015 during "COP 21" the "Paris Agreement" has been signed. The aim is to guarantee a trend of emission reduction in order to keep the thermal increasing within +2° C till 2020.

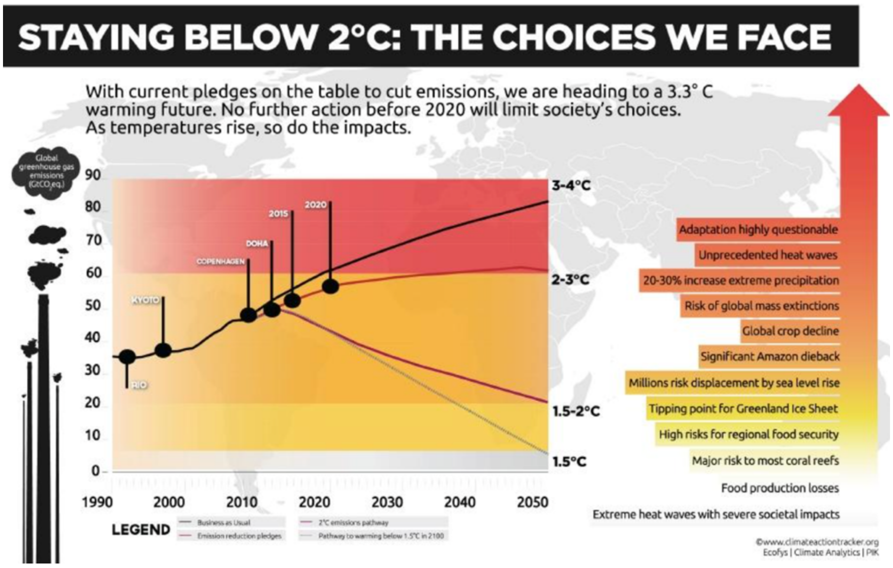

Figure 3.1: CO2 increasing vs Consequences

However Japan, New Zealand, Canada and Russia have left the previous concordat so from that day the treaty covers only about 15% of global greenhouse gas emissions, with European Union and Australia in first place. [11]

3.3 European norms

From 2012 till 2015 since nothing has been stated from the COP, nevertheless the European Union still followed the path outlined during the Kyoto protocol. In 2012 it set a target of 130 g/km of CO_2 for new passenger cars, that correspond to a fuel consumption of around 5.6 l/100 km for petrol or 4.9 l/100 km of diesel during the NEDC (*New European Driving Cycle*) that has to be achieved till the 2015.
The target has been reached 2 years before the deadline, in the 2013, with some tricks however.
In the 18th September 2015 in fact, the so called "Diesel Gate" scandal came out. Some American car makers were incredulous in reading the average consumption of Volkswagen's cars in the homologation cycles, values that they claimed they were impossible to reach with the technology of that time, so a light bulb went on and they investigate deeper. After few days, EPA (*United States Environmental Protection Agency*) announced that a specifically designed manipulation software has been illegally installed to circumvent environmental regulations on NOx emissions and diesel pollution. The software was able to detect when cars were subjected to emissions tests reducing performance and emissions allowing them to fully pass the tests while under normal driving conditions, the cars would have exceeded the legal limit for pollution by 40 times.
Also other European car makers, like PSA and FCA groups, where investigated but they were judged not guilty on contrary, Volkswagen group was punished with an expensive forfeit of

27 billions Euros between car recalls campaigns, fines and the title that collapsed on the stock exchange.

Despite this disgusting attempt to circumvent the rules, the topic has entered, all the more reason, in everyday discussions. Car makers were terrified of the possible economic consequences when they were caught cheating, so improving their R&D (*Research and Development*) department where able to reach in 2019 an average emission of 122.4 g CO_2/km.

In 2019, European Union revealed the "European Green Deal" one of the six Commission priorities for 2019-24. It's an action plan to make the European economy sustainable, in order to boost the efficient use of resources, promote the circular economy, restore biodiversity and cut pollutions and waste. The final objective is to make EU climate neutral by 2050, and the intermediate target to reduce of an at least 55% net reduction of greenhouse gas emissions. For this reason, EU imposes more restrictive regulations upon passenger cars, imposing that from 2021 the EU fleet-wide average emission target will be 95 g CO_2/km which corresponds to a fuel consumption of around 4.1 l/100 km of petrol or 3.6 l/100 km of diesel. The binding emission targets for manufacturers are set according to the average mass of their vehicles**,** using a limit value curve. This means that manufacturers of heavier cars are allowed higher emissions than manufacturers of lighter cars. The curve is set in such a way that the targets for the EU fleet-wide average emissions are achieved. The 2020, was a break-in year in which the emission targets will apply for each manufacturer's 95% least emitting new cars, while from 2021 onward, the average emissions of all newly registered cars of a manufacturer will have to be below the target.

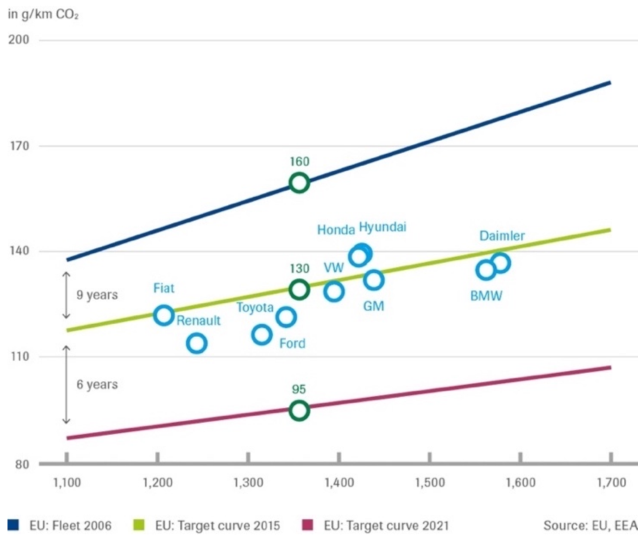

Figure 3.2: Limit emissions curves EU

Penalty payments for excess of emissions were introduced as reported in the EU official site, the statement says: "If the average CO_2 emissions of a manufacturer's fleet exceed its target in a given year, the manufacturer has to pay an excess emissions premium for each car registered". This rule was quite permissive till 2018:

- €5 for the first g/km of exceedance
- €15 for the second g/km
- €25 for the third g/km
- €95 for each subsequent g/km.

While since 2019, the penalty is €95 for each g/km of target exceedance. Also, incentives were introduced in order to promote green mobility, in fact if the so called ZLEV (*zero-and-low-emission vehicles*), vehicle which emissions are less than 50 g CO_2/km, the manufacturer is awarded through the so called "super-credits" system from 2025 on.

From 2020 onwards, further improvements are expected:

- A 23% reduction of greenhouse gas emissions from road transport in 2030 compared to 2005;
- Savings for consumers of around €1,100 over the lifetime of an average new car bought in 2030;
- Positive impacts on employment across the overall economy, with around 60,000 jobs created by 2030 and up to 80,000 if batteries are produced in the EU;
- A smooth and gradual transition towards zero-emission mobility allowing for sufficient time to provide for an adequate reskilling and reallocation of workers in the automotive sector;
- A signal for investors in re-fueling and recharging infrastructure, which will ensure that the enabling conditions for deploying ZLEV are fulfilled.

Regulation (EU) 2019/631 sets new EU fleet-wide CO_2 emission targets are set for the years 2025 and 2030. These targets are defined as a percentage reduction from the 2021 starting points:

- Cars: 15% reduction from 2025 on and 37.5% reduction from 2030 on

The specific emission targets for manufacturers to comply with, are based on the EU fleet-wide targets, taking into account the average test mass of a manufacturer's newly registered vehicles. The specific CO_2 emission target of a manufacturer will be relaxed if its share of ZLEV registered in a given year exceeds the following benchmarks:

- Cars: 15% ZLEV from 2025 on and 35% ZLEV from 2030 on

A one percentage point exceedance of the ZLEV benchmark will increase the manufacturer's CO_2 target (in g CO_2/km) by one percent. The target relaxation is capped at maximum 5% to safeguard the environmental integrity of the Regulation. For calculating the ZLEV share in a manufacturer's fleet, an accounting rule applies. This gives a greater weight to ZLEV with lower CO_2 emissions. In addition, during the period 2025 to 2030, a greater weight is given to ZLEV registered in Member States with a low ZLEV uptake in 2017, and this as long as the ZLEV share in the Member State's fleet of newly registered cars does not exceed 5%. [12]

The derogation possibility for "niche" car manufacturers, i.e. those registering between 10,000 and 300,000 cars per year, will end after the year 2028. In the years 2025 to 2028, the derogation target for those manufacturers will be 15% below the 2021 derogation target.

Also NEDC (*New European Driving* Cycle) has been eliminated since it's not representative of a real-world driving situation. The verification of CO_2 emissions of vehicles in-service and measures to ensure that the emission test procedure yields result which are representative of real-world emissions. Manufacturers are required to ensure correspondence between the CO_2 emissions recorded in the certificates of conformity of their vehicles and the CO_2 emissions of vehicles in-service measured according to the WLTP (*Worldwide Harmonized Light Vehicle Test Procedure*).

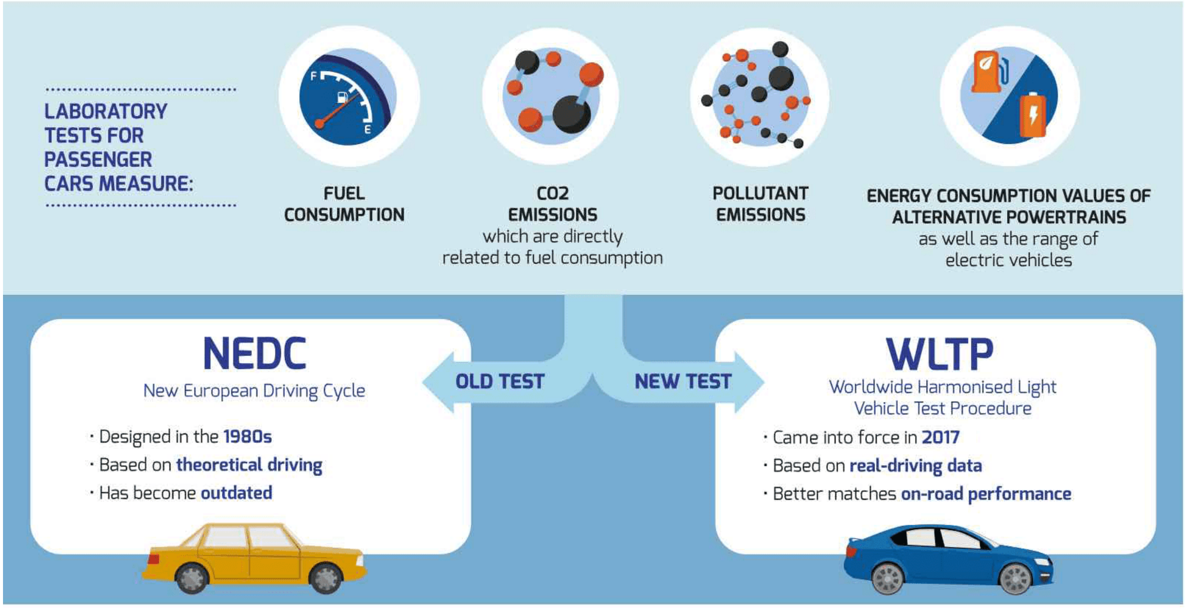

Figure 3.3: NEDC vs WLTP [14]

This correspondence shall be verified by type-approval authorities in selected vehicles. The authorities shall also verify the presence of any strategies artificially improving the vehicle's performance in the type-approval tests.

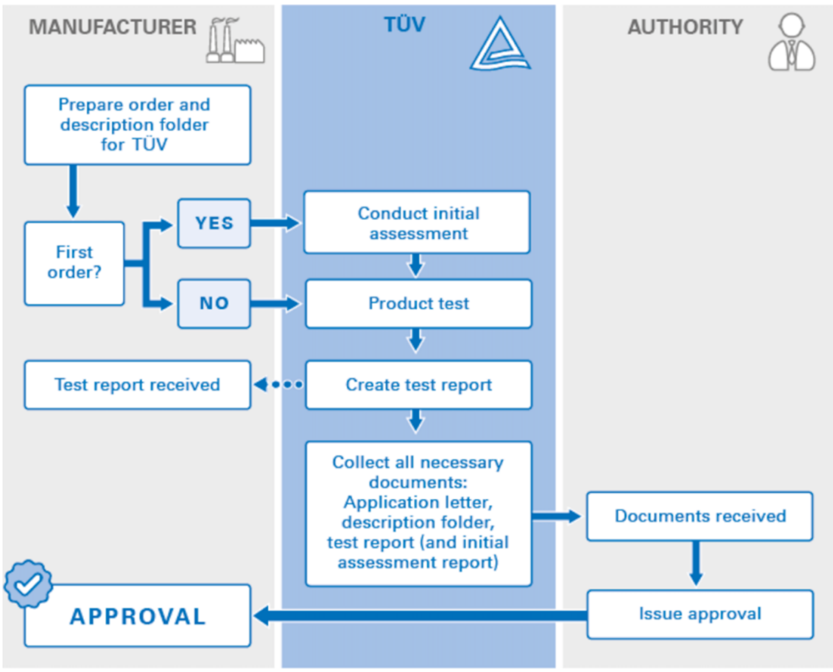

Figure 3.4:Example of TUV approval system

On the basis of their findings, type-approval authorities shall, where needed, ensure the correction of the certificates of conformity and may take other necessary measures set out in the Type Approval Framework Regulation. Deviations found in the CO_2 emissions of vehicles in service shall be reported to the Commission, who shall take them into account for the purpose of calculating the average specific emissions of a manufacturer.

Figure 3.5: Europe type-approval authorities.

From 2021 on, the so called OBFCM (*On-board fuel consumption monitoring devices*) will be used to prevent the gap between emissions tested in the laboratory and real-world emissions from increasing. This devices will regularly collect data on the real-world CO_2 emissions and energy consumption of cars. The Commission shall monitor how that gap evolves between 2021 and 2026 and, on that basis, assess the feasibility of a mechanism to adjust the manufacturer's average specific CO_2 emissions as of 2030.

In order to help the final customer to choose upon different vehicles in a "green" manner, car labelling directive has been introduced by the EU Directive 1999/94/EC. This directive has been reinforced in 2009 by the Regulation EC 443/2009. The directive requires:

- A label showing fuel economy and CO2 emissions to be attached to all new cars or displayed nearby at the point of sale;
- A poster or display showing prominently the official fuel consumption and CO2 emissions data of all new car models displayed or offered for sale or lease at or through the respective point of sale;
- A guide on fuel economy and CO2 emissions from new cars to be produced in consultation with manufacturers.
- All promotional literature to contain the official fuel consumption and specific CO2 emissions data for the passenger car model to which it refers.

Annexes to the directive set out minimum requirements that each of these items must meet. [15]

A Commission Recommendation (EU) 2017/948 was also published in May 2017 seeks to further improve car labelling by:

- supporting Member States to make full use of the new test procedure (WLTP) in a coordinated way to provide improved information to consumers,
- encouraging Member States to make air pollution related information available to consumers.

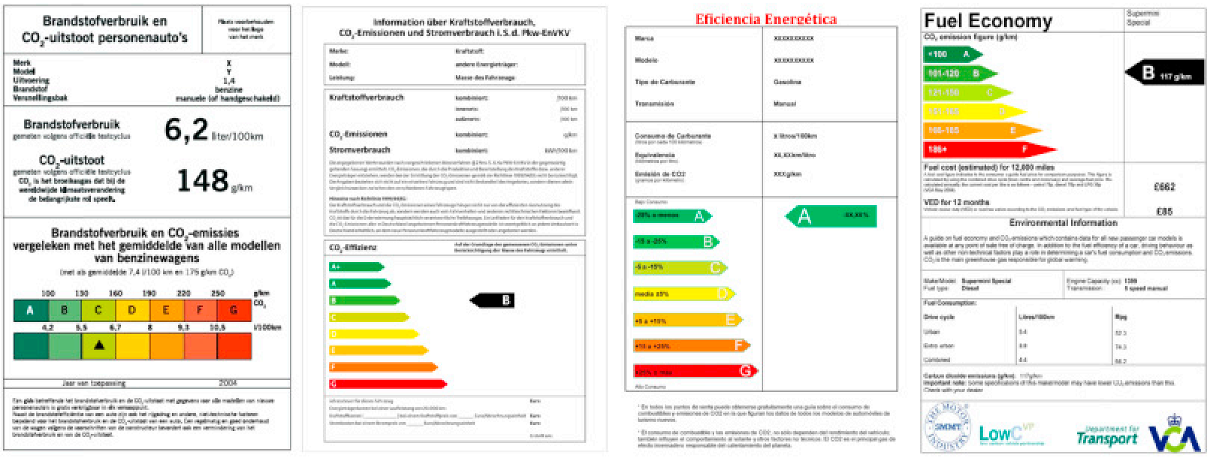

Figure 3.6: Car labelling directives.

4. HEV Batteries

4.1 Introduction

Batteries are one of the key components in HEV powertrain. Different composition determines different kind of batteries and properties. It can be classified upon different types, sizes, kWh and C coefficient. Basically they all are constituted of two chemical components placed respectively in the positive, Cathode and negative, Anode regions separated by an semi-insulant material. On top of the case which keep these chemicals there are two connectors where the load can be attached.

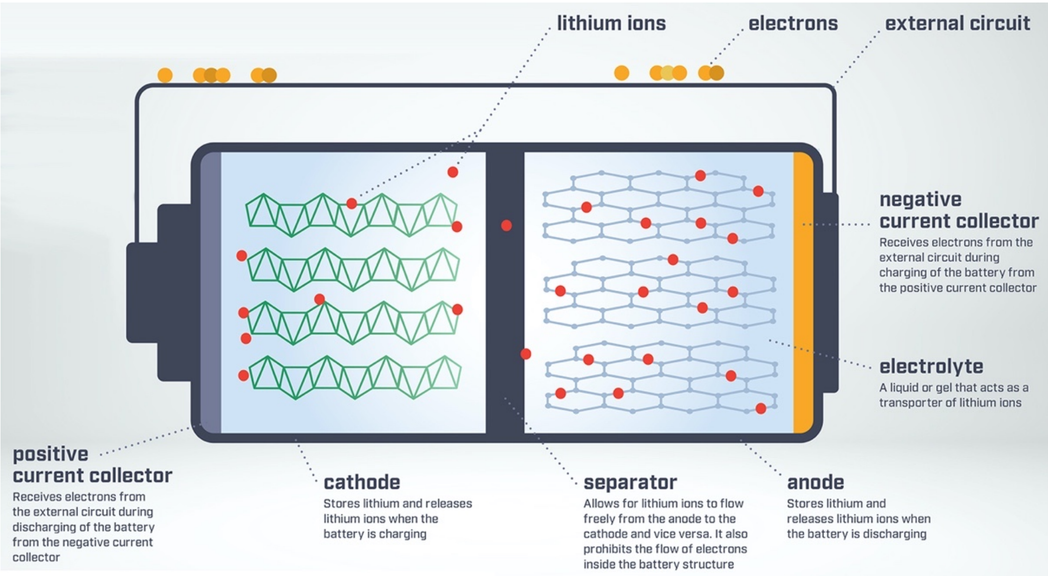

Figure 4.1: Lithium battery

Electrical energy is produced by the electrons that can flow inside the circuit, going from positive to negative side. One element oxides, let electrons to flow away and the other reduces, collecting the electrons that is flowing inside the circuit. In this case, discharging is taking place, while on recharging the electrons flow in the opposite way restoring, theoretically, the original composition of the material. However, since real chemical reactions instead of theoretical ones, are taking place, losses can take place and the battery it's not able to restore its full capacity.
The most important characteristics, not taking into account the chemical composition of the batteries themselves, are the voltage, current, capacity and C coefficient.

Voltage is measured in Volts [V] and represent the pressure that from the power source of an electric circuit pushes electrons along a conduction loop. It can be of two different types AC or DC voltage. The AC voltage source are often three-phases power sources while the DC one is mono-phase power source or batteries. These electrons that flows inside the circuit, are the current which is measured in Ampere [A].
The capacity or, in other words, battery charge is measured in Ampere per hours [Ah]. It measures the ability of a battery to provide an almost constant current in a period of time. This is one of the key characteristics to focus on while choosing a battery application oriented, the load must be always taken into account, different loads need different currents which mean that the battery discharging time will differ. The more the load request current to the battery, the lower the battery will be able to feed it. However, it's fundamental to watch out the battery datasheet, because each battery has a current limit that can provide, if the limit

will be overcome, the battery impedance will saturate the current output, losing capacity in thermal losses.

Items			Specifications	Notes
5.1 Rated Capacity			3000 mAh	0.61A discharge at 20℃
5.2 Capacity	Minimum※1		3080 mAh	0.61A discharge at 25℃
	Typical		3180 mAh	Reference only 0.61A discharge at 25℃
5.3 Nominal Voltage			3.60V	0.61A discharge at 25℃
5.4 Discharging End Voltage			2.5V	
5.5 Charging Current (Std.)			0.9A	Max.1.5A
5.6 Charging Voltage			4.20 ± 0.03V	
5.7 Charging Time (Std.)			8.0 hours	
5.8 Continuous Discharging Current (Max.) ※2※3			10A	0 ~ +40℃
5.9 Internal Resistance			less than 35mΩ	AC Impedance 1 kHz
5.10 Weight			less than 49g	
5.11 Operating Temperature	Charge		10 ~ +45℃※6	
	Discharge		-20 ~ +60℃	
5.12 Storing Conditions	less than 1 month		-20 ~ +50℃	Percentage of recoverable capacity 80%※4
	less than 3 months		-20 ~ + 40℃	
	less than 1 year		-20 ~ + 20℃	

Figure 4.2: Datasheet of a Panasonic Lithium battery

Due to internal chemical reactions, all the batteries work as designed only within a specific range, which is often from -20°C to +60°C. Outside from that region, capacity will change. Correct charging and discharging cycles will determine how long will a battery lasts, for examples, first HEV batteries based on lead-acid suffered a memory phenomenon, in which the battery loses some capacity if not completely discharged before being recharged, they were also bulky and with low capacity.
Two batteries of the same capacity [Ah] but different voltage [V], can provide the same amount of current for the same time, but at different voltages, so in order to distinguish them a further measure unit is introduced, the Watt-hours [Wh], it represents the stored energy inside the battery:

Volts [V] x Amp-hours [Ah] = Watt-hours [Wh]

C coefficient is another fundamental parameter to watch out while choosing upon different batteries, it provides a further distinction between batteries with same voltage and capacity. It's an index that determines, in a direct way, how much current a battery can deliver without suffering thermal issues. For example, a battery with a capacity of 3 [Ah] and a C rating of 20 can easily provide a current of 60 A, instead the same capacity battery with an higher C rating can provide an higher current value. However, the same cannot be said for what concern degradation, in fact this is always present due to charging and discharging cycles, time and environment condition despite the C coefficient of a specific battery.

$$C = \frac{Nominal\ current\ (\ charge\ or\ discharge)\ [A]}{Rated\ capacity\ of\ the\ battery\ [Ah]}$$

A further distinction can be done, into primary and secondary batteries. Primary batteries cannot be recharged they are single-use batteries are often dry cells of zinc-carbon, like the common AA, while secondary batteries can be recharged and are the most common used into smartphones, electronics and automotive field. [16]

4.2 Most used battery types in HEV

4.2.1 Lead Acid

Lead acid battery has low energy density but is widely used in automotive field because of its ability to provide high currents instantaneously, typically while starting the car. It is the cheapest of the three types of hybrid battery packs available on the market, and since it is the oldest auto battery used it is also well tested, and reliable. Lead acid battery pack offer safety and proven performance in hybrid and standard automobiles.

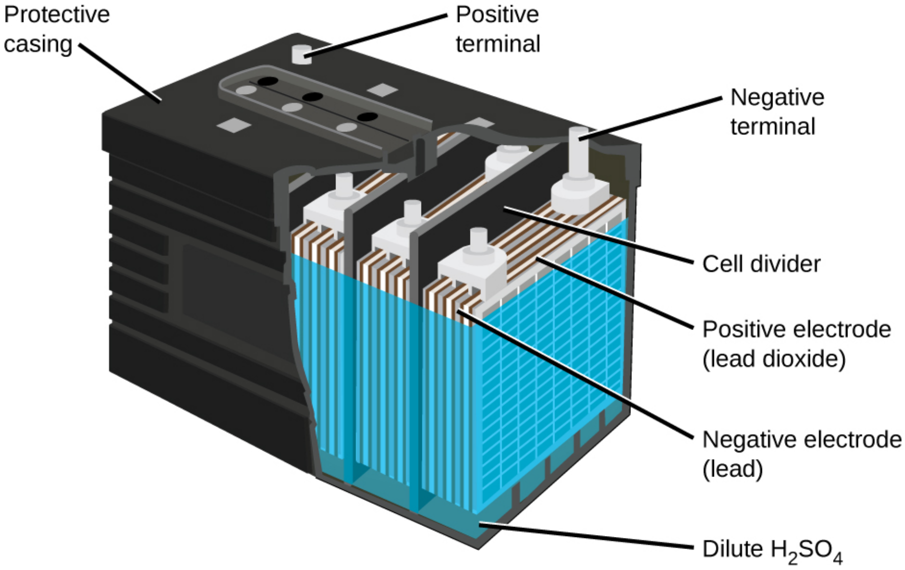

Figure 4.3: Lead acid battery cross section

Lead acid battery is fully recyclable, and incentives are given when consumers turn in their old battery while buying a new one. The newest lead acid batteries have longer battery life and are lighter compared to the very first ones. A huge drawback for HEV application is the low specific energy and low range that they can provide in fact, an HEV equipped with can travel just for around 15 Km in fully electric mode and around 30 Km when traveling in hybrid mode. Low life cycle is another Achille's heel of this kind of battery, it lasts in hundreds cycles. Whereby it is used as auxiliary battery within an HEV, leaving the propulsion duty to other more performing kinds of batteries. [17]

4.2.2 NiMH (Nickel Metal Hydride)

This particular battery uses hydrogen to store energy in combination with nickel and another metal to secure the hydrogen ions. NiMH battery has been on the market for a long time, being well tested and reliable, it is widespread on HEVs market. It offers reasonable specific energy and specific power capabilities, that leads to have 6-7 Km per kWh. NiMH battery pack are quite cheap and easy manageable when it comes to perform, this feature makes this pack versatile for different applications both of full electric and HEVs. This battery type is also flexible (e.g. ranging from 30 mAh to 250 Ah), requires low maintenance, provide high power and high energy density. The main challenges with NiMH battery are the high self-discharge, heat generation at high temperatures and the need to control the loss of hydrogen. NiMH battery pack is currently priced from $250 to $1,500 per kWh and has a cycle life of thousand cycles. [17] [18]

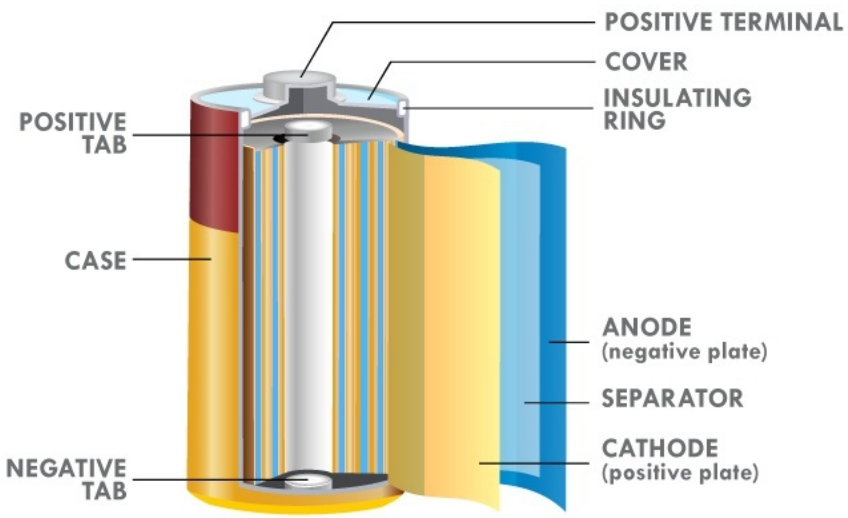

Figure 4.4: Battery cross section

The above figure represents a cross section of a cylindrical cell. In a specific case of a NiMH cell the yellow layer is cathode constituted by Nickel and it's placed in the inner part of the battery itself. The anode is the blue layer next to the shield and it's composed by metal and hydrogen.
The chemical reaction that take place is the following:

$$\text{Anode } (-) \quad M + e^- + H_2O \rightarrow MH + OH^-$$

$$\text{Cathode } (+) \quad Ni\,(OH)_2 + OH^- \rightarrow NiO(OH) + H_2O + e^-$$

$$\text{Overall reaction} \quad M + Ni\,(OH)_2 \rightarrow MH + NiO(OH)$$

4.2.3 Li-Ion (*Lithium Ion)*

This is the most sophisticated battery on the market, this mean that it's not cheap, but it weighs less than the other ones and can stores high amounts of energy. Its use in HEV is relatively new, but often the Lithium-Ion battery packs are guaranteed till 150,000 km/8 years battery life. This kind of battery guarantees fast charging time, depending on the kWh can be fully charged in less than 30 minutes.

An important thing that has to be taking into account is that lithium ion batteries are more efficient when they are smaller, so larger batteries may experience overheating and, is the worst case, catch fire. The technology is updating day by day in order to produce large batteries which can store even more energy, reduce their relatively high costs, extend their cycle life and manage safety concerning overheating. They also have a high energy efficiency, high power-to-weight ratio, good high-temperature performance and low self-discharge.

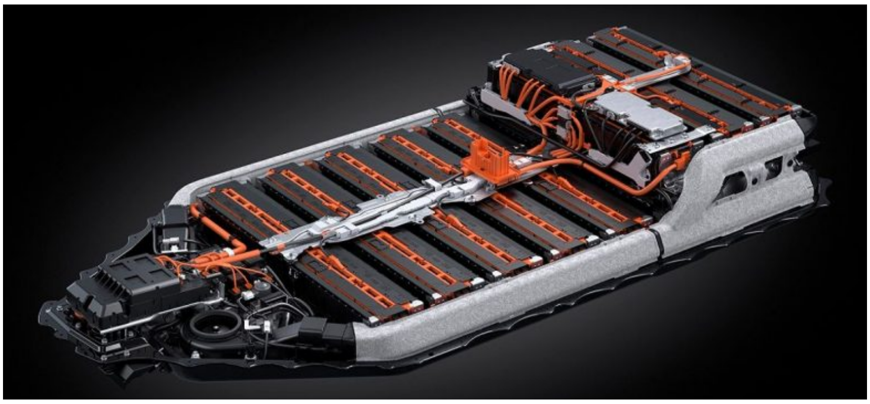

Figure 4.5: Lithium-Ion HEV battery pack.

Most components of lithium-ion batteries can be recycled, but recycling is still costly.
There are different kinds of Li-Ion batteries some examples are Cobalt Oxide LCO ($LiCoO_2$), Manganese Oxide LMO ($LiMn_2O_4$), Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$), Lithium and nickel, cobalt and aluminum oxide battery ($LiNiCoAlO_2$) - NCA, Iron Phosphate LFP ($LiFePO_4$), Lithium Titanite LTO (Li_2TiO_3).
Each of them has different characteristics that can be summarized in the following table, increasing scale from 1 to 4, where 4 is the max score:

Table 4.1: Resume table of Li-Ion batteries types.

	$LiCoO_2$	$LiMn_2O_4$	$LiNiMnCoO_2$	$LiFePO_4$	Li_2TiO_3	$LiNiCoAlO_2$
Specific energy	4	3	4	2	2	4
Specific power	2	3	3	4	3	3
Safety	2	3	3	4	4	2
Performance	3	2	3	3	4	3
Life cycle	2	2	3	4	4	3
Cost	3	3	3	3	1	2

As can be noted from table 4, all of them have pros and cons the choice of one cell over the other is only application oriented, choosing a good trade-off between performance, costs and life cycle. [19]

4.2.4 Comparison between these three types.

An easy-to-understand table in which all the main characteristic of lead-acid, NiMH and Li-Ion batteries are summarized is presented above:

Table 4.2: Resume of major characteristics of Lead-acid, NiMH and Li-Ion batteries [19]

Tref= 20° C	LEAD ACID	NICKEL METAL HYDRIDE	LITHIUM ION
Cell nominal voltage [V]	2	1.2	4
Energy density (Wh/Kg)	40 - 80	100 - 430	200 - 570
Power density	High	High	High for power cells
Operating range (°C)	-40 +55	-20 +65	-20 +50
Cycle life	200 - 700	500 - 1000	1000
Time life (years)	3-6	5-10	-
Self discharge rate per month	20-30%	15-30%	2%
Discharge profile	Flat	Flat	Sloping
Pros	Low cost, reliable, high rate capability	High energy density, cycle life	High specific and energy density, low self-discharging, long cycle life
Cons	Toxicity, hydrogen evolution	Memory effect: must be charged at moderate temps	BMS required due to safety issues
Major types	Prismatic cells	Button and cylindrical to 12Ah or large prismatic to 250 Ah	Cylindrical and prismatic cells in different chemistries

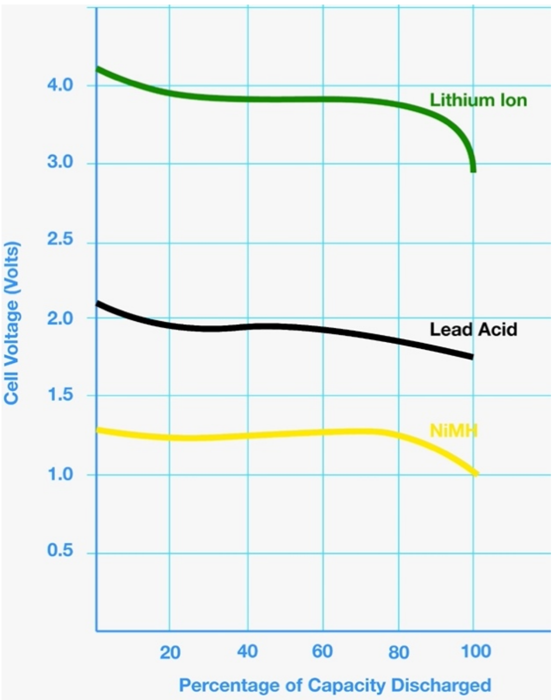

Figure 4.6: Performance of batteries of different chemistries in discharging phase [19]

In Figure 38 are represented the voltage drops of the single cell, and then of the overall battery pack, related to batteries different chemistries.
As can be noticed, despite Li-Ion battery has the higher starting voltage per unit cell, it suffers a brutal drop on the last part of its discharge curve which can damage the load, if sensitive or cell itself.
While for what concern NiMH and Lead acid batteries voltage drop is not so relevant in fact both have discharge lines almost linear from 0% to 100% leading to a wider range of utilization of the batteries, further benefits of those batteries over Li-Ion ones, is their simplicity and safety feature. In fact, Li-ion requires the so called BMS (*Battery Management System)* which is an especially designed circuit used to manage the battery's core. If any problem comes out while using the battery pack, the BMS acts in order to guarantee safety and avoid injuries to final users.

4.2.5 Li-Air: new types of Li-Ion batteries

Li-Air battery has higher energy density compared with the above types presented, so it could probably be the answer to provide long range to HEV.
What makes this battery be the winning choice over the classical Li-Ion ones is that rather than using the conventional compounds, it uses oxygen from the air to react with the lithium-based anode through the carbon-based cathode. Oxygen gas (O_2) introduced into the battery through the air cathode is essentially an unlimited cathode reactant source due to atmospheric air. [20] [21]

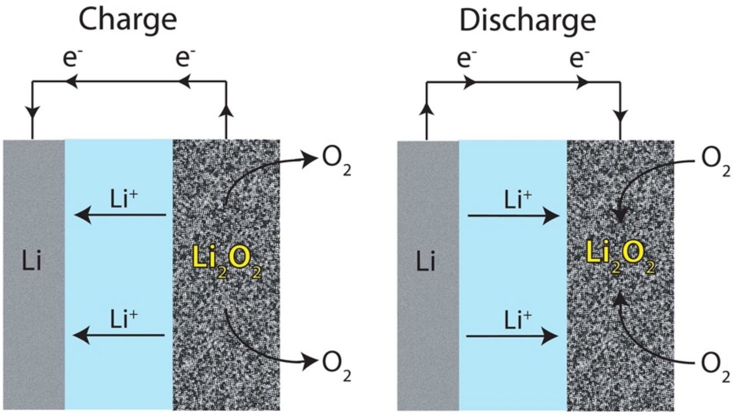

Figure 4.7: Li-Air battery working principle

The lithium metal reacts with oxygen gas to give electricity according to the following reactions in both discharging (1) and recharging (2) phases:

$$4Li^+ + 4e^- \rightarrow 4Li \text{ (lithium electrode)(cathode, since reduction}$$
$$2O^{2-} \rightarrow O_2 + 4e^- \text{ (gas electrode)(anode, since oxidation),}$$
$$2Li_2O \rightarrow 4Li + O_2 \text{ (cell),}$$
1) $$Li_2O_2 \rightarrow 2Li + O_2 \text{ (cell).}$$

$$4Li \rightarrow 4Li^+ + 4e^- \text{ (lithium electrode) (anode),}$$
$$O_2 + 4e^- \rightarrow 2O^{2-} \text{ (gas electrode) (cathode),}$$
$$4Li + O_2 \rightarrow 2Li_2O \text{ (cell),}$$
2) $$2Li + O_2 \rightarrow Li_2O_2 \text{ (cell).}$$

According to that, despite the cathode reactant is unlimited, the anode one it's a physical material that can be consumed, so the battery capacity is strictly related to it. The theoretical specific energy obtainable from this Li-Air batteries is around 11 kWh/kg which is a massive improvement with respect to the 0.57 kWh/kg obtainable from the best Li-Ion batteries, so for its performance is even better, it can theoretically extend the HEV range up to 3 times more. They also offer high operating voltage, flat discharge voltage profile, long storage life and more environmentally friendly compared with Li-Ion ones.
Li-air cells can have different voltages by having different catalysts present in the air cathode and also affect the amount of energy available.

Four different kinds of Li-Air batteries are studied till now, they are reported in the table below:

Table 4.3: Different kinds of Li-Air batteries [20]

Li-Air batteries:	Aprotic	Aqueous	Mixed Aprotic/Aqueous	Solid state
Cathode	Porous O_2	Porous C	Porous O_2	Porous C
Anode	Metallic Lithium	Metallic Lithium	Metallic Lithium	Metallic Lithium
Electrolyte	Lithium salt in organic solvent	H_2O	H_2O	Ceramic, Glass or ceramic-glass
Dividing element	-	Glass or Li-conducting ceramic	Glass or Li-conducting ceramic	Two layer of ceramic polymer
Characteristics	The battery can ignite if broken	Violent reactions	High reliability	Safe and low impedance

5. HEV Inverters

5.1 Introduction

Inverters are one of the fundamental components in HEV powertrain, they lead designers to implement powertrain control strategies which are a key to obtain good performance from the whole HEV system.
They are especially designed electronic components used to convert high voltage and high current DC, coming from the battery source, to AC to feed the EM which is a 3-phase AC load. They are designed to minimize switching losses, maximize thermal efficiency and also combined with a dedicated coolant system in order to keep the temperature at a desired level. They also capture energy released through regenerative breaking and feeds this back to the battery so for, the range of HEV is strictly related to the inverters' efficiency. The internal components should be able to withstand high temperatures (around 125°C), be as small and light as possible through compact packaging or integration of external components to reduce overall part count. Efficient power electronics with high-frequency switching and high resolution PWM control are desirable, and lead to smaller, more power-dense designs that require fewer/smaller passives.
Inverters are often combined with electronical devices called "Converters", they are transformers used to increase or decrease the voltage level, in the first case are called "Step-up" converters in the latter case are called "Step-down" converters.
The most used inverter types are the IGBT (Insulated Gate Bipolar Transistor) and the SiC (*Silicon Carbide)* ones. [21]

5.2 Si IGBT (*Insulated Gate Bipolar Transistor*)

This is the most common technology nowadays. Si IGBT inverters are constituted by a number of electronic switches called IGBT controlled by a controller. Opening and closing these switches in pairs let this device convert the DC current into AC one. The controller is a fundamental item inside the inverter because it does this operation automatically while receiving the input signals. In order to obtain the closer sine wave possible from the DC supply, PWM (*Pulse Width Modulation*) is required. PWM is a special technique of controlling the IGBTs that let open and close them in a specifically designed manner varying the frequency of opening and closing to get an almost sine wave output signal. The cycle is divided into smaller segments, each segment has a total amount of current that can flow through the IGBTs, by pulsating them, designer can control the output frequency, output voltage and the amount of flow occurring per segment. This will result into an average current per segment, which from the load point of view can be seen as a sine wave signal. The more is the resolution, number of segments within a unit of time, the closer the output signal will look like a sine wave. As in most cases, the load is a 3 phases EM, a 3 phases inverter would be needed to rectify 3 different waves, in this case the gap between each peak would be smaller, compared to the single phase one, leading to more usable and smoother current profile.

Figure 5.1: IGBT Inverter of a Tesla model S

They can be easily controlled with state of art algorithms and can hold high voltages up to 800V. Their efficiency is around 93-95% and there are big and bulky, since the space in HEVs is often limited by the car sizes, a more promising inverter has been created.

5.3 SiC (*Silicon Carbide)*

SiC inverters will be a key upgrade in future HEV and EV. These kind of inverter uses a different technology that let the whole circuit to be smaller, lighter and have better cooling performance compared to the Si IGBTs ones. The MOSFET used are composed of Silicon Carbide, they have faster switching frequency, can carry higher voltage, power and efficiency, almost 99%, compared to IGBTs ones. Although SiC devices cost more than their silicon counterparts, the system level benefits at 1,200V, more than compensate for the higher device cost, while at 600V, or below, they are marginal. SiC MOSFET also have wider temperature working range, this means that they are more reliable and have much more flexibility. However, higher frequency switching characteristic of SiC devices is not usually an advantage for lower-speed applications, in fact in such situations, the higher cost of these devices and the additional design considerations are not justifiable, making a silicon IGBT the more logical solution. [22]

Figure 5.2: McLaren MPU-200 SiC inverter [23]

5.4 GaN *(Gallium Nitride)*

GaN inverters are similar to the SiC ones. They are both constituted of WBG (*Wide Band Gap*) materials. WBG devices work smoothly at high temperatures, has high switching speeds and low losses. In high-power applications, robustness with short-circuit transients and surges is a very important issue. The inverter that controls the motor in electric vehicles is an example of a system that can take advantage of WBG devices. The main function of the inverter is to convert a DC voltage to a three-phase AC waveform to operate the car EM. Because the inverter converts battery energy into alternating current, the lower the losses during this conversion, the more efficient the system will be. [24]

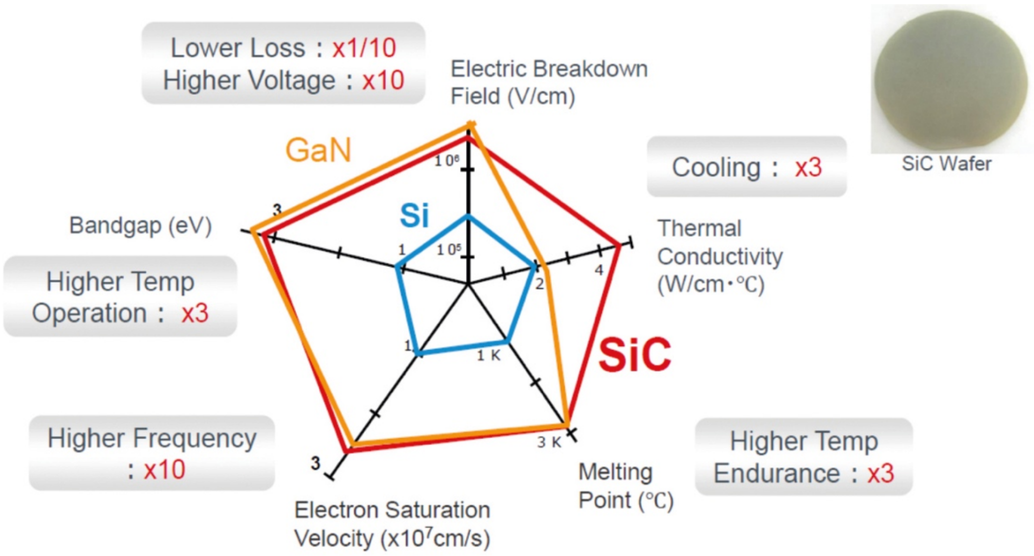

Figure 5.3: IGBT, SiC and GaN materials properties compared [24]

WBG power devices are expensive. So the benefit of using them rather than another technology has to be huge. GaN is faster than SiC and allows higher switching speed but it has had slow adoption due to its high cost and reliability problems. In addition, GaN voltages are currently limited near 650 V while SiC ones are above 800V.
As can be seen the above figure, GaN and, especially SiC technologies have huge performance benefits compared to the "old" IGBT technology leading them to be the future of HEV.

5.5 IGBT vs SiC

There's no rule of thumb while selecting one inverter with respect to another, however the final application defines requirements that have to be achieved. For this reason, the inverter choice upon SiC or IGBT stands on the following chart:

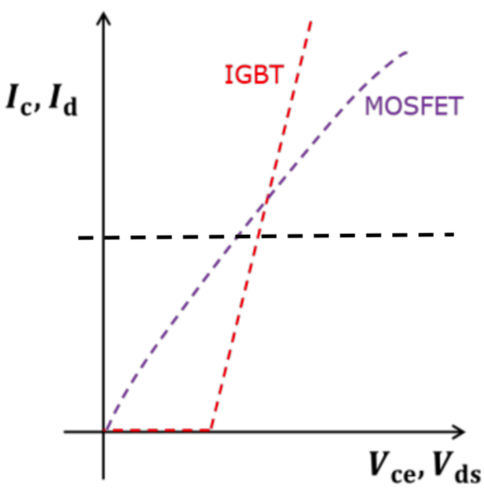

Figure 5.4: Si IGBT vs SiC inverters comparison [25]

In *Figure 5.4* are represented two lines which are strictly related to losses of two inverters of different type. As can be noticed, till a certain point represented by the black dashed line, SiC inverters performs better than IGBT ones, because at very low power, near the origin, IGBT inverters has a huge jump determined by the switching losses that the electronics have, while for what concern SiC ones, they don't suffer of that huge losses in the lowest part of the chart, while at the very top, in the right up corner where the power is huge, their losses are even higher and so for that kind of high power applications they are not advisable.

6. Electric motors

6.1 Electric motor (EM) introduction

The link between electricity, magnetism, and movement was originally discovered in 1820 by French physicist André-Marie Ampère and it's the basic science behind an electric motor. The first electric motor dates back in the early half of 1800's, it was invented by Thomas Davenport. It was fed by a battery and able to deploy the task of power a small-scale printing press. In the 1886 Frank Julian Sprague invented the DC motor and this was that provided the catalyst for the wider adoption of electric motors in industrial applications.
Nikola Tesla, after two years, patented one of the best inventions of the last 3 centuries, the AC motor.

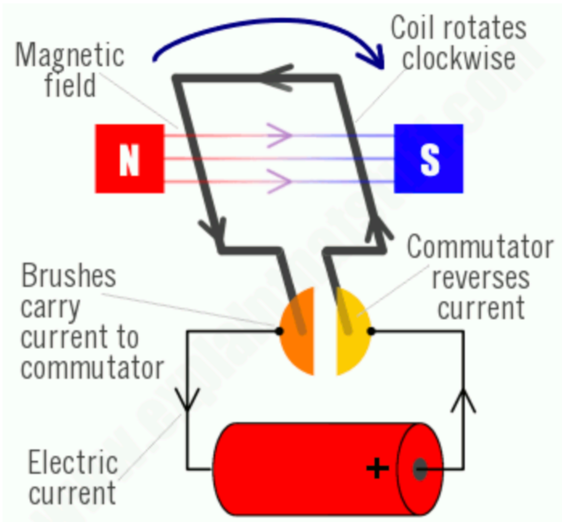

Figure 6.1: Simple schematic of EM working principle

There are different kind of EMs but they are basically composed of same components: rotor, stator, magnets and windings. The simplest EM is the DC motor with brushes as reported in the figure above. Basically the brushes close the current loop between the coils, the current flowing within the coils produces a magnetic flux which interacts with magnetic fields of the permanent magnets fitted on the stator. This interaction produces a rotary movement of the rotor following the "Fleming's left hand rule".

There are many typologies of EM in today market and can be easily classified over different kind of power source used, either AC or DC. They are widely used in industrial, automotive and energy production contexts and can resumed as in the following scheme:

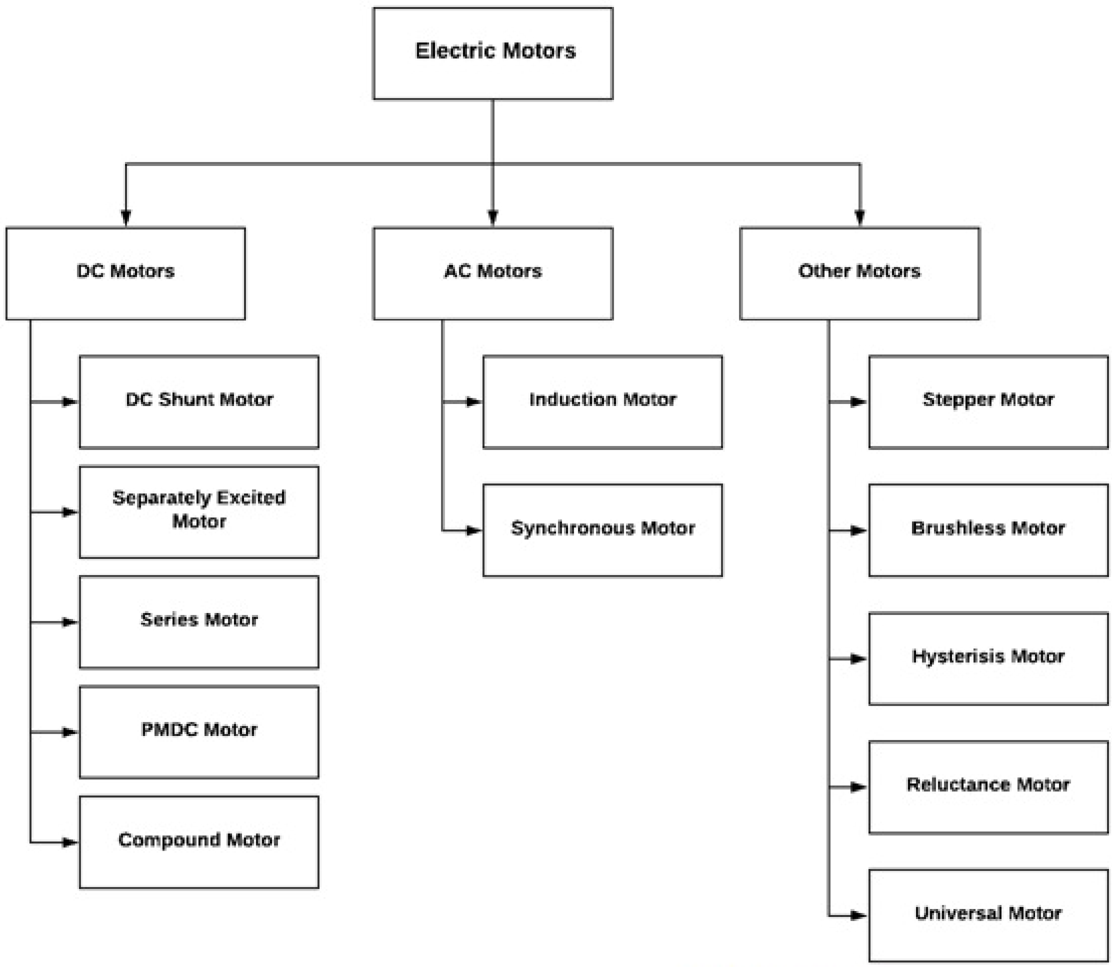

Figure 6.2: Resume scheme of EM typologies

A further distinction can be done considering the direction of the magnetic flux within the EM, therefore radial or axial flux motors can be obtained.

6.2 Radial EM

The basic structure is provided by the stator driving a moving rotor in a radial magnetic field, it is used in different shapes and power ranges for all kinds of EV.
The flexibility of this kind of motor also has an impact on the design of e-mobility platforms. A longitudinal shape with a simple gearbox can be the most economical way to drive two or even four wheels on a ground EV.
There are several types of this motor: with internal permanent magnets (IPMs) and surface permanent magnets (SPMs) can make use of the reluctance between the rotor and the magnets to boost the torque, while induction motor (IM) and wound field synchronous machine (WFSM) designs offer different trade-offs between power, torque and axle speed.
To be brief the focus will be on permanent magnet motors even IPM or SPM.
This kind of machine is characterized by the magnetic flux which is radial to the rotational axis of the machine, the bigger difference between IPM and SPM is the positioning of the magnets on the rotor, in the first case they are positioned inside the rotor itself, while the latter fit them on the surface of the rotor. The SPM is typically used for high speed applications which require high efficiency, because the torque is generated directly by the reaction of the magnetic field of the surface magnets and the field generated in the stator by the windings. There are minimal rotor losses since the magnetic field of the magnets is acting of the airgap between stator and rotor. However, the key drawback is the need of relatively high quantity of

magnetic material required with respect to the torque produced by the machine and high manufacturing costs.
On the contrary, IPM uses less magnetic material which is fitted inside a special multidisc rotor. The resulting torque-to-magnetic material ratio would be higher but lower peak efficiency and peak torque compared to SPM. Typically the higher is the rotor diameter, the higher is the magnetic surface and so, the higher is the torque produced by the machine. [26]

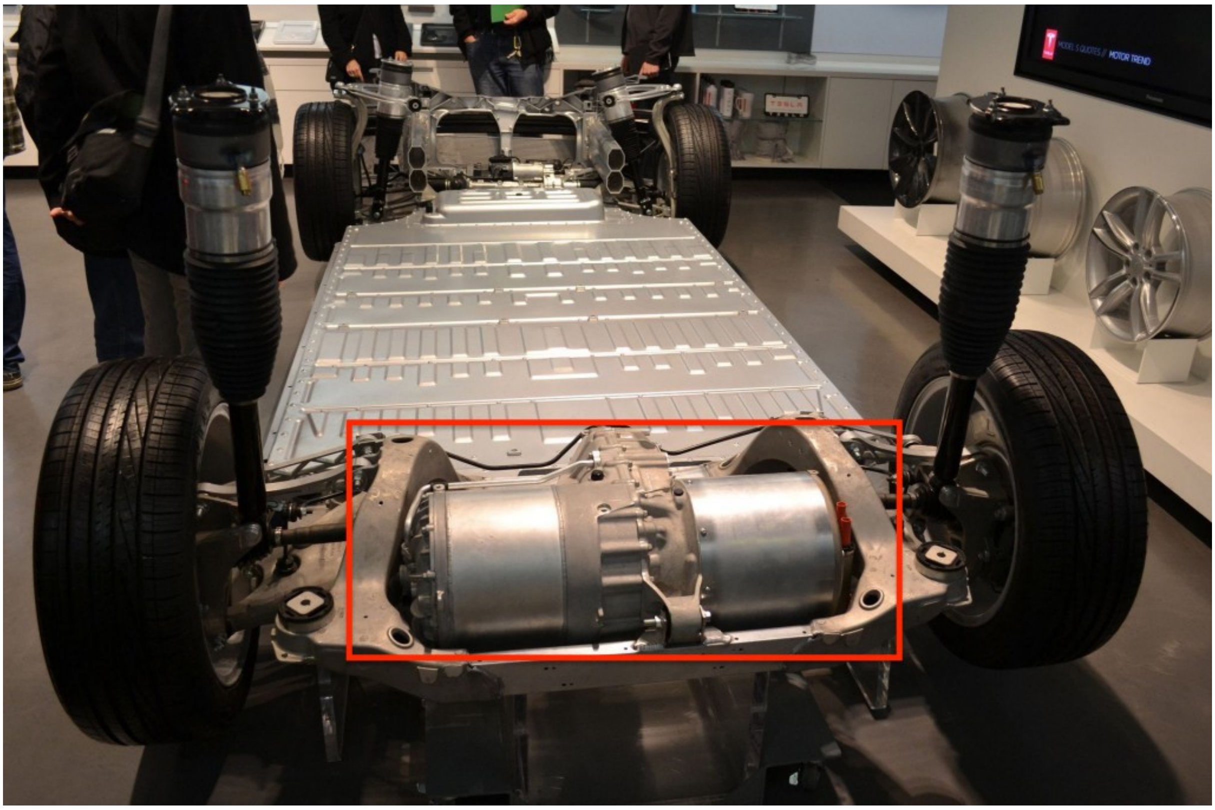

Figure 6.3: Tesla Model S radial flux motors

Almost every pure EV manufacturers use this kind of motor since they are cheap, relatively easy to be controlled, it has high overall performance and efficiency. However, its dimensions and a weak torque-to-weight ratio, can limit the versatility of this kind of EM.

6.3 Axial EM

In this case, the magnetic flux is axial with respect to the rotational axis. It has typically higher torque density and power compared to same dimensions radial flux EM due to the higher quantity of magnetic material present on the rotor. Also this kind of motor can be divided considering the different topologies:

- internal stator – external rotor (ISER)
- external stator – internal rotor (ESIR).

The ISER EM is characterized by the so called “pancake” shape which results in an extremely compact structure. The magnetic material is located on the inner surface of the rotor which is, in this case, divided into two cylindrical shaped plates that contain the stator. It has a lot of advantages like compact stator winding, which results in low copper quantity used and it is easy to be mass produced thanks to its easy shape. However, few drawbacks are present like complex rotor forms that lead to rotor stability issues that requires complex control, high rotor inertia since the axis of motion is far from the end of the rotor plate, the cooling system is also critical and high level of torque ripple can be caused by the segmented stator. On the contrary, ESIR has an easier rotor shape, resulting in even less magnetic material usage, a more compact structure and then an easier cooling system can be designed since two winded stators contains the rotor between them, resulting in a big heating exchange surface. However, the adoption of two stators increases the copper usage within the motor and the need of slots inserted stator windings means that high volume manufacturing requires very specialized machineries. [27]

Figure 6.4: Texa S.p.a.– Axial flux ISER motor[28]

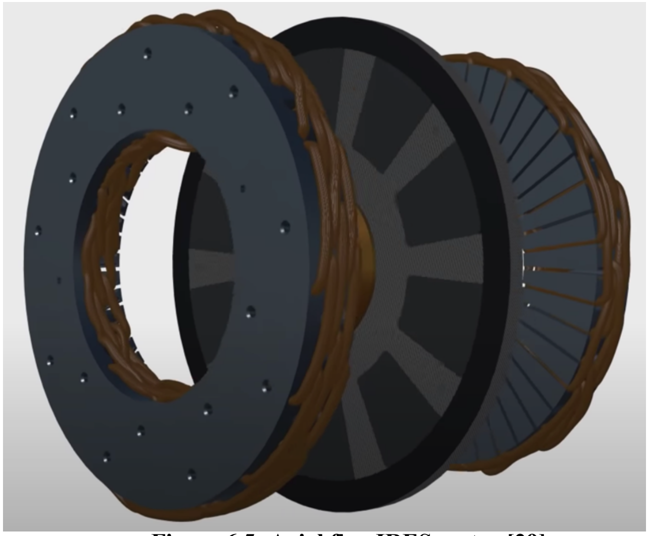

Figure 6.5: Axial flux IRES motor [29]

Compact dimensions and high torque-to-weight ratio are making this kind of EM more and more appreciated in HEV manufacturers. It can be fit almost everywhere, and its performance range let it be used in a wide range of applications from passengers HEV, where narrow spaces are always a problem during designing process, to agriculture vehicles.

6.4 Radial vs Axial EM

Axial EM offers big advantages compared to radial EM, one of them is the higher power density achievable. The sizes of the machine can be narrow because it has two rotors instead of just one and so the resulting magnetic surface will be higher. The electromagnetic flux moves on a 1-D surface and not in a 2-D as it happens on a radial EM, this means a shorter path to close the loop. Another key advantage is the reduced quantity of copper used for the windings inside the stator, in radial EM almost 50% of the cooper is not active and it's used for heat exchanging porpoises, resulting in poor performance-to-weight ratio compared to axial EM in which almost 100% of the concentrated windings are active. Also the cooling is improved since the stator windings are directly in contact with the cooling circuit and so, the water-glycol inside the jacket can dissipate more heat with respect to radial EM, where the stator windings are positioned in a manner called "coil overhang" resulting in poor heat dissipation. [30]
For what concern torque-to-weight ratio, the sizing equations of both machines can be analyzed:

1) $$T = \frac{m}{4m} K_e K_i K_p B_g A_s \lambda_0 D_0^2 L_e$$

2) $$T = \frac{\pi m}{16m} K_e K_i K_p B_g A_s (1-K_D^2)(1+K_D) D_0^3$$

Where 1) is referred to radial EM and 2) to axial EM. In the first case, the torque is directly proportional to the diameter of the machine squared, while in the second case it has a cubic exponential. However, the bigger is the machine the lower would be the rotational velocity that the machine can achieve due to mechanical limitations. [29]
In the following graph, the 1) and 2) equations are plotted considering different machine radius:

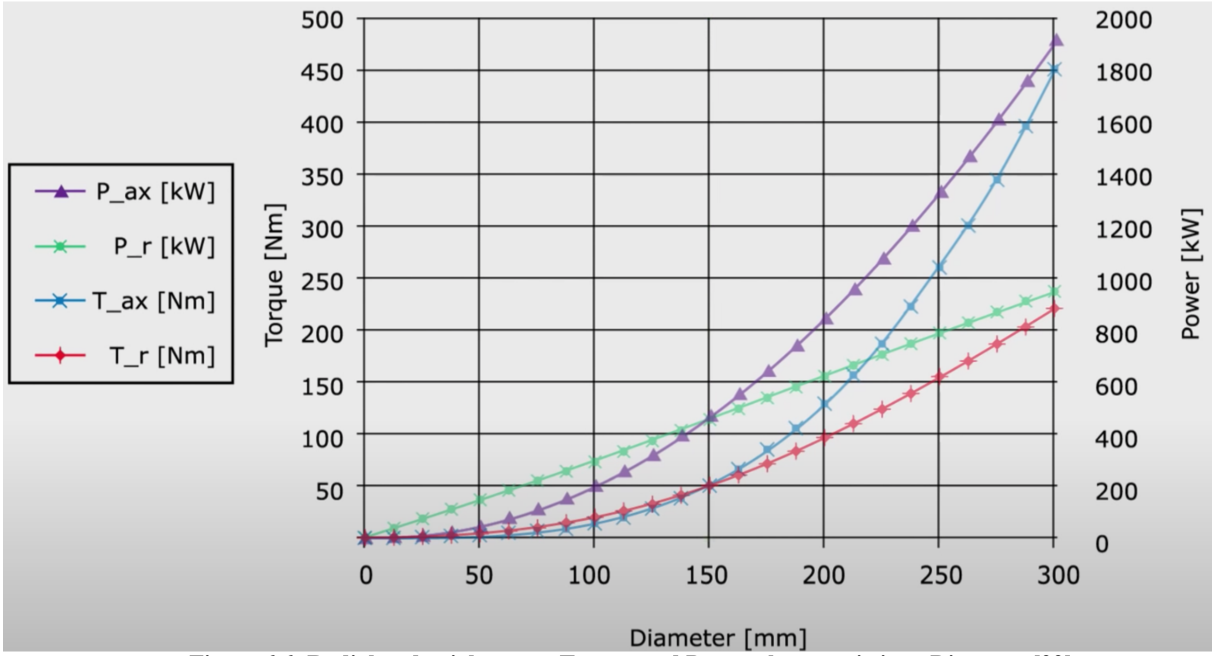

Figure 6.6: Radial and axial motors Torque and Power characteristic vs Diameter [29]

The lower is the diameter, the better is the radial motor till the diameter limit (150 mm) has been overcome in fact the trend reverse, revealing the supremacy of the axial motor in heavier applications.

7. Electric mode modelling of passenger HEV

The aim of the thesis is to find out the differences between IGBT or SiC inverter driven electric drive that spins the front wheel motors. For this reason, the full electric drive mode will be discussed only, other driving modes are out of the scope of this thesis.
The whole model will be developed in Matlab/Simulink™ environment using different libraries. In order to obtain valid results in relatively simple manner, library blocks need precise data, these data have been obtained from experimental procedures.
The model is developed as follows:

Figure 7.1: Vehicle model scheme

This simple scheme is intended to explain briefly how the model works, starting from "Driving cycle" speed and acceleration reference signals are obtained, in the "Vehicle" block these values are converted in motor speed "w" and motor torque "T" requested from the vehicle to follow the driving cycle profile. In the "Electric drive" block, two efficiency maps are developed for inverters and motors, in order to obtain a current that is needed in the "Battery" block, a power conversion would be needed. Within green "Battery" block a Simulink "datasheet battery" block has been used in order to obtain electrical efficiency and the overall system information. A focus of each block and at the modelling procedure will be held in the following paragraphs.

7.1 Driving cycle block

This block is one of the Simulink blocks used within the model, different driving cycles can be chosen, vehicle speed [m/s] and acceleration [m/s^2] outputs are obtained. The "WLTP class 3" driving cycle is the one chosen by European Union, it has been introduced in 2017 to replace the old NEDC that was introduced in 1980's.

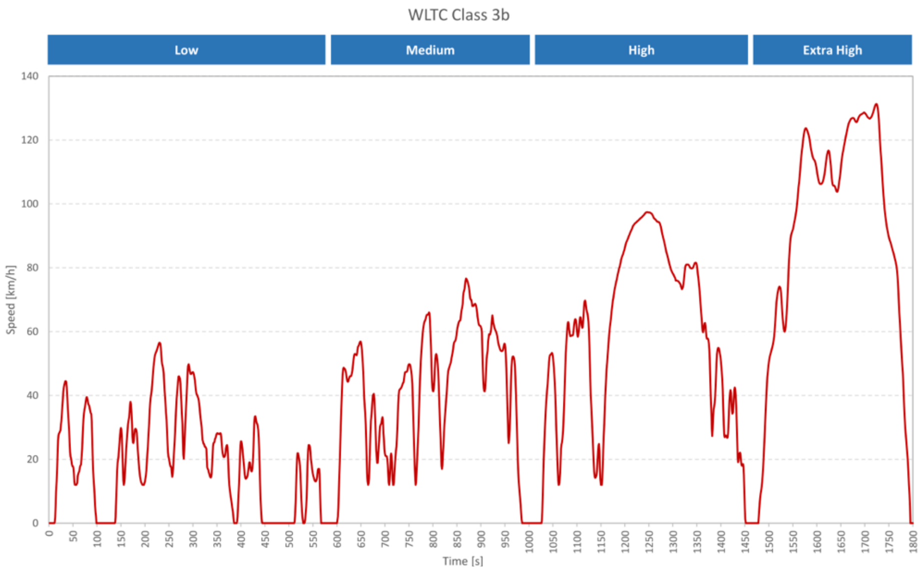

Figure 7.2: WLTP Class 3 complete cycle

The overall cycle is divided into 4 parts: low, medium, high and extra high.
Each part covers different driving scenarios, the first two parts are urban and extra-urban scenarios while the other two parts refer to highways driving scenarios. [31]

7.2 Vehicle block

This block is divided into two parts. The first one implements a conversion from speed expressed in [m/s] to rotational speed of the wheels [rad/s]. The used equation is:

$$W = \frac{V}{R}$$

Where W is the wheel rotational speed, V the longitudinal speed of the vehicle and R the wheel radius assumed to be 0.34 m. Also a gear system is implemented to multiply the rotational velocity of the wheel in order to obtain a motor speed within the optimal motor efficiency.
The second one implements the fundamental longitudinal equation [32] of a vehicle which moves on a flat road:

$$m * \dot{v} = F_t - F_a - F_r$$

Where m is the mass of the vehicle, assumed to be 1800 kg, $\dot{v}$ is the vehicle acceleration, Ft is the tractive force required to move the vehicle forward, Fa is the aerodynamic resistance force and Fr is the resistive force on the wheel-road contact.
The resultant tractive force is then multiplied by the wheel radius and divided by the number of tractive wheels, which in this case is 2, since the vehicle in full electric drive results to be front wheel drive only.
Velocity are then multiplied and the torque is divided by the gear ratio chosen.

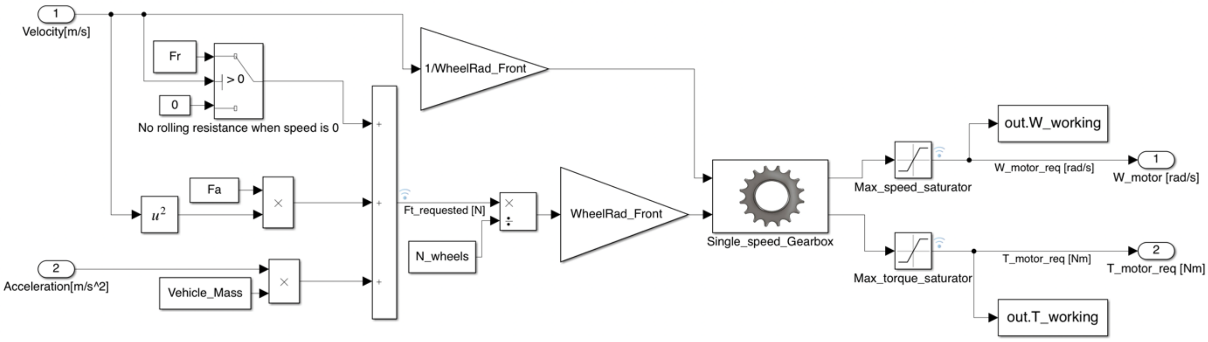

Figure 7.3 Vehicle subsystem

7.3 Electric drive

Motors and inverters efficiency maps are used in order to obtain the overall drive efficiency. These two efficiency maps have been two inputs, Torque [Nm] and Speed [rad/s], and the efficiency of each subsystem as output. These maps are evaluated from experimental data collected during tests on the test bench. The motor map is fixed since the motor will always remain the Texa S.p.a. axial flux motor, while for what concern the inverter map, it is not constant since the object of the thesis is to evaluate the differences between IGBT and SiC inverters, so a switch is present to choose one of the two.
The maps inside the Electric drive block are like the ones reported below:

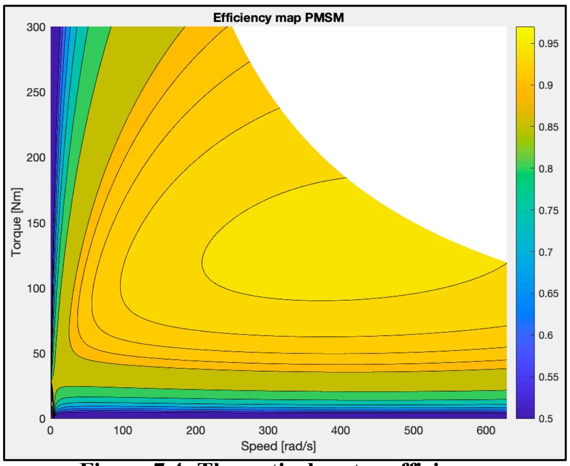

Figure 7.4: Theoretical motor efficiency map

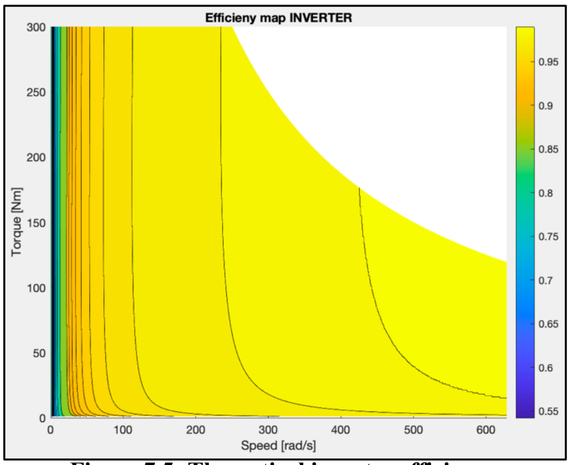

Figure 7.5: Theoretical inverter efficiency map

These maps are obtained by a developed Matlab code that will be attached on the appendix part of the thesis. [33]
The output efficiencies are multiplied, since inverters and motors are in series and then divided by the number of drives.

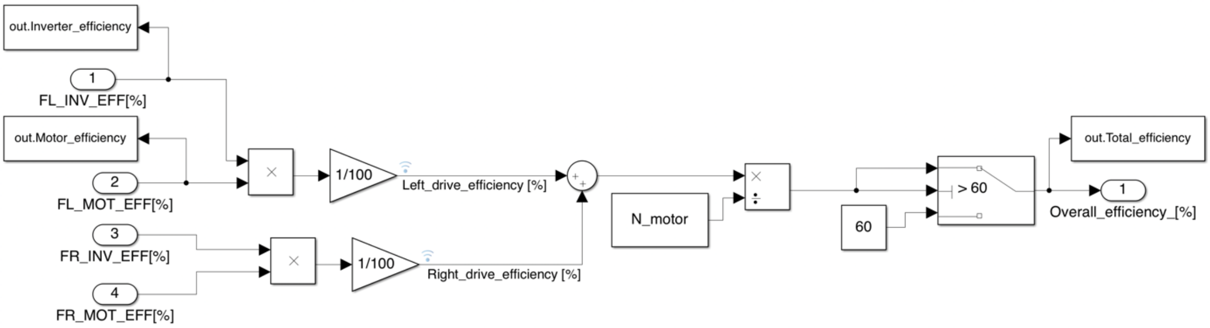

Figure 7.6: Efficiency calculations

Then a current has to be asked to the following block which is intended to implement a battery pack, in order to obtain that request an intermediate block is needed. In fact within the so called "Power to Current" block a power conversion is implemented:

$$P_m = P_e - P_{loss}$$

Where P_m is the mechanical power ($T*w$) needed to move the vehicle forward, P_e is the electrical power ($V*I$) and P_{loss} is the overall power losses which takes into account all the iron losses, joule losses and mechanical losses of the electric drive.
So the current is obtained as follows:

$$I = \frac{T * w + P_{loss}}{V}$$

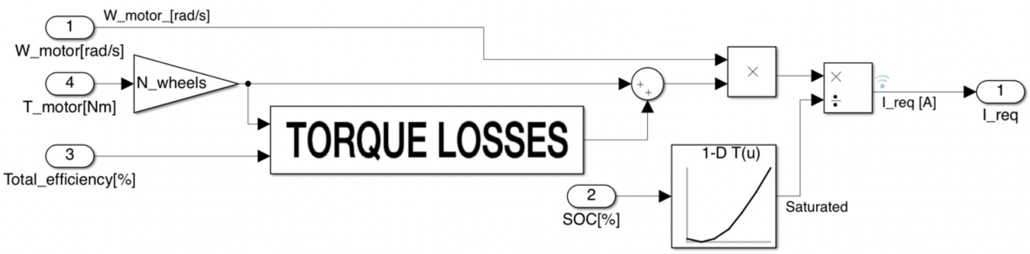

Figure 7.7: Power to current subsystem

Since the deliverable current and voltage of the battery are functions of SOC percentage, a look-up table is used to obtain a discharge plot for the battery.

7.4 Battery block

The "datasheet battery" block from Simulink library is used, within this block the number of parallel and series cells, single cell discharge characteristic and the battery capacity have to be known. The block inputs are the current requested and the temperature at which the battery is working, the higher the current is the higher would be the cells temperature so the lower would be the efficiency since the internal resistance of the single cell will increase proportionally. The outputs are the most relevant battery data like SOC, discharging voltage curve, the battery power delivered and the current profile.
Within this subsystem a current saturator is also needed, both on positive side, while discharging, since the higher current deliverable by the battery pack is 350 A and negative side, recharging, while energy recovery braking is working.

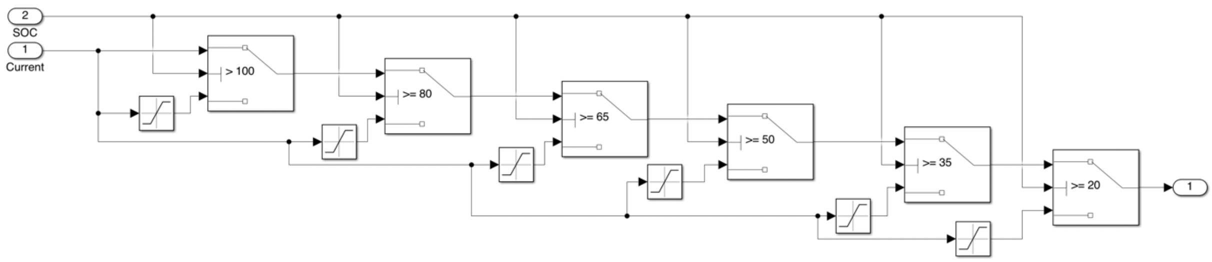

Figure 7.8: Current saturator

Obviously, the rechargeable capacity of the battery is strictly related to SOC percentage, in fact while battery is fully charged, the negative current needs to be low since over voltage has always to be avoided in order to use the battery properly and avoid possible damages and risks. Next to the battery a BMS (*Battery Management System*) is always needed, since voltage and current are huge, it is also needed because Li-ion batteries have to work within a temperature, voltage and current range.

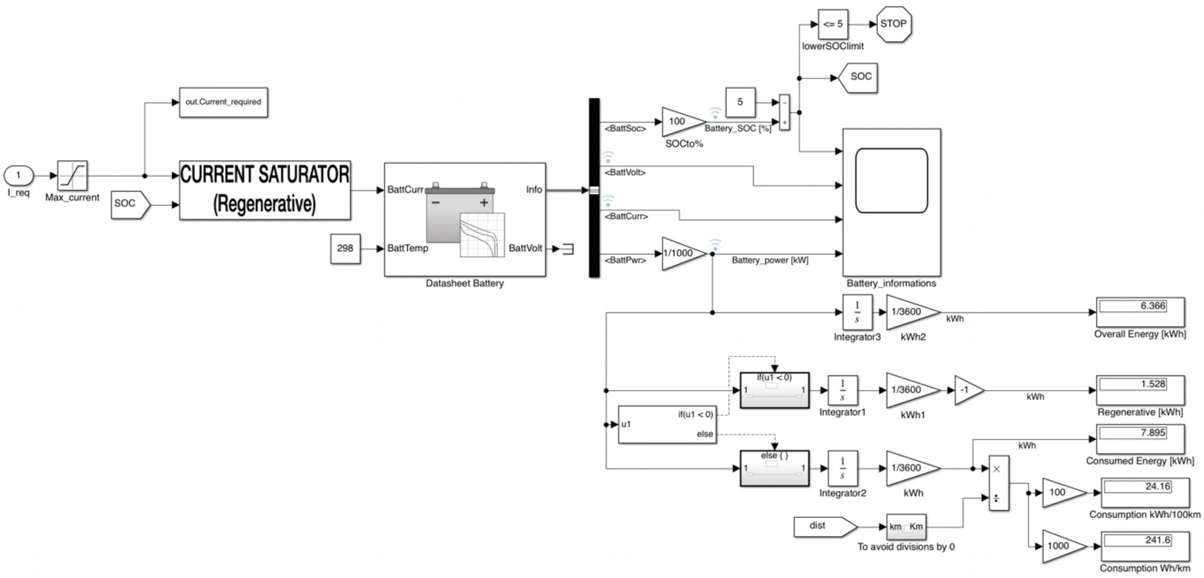

Figure 7.9: Battery pack subsystem

8. Matlab/Simulink™ model and results

In this chapter, the model developed and results obtained will be presented. The following figure represents the Simulink scheme developed to evaluate inverter differences and improvements on overall fuel economy.

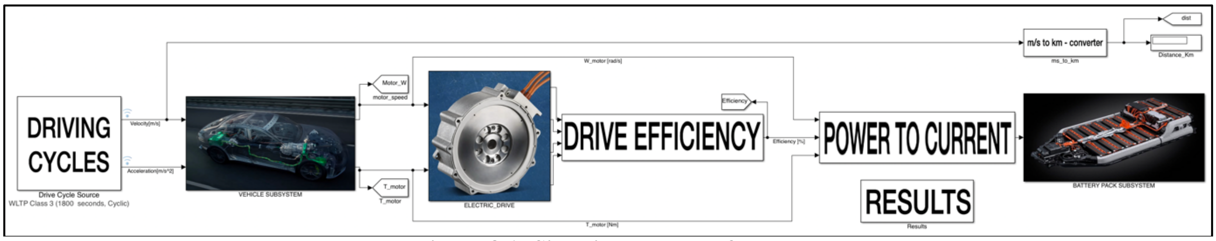

Figure 8.1: Simulink scheme of the system

Data used are reported in the tables below:

Table 8.1: Vehicle data

Vehicle mass	1800 kg
Rho coefficient	1.2
Front area	1.82 m^2
Cx (vehicle)	0.335
Cr (tires)	0.01
Gravity acceleration	9.81 m/s^2
Wheel radius	0.34 m
N of tractive wheels	2
Gear Ratio	3.14

Table 8.2: Battery data

Battery type	Li-Ion
Capacity [kWh]	8 kWh
Capacity [Ah]	20 Ah
Voltage [V]	400 V
Number of series	1
Number of parallels	108

The same Matlab code used to obtain efficiency maps presented in *Figures 7.3* and *7.4* has been slightly modified to obtain mirrored maps considering also negative torque values, in this way it's possible to obtain complete maps of both motor and inverter in order to understand at which operating points both devices are working. The working range of both inverters and motors are restricted by physical constraints of the axial flux motor, the speed range is between 0 and 6000 rpm, while for what concern the torque, its range is between -300 and 300 Nm maximum. Obviously the lower would be the rpms the lower would be the overall efficiency, since an amount of power is lost to overcome the inertia of the rotor.
As can be seen from the figures below, the operating points of electric drive are the ones reported with red crosses.
Figure 8.2 refers to the motor efficiency map, on the right side a scaled colored bar is present. The lowest efficiency points are identified as the dark blue one with a value of 50%, going up, light blue point reaches 70% till light yellow that reach maximum 97% value. The same happens for *Figure 8.3* in which the inverter map efficiency is reported.

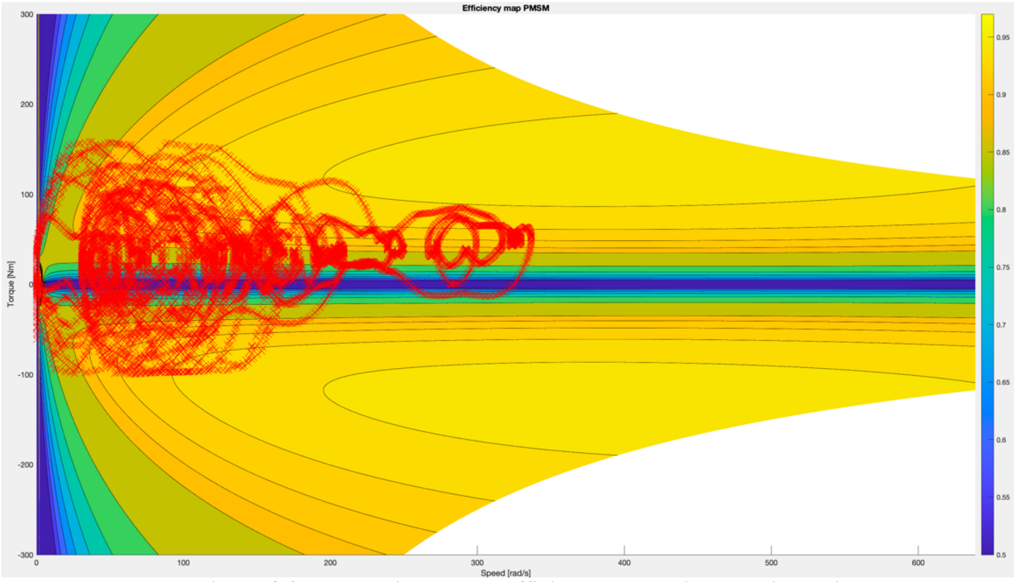

Figure 8.2: Theoretical motor efficiency map, with working points

As can be noticed, low efficiency working points are often reached so it highlights the need of keeping the motor in a point in which it can deliver higher torque value and in a rotating points in which the inertia it's already overcome. The most efficient points are in the middle right side of *Figure 8.2*, however they are reached not as frequently as the middle points, in which the efficiency is near the 85/90%, in order to avoid this to happen, a two or three speeds gearbox can be implemented, however in this case, also the efficiency of the gearbox has to be introduced in the calculation and its weight has to be considered within the system.

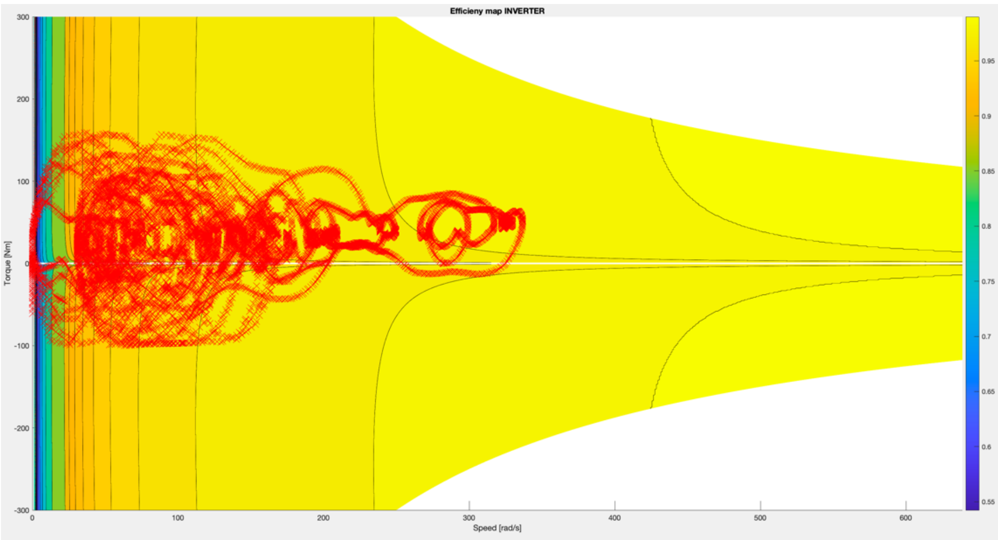

Figure 8.3: Theoretical inverter efficiency map, with working points

The same happens for the inverter efficiency map, however since inverter losses are different from the ones present in the motor calculation, the iso-efficiency lines have different shapes. As can been noticed, the majority of points is located in the middle left side of the plot, where inverter efficiency has low values from 85% up to 90%.
An estimated improvement in range ~ 10% and a huge reduction in thermal losses can be expected, so a smaller size battery can be used to cover the same distance or a better range can be achieved with the same battery size. A smaller and more efficient cooling system can be designed, saving space and avoiding losses resulting in a better performing and then, eco-friendly solution.

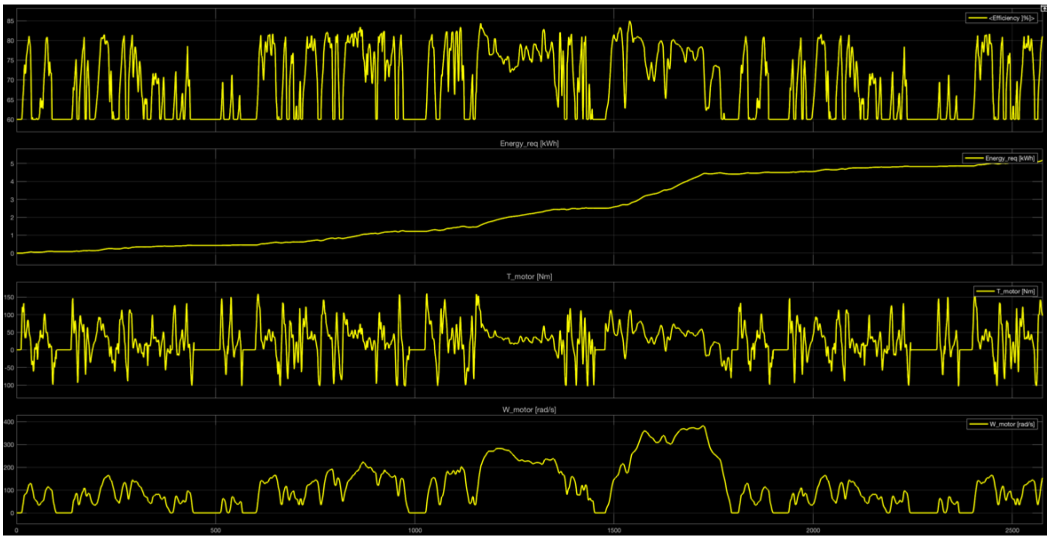

Figure 8.4: IGBT inverter solution overall results

In the above *Figure 8.4,* also reported bigger in *Appendix,* four different charts are presented. Starting from the upper side, the overall curve efficiency of the system from 0 to 100% is highlighted, in this case the average efficiency of the system is ~ 65% due to low values related in cases which torque and speed are equal to 0, so the vehicle has to perform a complete acceleration from stand still to x velocity. The chart immediately below represents the pure mechanical energy required by the vehicle to complete the driving cycle till SOC will become 5%, at the end of the simulation this value reaches ~ 4.2 kW. Again, below the last two charts are respectively the requested torque curves and the requested speed to each motor in order to let the vehicle follow the driving cycle path. As can be noticed, also negative torque values are present since the vehicle has to slow down in some cases, part of this energy will be recovered by the battery pack thanks to regenerative braking technology and part would be lost due to mechanical braking.

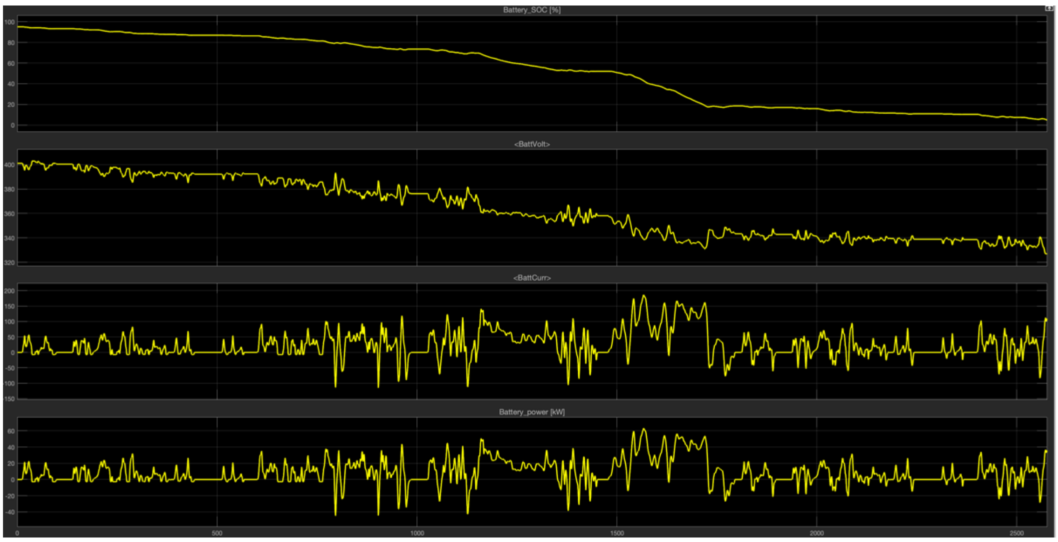

Figure 8.5: Battery pack info

As *Figure 8.4*, also this one is divided into four sub-charts. Starting from the top one, the battery SOC (*State of Charge*) can be seen, starting from 95% and reaching the lowest value at 5%. Also battery voltage chart, the second sub-chart from the top, has a similar shape since it varies related to the SOC, the higher will be the SOC the higher will be the voltage that the battery can provide to both motors. In this case, the last two sub-charts are related

respectively to electrical power and current required from the battery pack to let the vehicle follow the driving cycle profile. As can be noticed, till SOC is high, regenerative braking cannot be applied to avoid over voltage that can damage battery cells, so the BMS (*Battery Management System*) has to apply a control rule, strictly related to the SOC percentage in order to control the amount of current that the battery can provide or receive from the motors. Obviously, the higher is the number of electric drives applied into the vehicle, the higher would be the current that has to be requested to the battery.
In this context, the following table has been developed in order to empathize the BMS limits in regeneration:

Table 8.3: BMS limitations

INVERTER TYPE:	SOC [%]	Distance [km]	Consumed energy [kWh]	Regenerated energy [kWh]	Delta [%]
IGBT	95	24.41	7.193	0.839	11.67
	90	21.65	6.755	0.733	10.85
	80	20.80	6.492	0.802	12.36
	75	19.19	5.917	0.894	15.12
	65	18.10	5.588	0.902	16.15
	60	16.14	4.924	0.916	18.60
	55	15.25	4.570	0.900	19.69
	50	13.26	4.084	0.766	18.77
SiC					
	95	28.05	7.456	1.085	14.55
	90	26.45	7.105	1.069	15.05
	80	21.61	6.244	0.881	14.12
	75	20.51	5.919	0.892	15.08
	65	18.30	5.258	0.903	17.19
	60	16.14	4.921	0.915	18.60
	55	16.19	4.586	0.920	20.07
	50	15.19	4.229	0.912	21.57

This specific BMS has been designed in a way that the battery is capable of receiving current from the system in a really safe manner, in fact till the SOC reaches 55/60 % the battery cannot receive high currents and then, for the first part of the cycle, in which the SOC is very high, the regenerative braking cannot be fully used and then, a big amount of energy is lost. To empathize those limits, different simulations have been run, starting from different SOC levels as reported in *Table 8.3* and delta percentages of regenerated over consumed energy have been reported, noticing that after 60% of SOC deltas are increasing.

The obtained results are compared with in class leading vehicles who set the bars. The list of vehicles is reported in the following table, next to their specs and the obtained results from the model:

Table 8.4: List of hybrid supercars with similar performance

Make	EM power [kW]	Battery capacity [kWh]	Range [Km]
Ferrari SF90 [34]	100	7.9	25
McLaren Artura [35]	70	7.4	30
Porsche 918 [36]	95	6.8	29
Bmw i8 [37]	95	11.6	35
Modelled HEV	100	8	~ 26

So, the modelled vehicle seems to be in line with the average performance of different hybrid supercar makers with similar battery pack and power available.
A further consideration can be done while simulating a SiC inverter with respect to IGBT one, the results are reported in the table below:

Table 8.5: Comparison between different inverter tipologies within Matlab/Simulink™ developed model

Inverter type	EM power [kW]	Battery capacity [kWh]	Range [Km]
IGBT	~ 100	8	~ 26
SiC	~ 100	8	~ 29

Even if each motor can deploy up to 100 kW, since the two are directly connected to each front wheels, the torque requested to the vehicle motion is split and then each motor has to provide 50 kW only, then a tangible improvement can be obtained in term of pure efficiency of ~10%.
As can be noticed, what has been already mentioned in section 5.5 of this thesis, this particular application is positioned in the low power region of *Figure 5.4* such that SiC inverters perform better than IGBT ones.
Also other driving cycles are analyzed, in order to see the average improvement in different driving scenarios:

Table 8.5: Comparison between different driving cycles

Driving cycle	IGBT range [Km]	SiC range [Km]	Improvement [%]
WLTP C3	~ 26	~ 29	~ 10
NEDC	~ 30	~ 32	~ 7
FTP75	~ 36	~ 38	~ 6
ARTEMIS URBAN	~ 45	~ 49	~ 9
Average percentage improvement			~ 8

In addition, BMS limits' relaxation has been performed in order to understand physical limits related to vehicle itself, motors and inverters and reported in the following tables:

Table 8.6: BMS limits' relaxation: Ideal BMS

IDEAL BMS + REAL BATTERY SPECIFICATION					
INV.TYPE	SOC [%]	Distance [km]	Consumed energy [kWh]	Regenerated energy [kWh]	Delta [%]
IGBT	95	25.81	7.490	1.143	15.26
SiC	95	29.13	7.760	1.400	18.04
IGBT	55	15.25	4.570	0.906	19.83
SiC	55	16.19	4.586	0.920	20.07

In *Table 8.6*, an ideal BMS system has been implemented, in this case, the current limits in regeneration are not related to SOC percentage and then the battery is capable of receiving high currents from the very first braking during the whole driving cycle, even if the SOC is at 95%. As can be expected, higher deltas values are obtained at SOC percentage equal to 95% compared to *Table 8.3* results, while at SOC percentage equal to 55% the difference is negligible, since the BMS does apply any current limits.

In the following table, an ideal battery pack has been implemented, so any current limit in both tractive and regenerative phase. For what concern the simulation point of view, in order to have comparable results for both inverters typologies, two fixed distances have been chosen 1500 and 3000 km, which are far beyond the physical limits of a real battery pack.

Table 8.7: BMS limits' relaxation: Ideal battery pack

IDEAL BMS + REAL BATTERY SPECIFICATION					
INV.TYPE	**SOC [%]**	**Distance [km]**	**Consumed energy [kWh]**	**Regenerated energy [kWh]**	**Delta [%]**
IGBT	--	1500	441.1	64.3	14.59
SiC	--	1500	400.7	64.0	15.97
IGBT	--	3000	883.6	128.3	14.52
SiC	--	3000	803.3	127.8	15.91

In this case, deltas are not so different from the other cases since torque and speed demands to the vehicle's drive are still the same, for this reason the tractive and generative currents are similar to the ones present in the real case, highlighting that the regenerative braking feature is not dependent from the battery pack and its BMS only, but it's also strictly related to vehicle, motors and inverters physical limits.

9. Conclusions and future works

The future of automotive industries is well defined, the entire automotive system must adopt a more circular economy and wastes must be avoided. Petrol engine cars are still leading the market however, after the huge “Diesel gate” scandal, authorities all over the world are trying to avoid that to happen again, encouraging automotive factories to adopt technologies like hybrid and full electric vehicles. Hybrid platform, whether kind, would be the near future of on road transportation. In fact, a full EV needs proper designed infrastructures to be paired with, huge investments have to be done to prepare the world to run with electricity only. Renewable fonts must be used to produce it like wind, sun and water, on contrary, the final EV client’s feeling of being eco-friendly would be a lie. Technology innovation will prove, in an near future, that a big improvement can be done for what concern the automotive field CO_2 emissions. Another truth that has to be said is that cars, buses and trucks are often used as “mirrors for the larks” while the most CO_2 producing objects are big ships, planes and old boilers that we all have in our cities.

In this particular case, the utilization of Silicon Carbide inverters will improve HEV ranges of ~ 8% avoiding wastes, in term of both energy consumption and thermal losses.
Nowadays their prices are quite high due to the novelty of this technology and the difficulties that has to be faced while there are assembled but, within a 10 years period, their costs will decrease of ~ 24%.

A future work to further improve this thesis, will be to apply a gearbox and a proper control technique, to drive inverters and motors in their best efficiency area, in this way an estimated improvement of ~ 4% more can be achieved. This addition will for sure lead to a more complex design and a weight increasing, but for some application, it might be a proper solution to further improve vehicle ranges.

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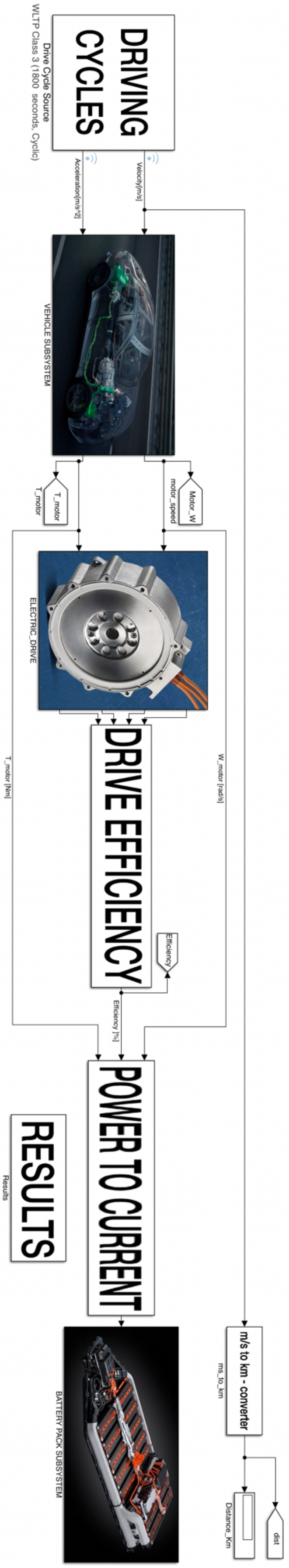
Appendix

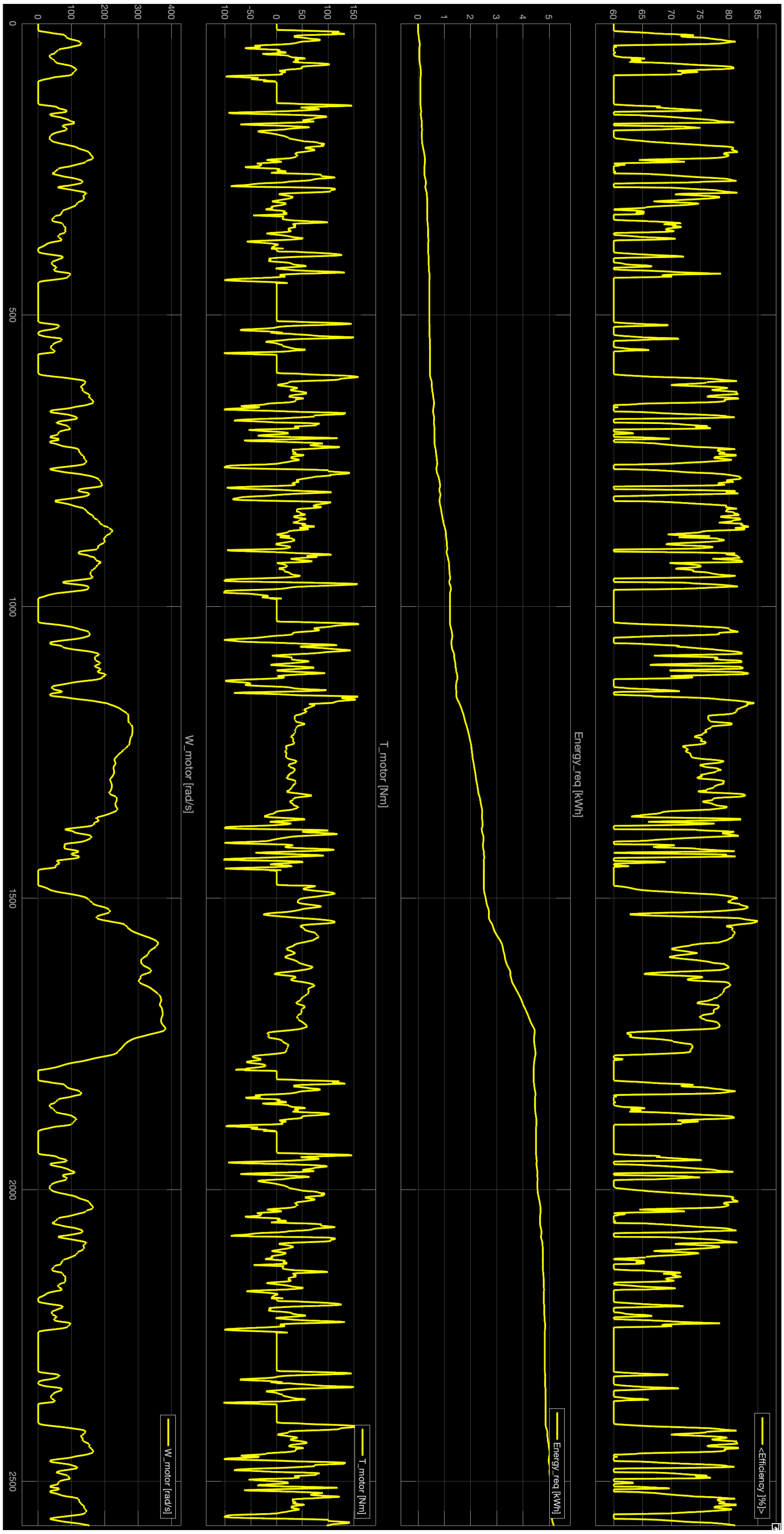
Code used to generate theoretical efficiency maps [33]

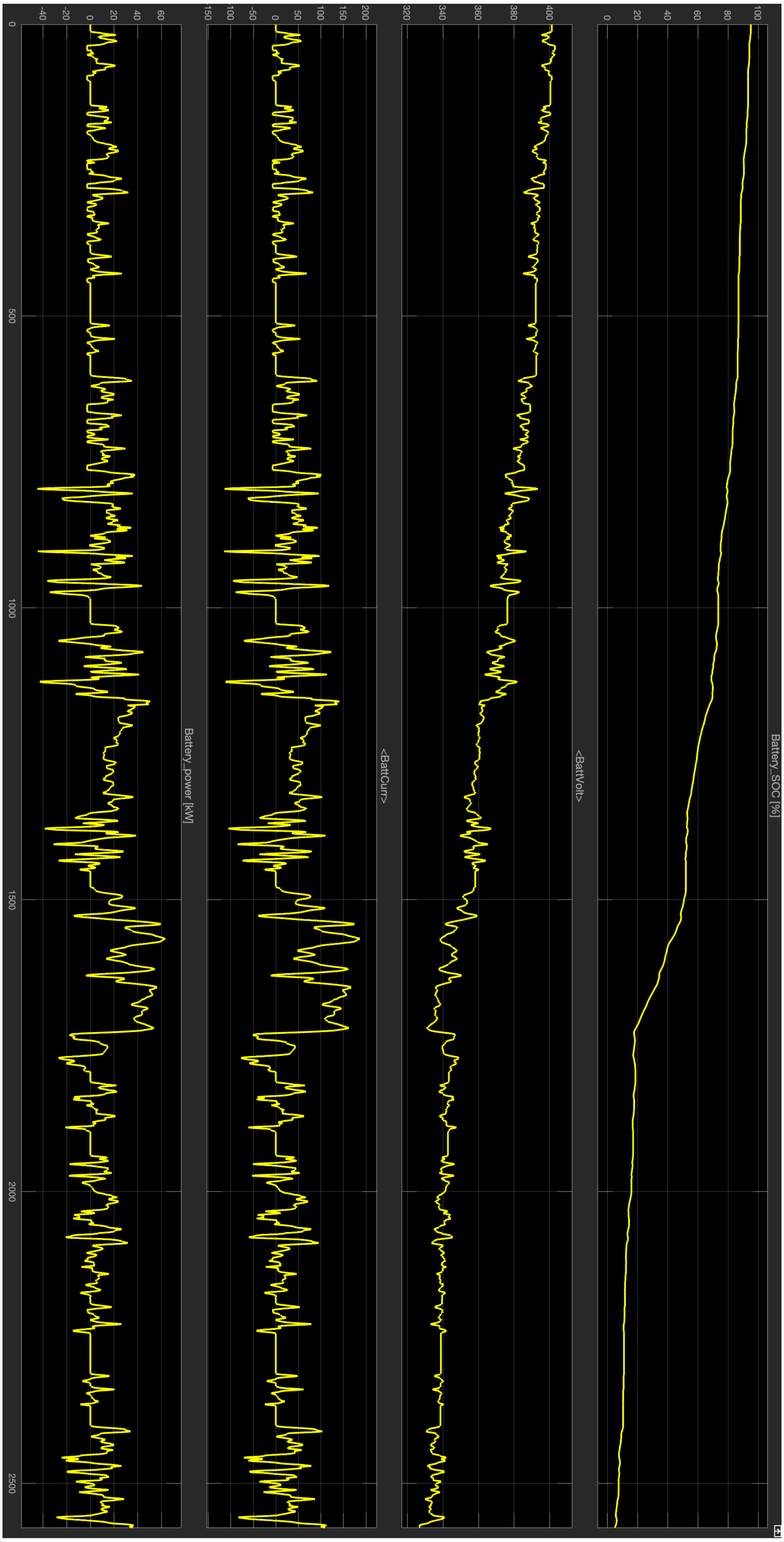
```
% MOTOR EFFICIENCY MAP GENERATOR
rpm=6100; %motor speed in rpm
w_max=rpm*2*pi/60; %motor speed in rad/s
T_b=300; %motor torque
x=linspace(0,w_max,w_max); % RPM 0 to max
y=linspace(0,Tb,Tb); % torque -Tb to Tb
%Creating mesh
[w,T]=meshgrid(x,y);
%Torque saturation i.e. field weakening
for c = 1:w_max
   for r=1:T_b

      if (T(r,c)*w(r,c)>75000)
         T(r,c) = 75000/w(r,c);
      end
   end
end
%% MOTOR
%Output power from motor
Output_power=(w.*T); % P=T*w
VettoreW=out.W_working.data;
VettoreT=out.T_working.data;
%Calculating loss components. Coefficient modified to meet measured map.
base_loss=5200;
L_1= -0.0033*base_loss;
L_w1_T0= 0.52*(w./w_max)*base_loss;
L_w0_T1=0.02*(T./Tb)*base_loss;
L_w1_T1=-1.022*(T./Tb).*(w./w_max)*(base_loss-4000);
L_w1_T2=1.3*(T./Tb).^2.*(w./w_max)*base_loss;
L_w0_T2=0.103*(T./Tb).^2*base_loss;
L_w2_T0=-0.334*(w./w_max).^2*base_loss;
L_w0_T3=0.45*(T./Tb).^3*base_loss;
L_w2_T1=0.5*(T./Tb).*(w./w_max).^2*(base_loss);
L_w3_T0=0.12*(w./w_max).^3*(base_loss+4000);
%Combining whole components losses
P_loss=L_1+L_w1_T0+L_w0_T1+L_w1_T1+L_w1_T2+L_w0_T2+L_w2_T0+L_w0_T3+L_w2_T1+L_w3_T
0;
Input_power=Output_power+P_loss;
%Creating efficiency map:
Map_motor= Output_power./Input_power;
%Further modification to meet target map:
Map_motor=Map_motor-0.01;
Map_motor(Map_motor>0.9642)=0.97;
Map_motor(Map_motor<=0.5)=0.5;
hold on
%Set contour lines to be drawn
V1=(0:0.05:.9);
V2=(0.9:0.01:1);
V=[V1,V2];
box off
grid off
%Plot using contour plot and color map:
z1=contourf (w,-T,Map_motor,V);
z2=contourf (w,T,Map_motor,V);
plot(z1)
plot(VettoreW,VettoreT,'xr','Markersize',10)
hold on
axis([0 w_max -Tb Tb])
```

Complete Simulink scheme



Results and overall information of the model

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