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Electrification of an ICE vehicle and design of the electromechanical system

TESI DI LAUREA MAGISTRALE IN
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Abstract

This thesis pursued several goals, the first one was to analyze the history of electric vehicles and the main innovations of the last years in order to make a conclusion on the pros and cons of all the industry, this information was used in order to understand what type of motor can be used and how it have to be controlled, what type of battery cells are the most suitable for our purpose. At the end of our analysis an asynchronous motor was chosen because of its reliability and energy efficiency, as a source of electric energy it was decided to use 338 prismatic battery cells that most suitably fit in our vehicle thanks to their form. The next goal was to develop a control system for our electric motor to guarantee a high precision working out of our experimental track and input torque and to check the performance of our model in MATLAB Simulink, the goal was reached – the model shown a high precision with low error on different input tracks and finally on the experimental one. As a finally goal was the selection of components of our electric drive and the economical calculation of our modification, that shown us the expediency of this modification. Finally, it can be stated that the future electrification of all our transport will reduce the dependence from fossil fuels.

To sum up – the main goal of this thesis was the electrification of a serial model van that is widely used by companies in Italy.

Key word: Electric transport, load diagram, asynchronous motor, torque control

Abstract in italiano

Questa tesi ha perseguito diversi obiettivi, il primo è stato quello di analizzare la storia dei veicoli elettrici e le principali innovazioni degli ultimi anni al fine di trarre una conclusione sui pro e contro di tutto il settore, queste informazioni sono state utilizzate per capire quale tipo di motore può essere utilizzato e come deve essere controllato, quale tipo di celle della batteria sono le più adatte al nostro scopo. Al termine della nostra analisi è stato scelto un motore asincrono per la sua affidabilità ed efficienza energetica, come fonte di energia elettrica si è deciso di utilizzare 338 celle di batteria prismatiche che si adattano di piu al nostro veicolo grazie alla loro forma. L'obiettivo successivo era sviluppare un sistema di controllo per il nostro motore elettrico al fine di garantire un'elaborazione ad alta precisione della nostra pista sperimentale e della coppia in ingresso e per verificare le prestazioni del nostro modello in MATLAB Simulink, l'obiettivo è stato raggiunto: il modello ha mostrato un alta precisione con basso errore su diverse tracce di input ed infine su quella sperimentale. Come obiettivo finale c'era la selezione dei componenti del nostro sistema e il calcolo economico della nostra modifica, che ci ha mostrato la giustificazione di questa modifica. Infine, si può affermare che la futura elettrificazione di tutti i nostri trasporti ridurrà la dipendenza dai combustibili fossili.

Per riassumere, l'obiettivo principale di questa tesi era l'elettrificazione di un modello di furgone di serie ampiamente utilizzato dalle aziende in Italia.

Key word: Veicolo elettrico, diagramma di carico, motore asincrono, controllo della coppia

Contents

Introduction

Since the invention of the car the life of persons became easier, the trip to work or final destination don't take so much time as before, but despite that, the car is the most widely used and comportable transport, it, as many other inventions has its pros and cons, that's why humanity start the developing of electric vehicles. The main disadvantage of a typical ICE vehicle – is the pollution of our environment with toxic gasses that come from the exhaust pipe. These gasses are very dangerous, because they are the product of oxidation and not full burning of different kinds of fuel. For example, in many developed cities around the world, there is a restriction for vehicles entering the city with standard lower than EURO 3. One of the solutions to this problem is the total or electrification of our vehicles or at least a part.

The next disadvantage of a classic ICE vehicle is the non-effective and high fuel consumption. The efficiency of diesel and gasoline engines is around 40%. Transition to more efficient and ecological electric motors will allow us to reduce the extraction of fossil fuels, and using recuperative braking, where the energy, produced during braking, will charge the battery, lead us to an increasing of the maximum trip distance.

In modern cities around the world electric vehicles are not a news and many people are using them for different purposes, starting from public transport, followed by private transport and finishing with electric scooter, and every year prices on electric vehicles are reducing.

1 Analysis and various solutions

1.1. History of developing and general information

Basically, an electric car or as we can also call it – battery electric car is an automobile that is driven by at least one electric motor, and not by an internal combustion engine, using energy stored in batteries. Using the term "electric car" we refer to a highway-capable vehicle, but there are also low-speed EV with some limitations on: power, maximum speed that are allowed for using on public roads, for example in European Union they are classified as electric motorized quadricycles. Also, we must remember that a hybrid car is not a fully electric vehicle, the reason for the circumstance is that a hybrid is also equipped with combustion engines that run on different type of fossil fuels.

The first historically proved electric car was presented by Gustave Trouve at the "Exposition internationale d'Électricité de Paris" in 1881 [1], which was part of international meetings. In 1884, more than 20 years before the first stock car Ford Model T was produced, an electronic engineer Thomas Parker built a practical production electric car using his self-designed high-capacity rechargeable batteries.

To understand the popularity of electric cars in the 20th century, we need to consider that at the beginning of the century, the horse was still the primary mode of travelling, but as the economic situation in the world was keeping growing, people turned to newly invented motor car – among them the electric one. If we try to compare briefly with steam powered cars, we can find that they require long startup times (up to 40 minutes in the cold) and would need to be refilled with water, limiting the range. Going to an internal combustion engine we can say that the require a lot of manual effort to drive, changing gears, to start this type of cars in the early 1900 you need a crank, making them difficult to operate by people, also they were very noisy and, their exhaust was unpleasant.

On the figure 1.1 we can see an electric car developed by Thomas Parker.

Figure 1.1: Electric car developed by Thomas Parker

On the other hand, electric cars didn't have any issues in common with steam or gasoline. They didn't emit smelly pollutant; they were quiet and easy to drive. As more people gained access to electricity in the 1910s, electric cars quickly became popular with urban residents.

Then in the 1908 when the Model T gasoline-powered car was introduced, and by 1913, the gasoline car cost only around 700$, while an electric car was around 2000$. In the same year, Kettering introduced the electric starter, that eliminates the hand crank and gives the gasoline vehicle a rise of sales. As another reason of decline of the electric vehicle we can mention the reduction in price of fossil fuels (with the discovery of Texas oil deposits), in addition refueling a gas tank was much faster than charging a battery. As a result, the part of electric cars was near 1%.

The next 40 years became a sort of dark ages for electric cars, with some big steps in technology. But in the early 1970s, the increasing price of oil and gasoline shortages create a growing interest to the development of electric cars. Many governments start to support research and development in electric and hybrid vehicles. But still some "old" problems remain, electric cars usually have low speed performance (near 80 km/h) and their range was around 60 km before needing to recharge.

A "second breath" was given to electric cars around 1990. The environmental situation in the world was deteriorating, and humanity understand that one of the big problems was – internal combustion engine. So, there was an urgent need to develop a vehicle that will not release exhaust.

Many car manufacturing companies like Honda, Ford, Toyota, Nissan where interested firstly in developing hybrid vehicles and then start working on fully electric powered cars.

As we can see from the graph represented in the Figure 1.2 [2], the annual sales of Hybrid cars versus Plug-in electric vehicle are almost the same in the 2018, with a slightly decreasing in the 2019 and 2020 of the number of sold PEV. But the trend is obvious, starting from the 2011 electric cars are gaining more and more marketplace.

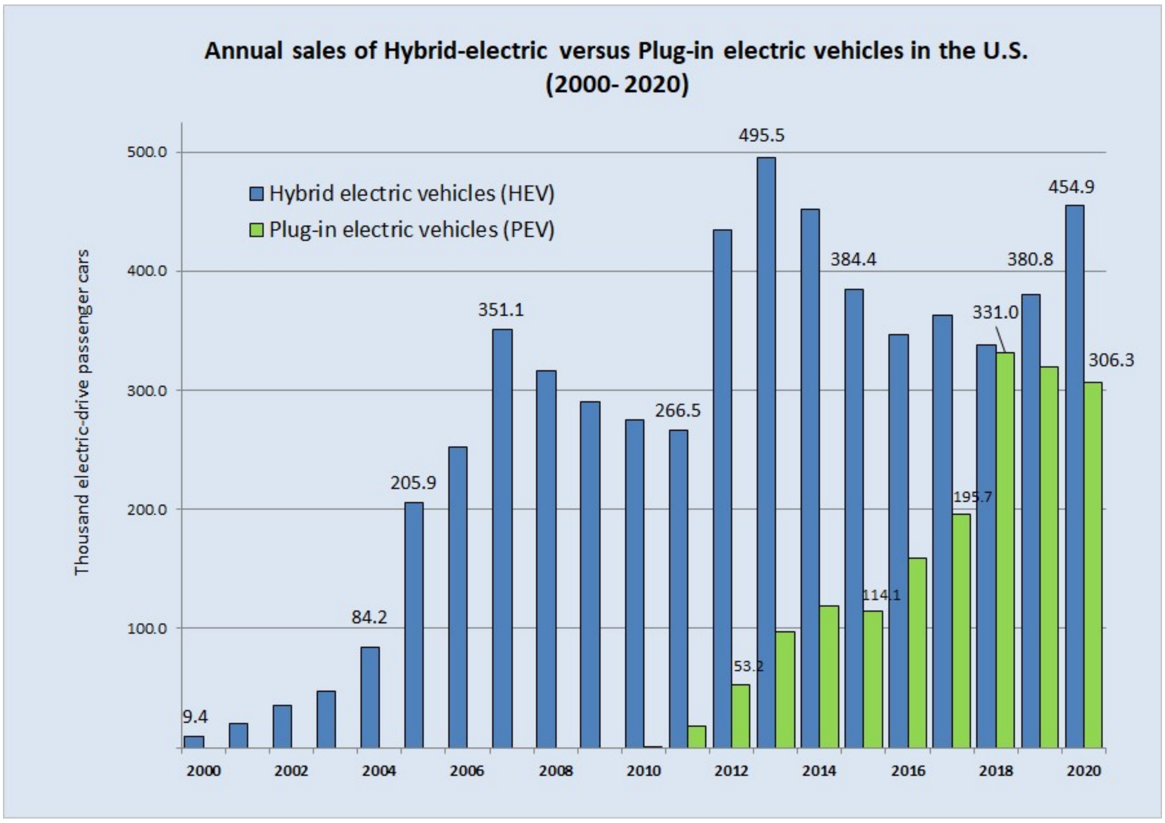

Figure 1.2: Annual sales of HEV and PEV

One of the first stock electric car that was presented to the market in 2009 is Nissan Leaf, it was equipped with an 80 kW (nearly to 108 h.p.) electric motor, its battery was from 18 to 24 kWh – it was a lithium-ion battery made by 192 cells and have a mass of 280 kg. The battery was able to accumulate energy through recuperation. Its actual range was between 180 and 240 km. This model is characterized by its low price and medium performance.

In the year before the presentation of Nissan Leaf a new big role player came out – Tesla. Its announcement and very rush success prompted many big automakers to accelerate the work on their own electric vehicles. Tesla electric cars are characterized by their high performance, high price in comparison to other electric vehicles of the same category. But Tesla has also one of the most long-range capability between electric cars (close to 500 km), it is also equipped with intelligent system like autopilot and many other safety systems.

In the last years more car manufacturers have developed their own fully electric car, as we can see from the diagram shown on the Figure 1.3 [3], that is showing to us the quantity of electric cars selled in 2020 (December) in the world, Tesla with its Model 3 is on the first place followed by Wulling, Volkswagen, Renault, Hyundai… and in the middle we can see the first electric stock car – Nissan Leaf.

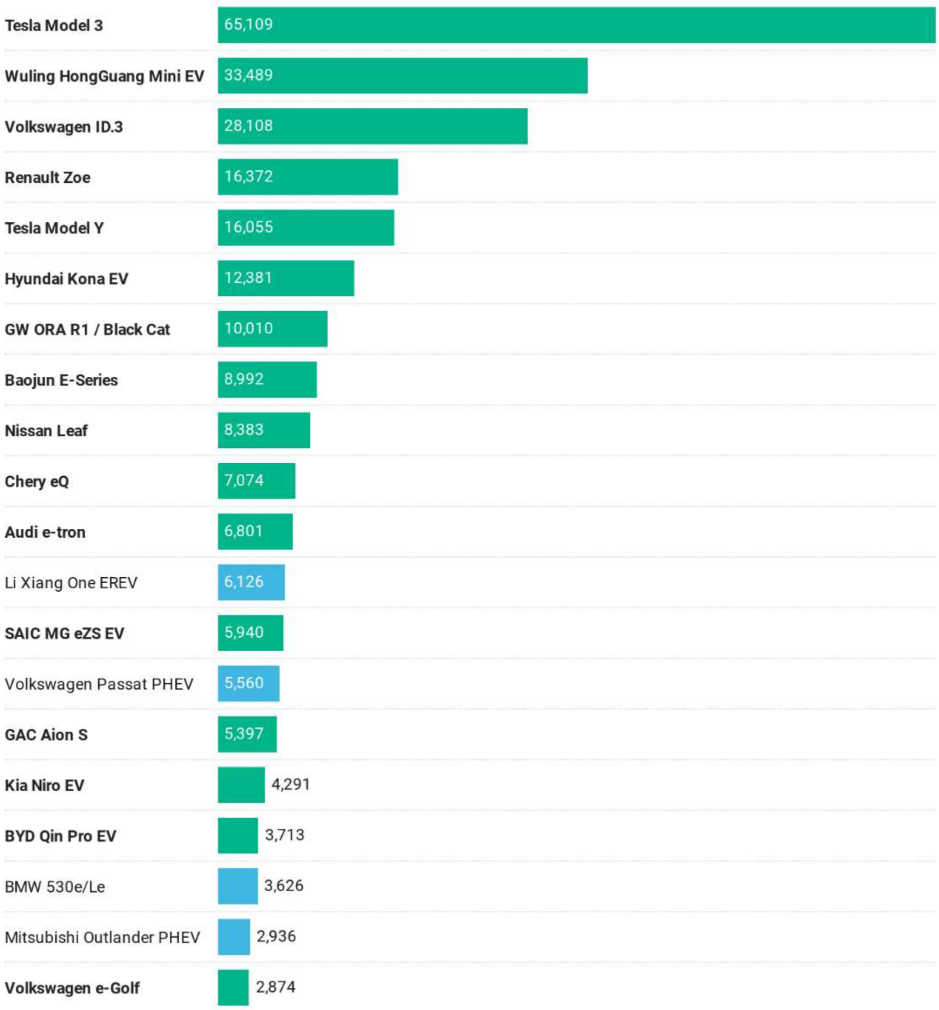

Figure 1.3: World plugin vehicle Sales (December 2020)

To sum up everything that has been stated above, electric cars have various advantages and disadvantages.

Beginning from benefits:

- No dependency on fuel cost increase. There is no gasoline required to use an electric car. Driving fuel-based cars cost much more because of the constant increasing of fuel price.
- Incentives from government. Many countries offer to people the possibility of getting a part of their money back while buying an electric car.
- Zero emissions. Electric vehicles won't emit toxic gases or smoke in the environment because they run on a clean energy source.
- Low maintenance. An internal combustion engine car has more moving parts, that of course need lubrification and a lot of service work during its lifecycle.
- Popularity. With time the price of electric cars is going down, first because the technology is widely studied during the last 10 years – and so the cost of production is decreased. Second – there is a lot of choice between different car manufacturer, this also will lead to a decrease of price in the future.

Disadvantages:

- Recharge points. Especially in rural areas, far away from cities, it can be a problem to find a "fast" recharging station. This disadvantage has a solution if you live in a house – you can place a recharging station, or just plug in the charging cable in the power socket.

- Starting investment. Nowadays electric vehicles are still a big investment on the start. The more affordable solutions can be around 25000 € to 35000 €. If you prefer something more luxury, you may be paying from 70000 €.
- Minimal amount of pollution. It is a myth that electric cars are 100% eco-friendly. The reason is that they cause a little amount of pollution indirectly. The electricity that is used to charge the battery is not necessarily generated from "clean" energy sources.

Old fashion disadvantages:

- Long recharge time. Nowadays with a powerful charging station you can charge your vehicle in 20 minutes to 80%.
- Short driving range and speed. Modern electric cars keep the record in acceleration from 0 to 100 km/h. And typically, their range is near to 300 km.

1.2. Electric cars amplification in Italy

Italy is one of the European Union countries that have the most sharp growth of electric cars registration in the last 2 years. As we can see from the Figure 1.4, the total number of registration in 2020 has inreased more than 200%. [4]

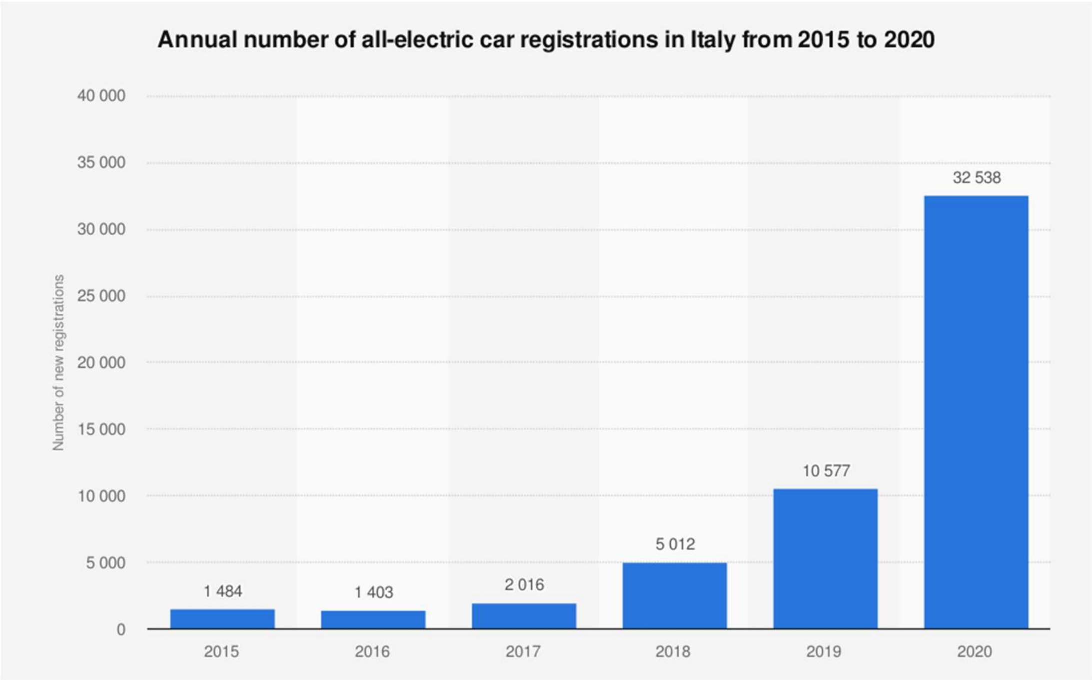

Figure 1.4: Annual number of electric car registrations in Italy

The sharp growth that we see above is reasonable – starting from past years the Italian government introduced incentives on electric cars and hybrid vehicles, this gives customer an important possibility to save costs in buying a new car. The so called "ecobonus" gives the opportunity to save up to 40 %. For example, if we are interested in buying a Fiat 500 E and we decide to scrap our old car, the price of the new one will be 16150 € instead of 26150 €. [5]

On the other hand, Italy is far away from countries with the greatest number of electric cars, and Italy is even not in the TOP 17. For example, Norway is on the 1st place, and detain a 70% of electric cars in new passenger car sales, followed by Iceland with 45%, Germany is placed on the 9th place with 13,5% while France is on 11th position with 11,3%. [6]. In Italy only 2,3 % of cars sold in 2020 are fully electric. [7]

One of the reasons can be the low expanded network of charging station, especially if we are speaking about rural areas. In cities the problem is less because there are a lot of public parking with charging station, also travelling by highway is convenient on an electric car – many "Autogril" have quick charger stations on their parking.

1.3. Design and main parts of an electric car

The construction of an electric car is much easier that the one of an internal combustion engine car, and it is more reliable, because it has fewer moving elements, and nodes. For example, we are missing the exhaust or the lubrification system, most of the electric vehicles don't have a gearbox, even a cooling system is not required most of the times.

The main parts of an electric vehicle can be divided into the electric motor, the motor controller, and an electric battery. [8]

On the Figure 1.5 we can see the main components of an electric vehicle.

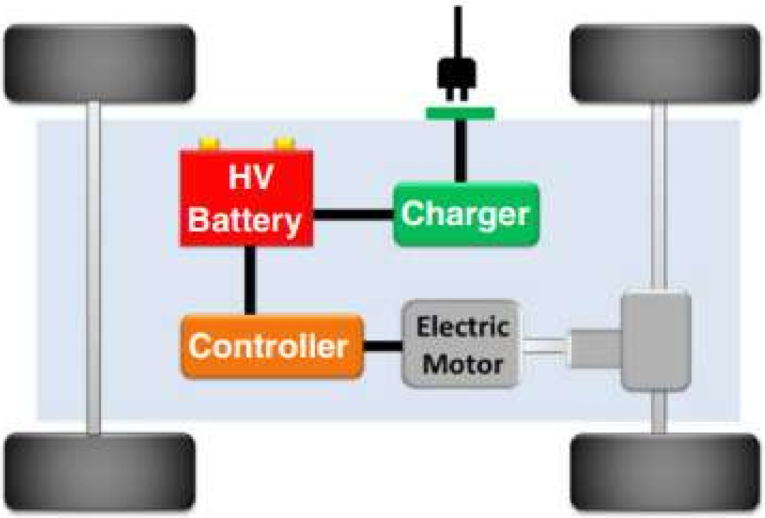

Figure 1.5: Main components of an electric vehicle

Batteries are one of the most important components of an electric vehicle, there are increasing developers like: LG, Samsung, Panasonic, Bosch, Sony, that invest costs into developing higher capacity and cheaper batteries.

Nowadays batteries are one of the most expensive components of an electric vehicle. But things can change in the next few years. Research published in the 2017 shows us that the average cost of one kilowatt-hour battery pack is around 210$ or 179€, and the price is about to go down, and by 2025 the price can be around 100$ for one kilowatt-hour [9]. At the first year of production, the Nissan Leaf battery cost was near to 40% of the total value of the whole vehicle.

The battery is characterized by some main characteristics [10]:

- Capacity – represents the maximum amount of energy that can be stored into the battery concerning some specified conditions. Typically, the unit of measure is expressed in watt hour (Wh) or in ampere hour (Ah).

- Energy density – represents the energy that can be provided by the battery per unit volume (Wh/L).

- Lifespan – represents the number of cycles that a battery can resist.

- Internal resistance – thus the components of batteries are not 100% ideal conductors, they offer a certain resistance to the transmission of electricity. So, during the charging we are expecting some energy dissipation in heat.

- Working temperature

- Specific energy

Most of electric vehicles presented in 2020 has an average battery capacity of 63 kWh. The most capable battery is mounted on the Audi E-tron with a battery of 95 kWh, followed by the Mercedes EQC – 80kWh.

There are different battery components used in electric vehicles, from them we can highlight the following types:

1) Lead-acid batteries – this type of batteries was invented in the 1859 by Gaston Plante. His invention was the first battery that could be recharged by passing a reverse current through it. Lead-acid battery was previously used in electric vehicle due to their well-known technology and low cost. One of the most significant disadvantages of this type of battery is their low lifecycle, typically after 3 year there is a need of replacement [11].

2) Nickel-cadmium batteries – a cadmium electrode associated with a nickel structure, allows in 90s a very promising alternative power source for electric cars [12]. Those batteries were characterized by a good energy density, but they have low lifespan, and a very strong environmental impact, because one of the components – cadmium is a very polluting element, in addition it is very expensive.

3) Nickel-metal hydride batteries – those type of batteries is mostly used on hybrids. Here instead of using cadmium an alloy that is storing hydrogen is used. They are characterized by their very long lifecycle, that was demonstrated on some models of Toyota that still operate after 160000 km [13].

4) Sodium nickel chloride – also called Zebra battery, it uses a sodium chloroaluminate salt as the electrolyte. The most significant disadvantage is that the battery must be heated for use, that waste some energy. One of the larger users of those type of batteries was Modec company [14],

5) Lithium-ion – initially were created and commercialized for use in telephones, laptops, and other consumer electronics. They are characterized by a high energy density and long lifecycle. Early cells of those type pose a fire risk if damaged or charged improperly. Also, they were less effective in cold climate zones, the reason was that they didn't supply of accept charge in extremely cold temperature, so a heater was required. Modern manufacturers are using a variation of lithium-ion chemistry that provides fast charging, resistance to fire, long lifespan. Variants with titanites, spinel's, phosphates have shown a much longer lifetime. And LG expects that their lithium-manganese spinel batteries will last up to 45 years [15].

Table 1.1 is comparing different type of batteries main characteristics, that were previously specified.

Table 1.1: Batteries Characteristics [16,17,18]

	Lead-acid	Nickel-cadmium	Nickel-metal hydride	Sodium chloride	Lithium-ion
Energy density, Wh/L	70-100	60-140	110-290	160-200	200-375
Lifespan	200-300	1000	300-500	1500	1500-2000

Working temperature, ° C	-20 to 50	0 to 45	0 to 45	0 to 45	-20 to 60
Specific energy, Wh/kg	30-50	45-80	60-120	160	100-200
Toxicity	High	High	Low	Medium	Low

Batteries can also be characterized by their type of cells, the most known are [19]

1) Prismatic – mainly are produced with Lithium-iron-phosphate. In sense of battery packing, it is easier to develop a battery using those type of cells, but some problem can persist while assembling on the vehicle. The figure 1.6 show us the form of prismatic cells.

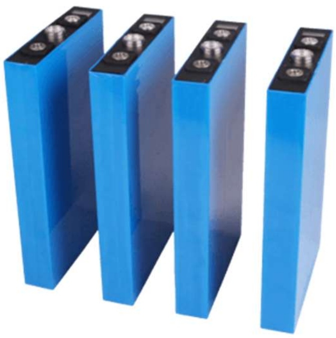

Figure 1.6: Prismatic cells

This type of battery is widely produced by A123, CALB, Sinopoly, Samsung, Lec.

2) Cylindrical – here the Lithium-nickel-manganese-cobalt chemistry is preferred. With those type of cells is difficult to develop the battery pack, but most efficient volume and minimum cost can be achieved. Tesla is using those cells for their batteries. The figure 1.7 show us the form of cylindrical cells.

Figure 1.7: Cylindrical cells

Tesla utilize batteries in the most efficient way, the use of the same structure in commercial vehicle will lead to a significant decrease on car cost. Another advantage of this type of cells is the easiness of packing. The disadvantage of using cylindrical cells is low lifecycle.

There are only two major manufacturers of those type of cells: Samsung and A123.

3) Pouch. Basically, a prismatic cell is made of some pouches packed, gathered, and covered with some enclosure. But the previously assembled prismatic cell decrease the flexibility during assembling in the vehicle. Using pouch cells directly in battery assembly allows to manufacture lighter and thinner packs or modules.

LEC, BestGo, CALB, A123 are the larger producer of those type of cells.

The main advantage of those cells is their flexibility in installation, battery modules could be designed with the most suitable combination, in addition they offer a good lifecycle. Pouch cells are shown on figure 1.8.

Figure 1.8: Pouch cells

Changing the battery pack in an electric car is possible, but it is not an easy procedure. After the installation of the battery, it might be connected and registered with the on-board computer. The need of changing the battery comes actual when its capacity is reduced, so the total range is limited.

The main reason of battery degradation is it weakness to hot climates. Extreme temperature is the first problem of Lithium-ion batteries, that the reason why many car manufacturers use liquid-cooled system to keep the temperature of the battery in allowed limits. Another reason is that cars with a short range may suffer quicker deterioration, that's because using most of the charge on an everyday use led to a quicker cutting of its capacity over time. But also using Level 3 DC Fast Charging stations is not healthy for the battery, they can bring an electric car to 80 percent in only 20 minutes, but they also affect the battery long term performance. Again, the reason is temperature the faster you charge – the hotter become the battery [20].

So, the main reason of battery degradation is high temperature or hot climate, on the figure 1.9 we can see a graph showing us the battery capacity level depending on time (month). It is easy to understand that already at first year of operation the total battery capacity level is about 97%, going down with a step of about 2% every year. Also, at the beginning there is no strong dependency in terms of “high use” or “low use”, but after 16 month the situation is changing, creating a slightly difference, about 1-1.5 % between “high” and “low” use. On the graph the situation represented is considering a Charging Level 2, if Charging Level 3 be used, the situation will lead to a deterioration with a sharper descent [21] .

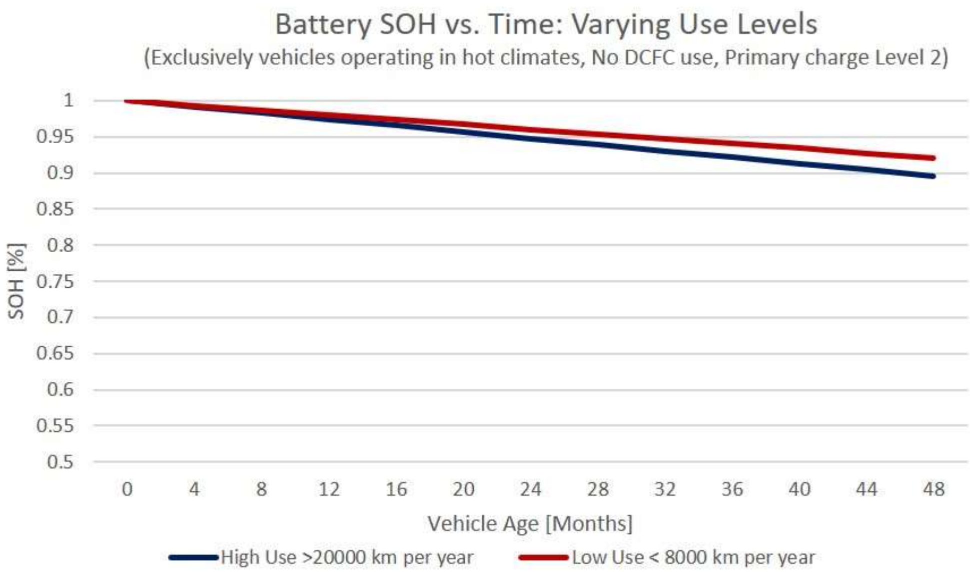

Figure 1.9: Dependency of the capacity in time (hot climates)

An important question nowadays is the battery recycling. A battery that is not rightly recycled is very dangerous for our environment. There exists a solution to give a second life to batteries that loses its capacity to power vehicle:

- Energy storage system – it stores energy that can be used when its need, for powering home or buildings. For example, powering a house with a renewable energy like solar or wind, there is a possibility to pair those system with an electric car battery that can store energy when wind or sunlight is reduced.

Then when the battery comes to the end of its working cycle, it is now time to recycle it – which includes separating out valuable elements such as lithium and cobalt salts, copper, stainless steel, and plastic. But only about 50% of those materials in an electric car battery are supposed to recycle now, many car manufacturers are looking to improve this in the next years. Volkswagen announced that they are working on building a plant for battery recycling with a capability of recycling around 97% of battery components.

A conclusion can be made – now, batteries for electric vehicles are not 100% eco-friendly, but important steps are made to reach that.

In terms of propulsion it is used an electric motor. The electric motor converts electrical that is taken from the battery into mechanical energy which is used to enable the vehicle to move. Typically, it can also act as a generator during braking (regenerative action) and send energy back to the battery. Different electric cars have different number of electric motors mounted on them. For example Toyota Prius – a hybrid car has only one electric motor [22], while the more performant Tesla Model S has 3 electric motors [23]. The quantity of motors mounted on an electric car is always based on the requirements, if you need more performance – you need more electric motors, and if you need long range capability – less motors and more battery size.

The development of modern control systems and power electronics in the last 50 years let emerge many different types of motors that match the needs of the electric cars [24].

The most used of them are the following [25]:

1) Brushed DC Motor – a motor that can provide high torque with low rotating speed, but on the other hand have a cumbersome structure, generate a lot of heat because of the brushes, low efficiency and low reliability. Mostly the heat is concentrated in the center of the rotor and is very difficult to remove. As for all the reasoning mentioned above DC Brushed motors are not more used in electric vehicles. The motor is composed by permanent magnets (stator) and have brushes to provide supply to the stator.
2) Permanent Magnet Brushless DC Motor (BLDC) – this type of motor is composed by a rotor that is made of permanent magnets, while the stator is provided an AC current supply from a DC source using an inverter. The absence of windings in the rotor guarantee a higher efficiency in comparison with the induction machine, because there is no copper loss. Also, this kind of motors are lighter, better in dissipating heat, more reliable. But the main problem is that this motor have a short constant power range, the reason is the limited weakening capability resulting from the PM field that can be weakened by a stator field. Another disadvantage can be the cost of Permanent Magnets. The figure number 1.9 show that the constant power region is short, the torque remains constant at the maximum, but starts to decrease when reaching the base speed [26]. An extension of the operating region at constant power can be performed by a conduction-angle control three to four times. Figure 1.10 show us the typical characteristics of PM Brushless DC Motor.

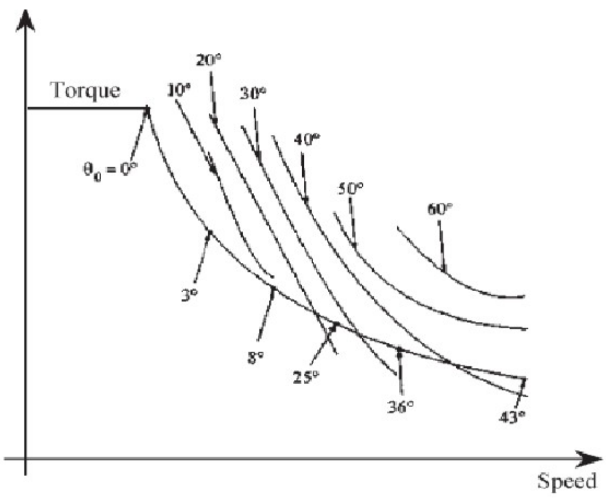

Figure 1.10: Typical characteristics of Permanent Magnet Brushless DC Motor

3) Permanent Magnet Synchronous Motor – nowadays this type of motors are the most advanced ones, making them also one of the most popular choice of electric car manufacturers. They are characterized by high efficiency and compact size. As for their size they are very suitable for in-wheel applications, and they can provide a very high torque at low speeds. On the other hand the disadvantage come when operating them at high speed – they face a big iron losses making the system unstable [27].
4) Induction Motor – it is one of the most mature motor drive system present on the market and it is mounted on the most of electric cars of Tesla [28]. On the Figure 1.11 an IM mounted on Tesla Model S is shown.

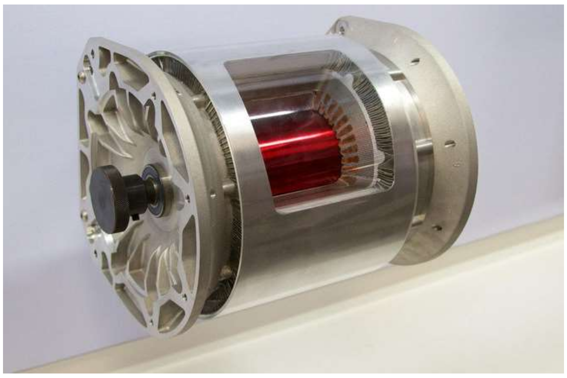

Figure 1.11: Tesla Model S IM

IM are simple in their construction, they have a very high reliability, they don't require frequent maintenance, have a low cost. It can be two types of induction machine:

- Wound-rotor induction machine – characterized by higher cost and need more maintenance.
- Squirrel cage – more attractive for electric vehicles.

There exist three most common way to control the induction machine [29]:

a) Variable-Voltage Variable-Frequency

Basically, it adopts with constant voltage control for frequencies below the rated frequency, and variable-frequency control with constant rated voltage for frequencies over the rated one. In this type of control, we can observe from the Figure 1.12 – three different operating regions.

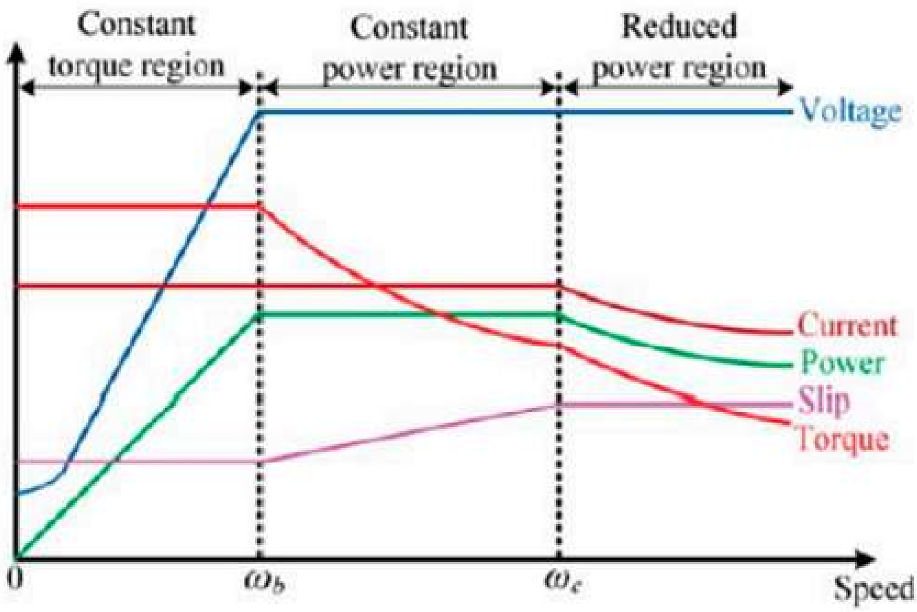

Figure 1.12: Operating regions with VVVF control

1. Constant torque region delivered by the motor below the rated speed.
2. Constant power region, over the base speed the torque starts to decrease. Still observing constant stator current, motor running at the rated power.
3. Reduced power region, observing a decrement of the stator current and the torque is decreasing with the square of the speed.

b) Field oriented control (FOC) can be divided into two different types:
    1. Direct FOC – also known as Direct Vector Control, it identifies the rotor flux linkage instantaneously by measuring the air-gap flux from stator voltage or current.
    2. Indirect FOC – Indirect Vector Control, there is no need to identify the rotor flux linkage. It is the one of the most widely used in Electric Vehicles.

c) Direct Torque control – the system selects the switching modes of the voltage-fed PWM inverter directly to controlling the stator flux linkage and the torque application of the IM in electric cars.

5) Synchronous Reluctance Machine – this kind of motors are synchronous motors that demonstrate robust and simple construction, high speed, low cost, long constant power range. As their most common disadvantage it can be mentioned that they are very noisy because of their variable torque nature, they also have low efficiency and have a bigger size in comparison with PM machines. Their control is not easy because of the presence of high saturation in addition to fringe effect of slots and poles. Nowadays this type of motors is becoming more common because of their low cost in comparison with PM motors, and a lot of researches are concerned in

reducing their noise and torque ripple, so they can be widely used in electric vehicles.

Summarizing all the above – the most popular solutions for an electric car today are – Induction machine or PM Synchronous Motor.

1.4. Characteristics of the vehicle

The Van Iveco Daily is a large light commercial van that is powered by different types of internal combustion engine of EURO 6 standard:

- Diesel 3.0L 107 kW (144 hp)/350 Nm
- Diesel 3.0L 126 kW (170 hp)/400 Nm
- Compressed Natural Gas 3.0L 100 kW (136 hp)/350 Nm

Different kinds of motors can have different masses, because of variation in their transmission and equipment.

Overall characteristics, as: length, width, height, wheelbase (front and bottom), clearance, wheel dimension, mass of the vehicle, are shown in the table 1.2.

Table 1.2: Overall Characteristics

Length, mm	7012	Wheel Track Bottom, mm	1540
Width, mm	1996	Clearance, mm	210
Height, mm	2750	Wheel Dimension	215/65 R16
Wheelbase, mm	4100	Vehicle Mass, kg	3500
Wheel Track Front, mm	1696		

1.5. Main purpose for the research

The main goal of this research is the replacement of the internal combustion engine of this car with an electric motor. There will be also developed a control system and a battery.

This car is used for making delivery in the city of Milan. In one working day this car used to have a working cycle of typically 50-100 km, on Saturday and Sunday this distance is lower – about 50 km. The average fuel consumption is around 14l on 100km. In the last year the price of fuel for internal combustion engine has increased by 10 percent and the need to use an electric vehicle is increasing.

In this work some tasks will be solved:

- Calculation of an electric battery
- Calculation of the electric motor, that is suitable by power, and overall characteristics
- Developing of the control systems
- Economical calculation

2 Selection of the motor and battery for the vehicle

2.1. Calculus of the power of the electric motor

For the calculation of the power of the electric motor we need to consider some main parameters of our vehicles, and the characteristics of the track. We need to know the mass of the vehicle $m = 2500\ kg$; mass of one wheel $m_w = 27\ kg$; radius of the wheel $R_w = 0{,}349\ m$; the ratio of the main drive $i_d = 1{,}8$; the gear ratio $i_g = 5{,}15$; the moment of inertia of the Asynchronous motor, that is approximately $J_m = 0{,}15\ kg \cdot m^2$. Between the main parameters of the motion of our vehicle there are: the total distance of the track, the maximum acceleration/deceleration, that is reached by the vehicle $a_m = b_m = 1{,}475\ m/s^2$; maximum steady speed of the vehicle $V_m = 91\ km/h\ (25{,}3\ m/s)$ and its nominal steady speed $V_n = 50\ km/h\ (13{,}89\ m/s)$.

The equation of motion of the mechanical part of the electric drive for this vehicle can be represented as in equation (2.1), considering that the friction component is small in comparison with T_d we can neglect it:

$$J\frac{d\omega}{dt} = T_d \tag{2.1}$$

Where J – the total moment of inertia of the vehicle, ${}^{d\omega}/_{dt} = {}^{a_m}/_{R_w}$ – angular acceleration, T_d – dynamic torque of the electric drive.

The total moment of inertia is represented in the equation (2.2):

$$J = J_v + J_m + J_w = m \cdot \frac{{R_w}^2}{i^2} + J_m + \frac{4 \cdot m_w \cdot R_w^2}{2 \cdot i^2} \qquad (2.2)$$

Where J_m – the moment of inertia of the vehicle; J_w – the total moment of inertia of the wheels of the vehicle; i – the product of the ratio of the main drive and the gear ratio.

After some calculation the total moment of inertia is $J = 3{,}77\ kg \cdot m^2$

The maximum angular speed of the wheel ω_{wm} and the angular speed of the motor shaft will be calculated as in the equation (2.3) and (2.4):

$$\omega_{wm} = \frac{V_m}{R_w} = \frac{25{,}3}{0{,}349} = 72{,}4928 \left(\frac{rad}{s}\right) \qquad (2.3)$$

$$\omega_m = \frac{V_m \cdot i}{R_w} = \frac{25{,}3 \cdot 9{,}27}{0{,}349} = 673{,}2012 \left(\frac{rad}{s}\right) \qquad (2.4)$$

As next, the nominal angular speed of the wheel ω_{wn} and the angular speed of the motor shaft ω_n are represented in the equation (2.5) and (2.6):

$$\omega_{wn} = \frac{V_n}{R_w} = \frac{13{,}89}{0{,}349} = 39{,}7994 \left(\frac{rad}{s}\right) \qquad (2.5)$$

$$\omega_n = \frac{V_n \cdot i}{R_w} = \frac{13{,}89 \cdot 9{,}27}{0{,}349} = 368{,}940 \left(\frac{rad}{s}\right) \qquad (2.6)$$

For a two-pole pair Asynchronous motor, the nearest standard value of the nominal angular speed is $\omega_n = 157 \frac{rad}{s}$. So, in further calculation this value will be used.

While accelerating to the nominal speed with the maximum acceleration will be used the torque overload capability of the motor. Operation over the nominal speed will be performed using the flux weakening, that requires a reducing of the torque, so the motor works with constant power.

The coefficient of weakening is represented in the equation (2.7):

$$D = {}^{\omega_m}/_{\omega_n} = {}^{673,2012}/_{157} = 4.2 \tag{2.7}$$

The static torque is calculated using such parameters as the speed of the vehicle, the vehicle frontal area, shape of the vehicle body and the air density, in its maximum is equal to 25 Nm.

The dynamic torque of the electric motor is represented in the equation (2.8):

$$T_d = J \cdot \frac{a_m \cdot i}{R_w} = 3,77 \cdot \frac{1,475 \cdot 9,27}{0,349} = 148\ N \cdot m\ (2.8)$$

The maximum accelerating torque braking torque, considering the presence of static torque is represented in the equation (2.9) and (2.10):

$$T_a = 157\ N \cdot m \tag{2.9}$$

$$T_b = 143\ N \cdot m \tag{2.10}$$

As the acceleration and braking torque differ in modulus, the time needed to accelerate and brake to the nominal speed is different. The time of acceleration and braking are represented in the equation (2.11) and (2.12):

$$\Delta t_{a1} = J \cdot \frac{\omega_n}{T_a} = 3,77 \cdot \frac{157}{157} = 3,77\ s \tag{2.11}$$

$$\Delta t_{d1} = J \cdot \frac{\omega_n}{|T_b|} = 3,77 \cdot \frac{157}{143} = 4,13\ s \tag{2.12}$$

From a practical point of view the graph of the speed of motion of the vehicle will be represented in km/h. The experimental cycle was got while the vehicle was on a typical working trip in the city of Milan. As a result – a diagram with speed time dependency was received.

Using the array of the speed the calculation of the acceleration is performed using the following formula (2.13):

$$a_j = \frac{V_{j+1} - V_j}{t_{j+1} - t_j} \tag{2.13}$$

Where j – is the number of the element in the array;

The angular speed of rotation of the motor represented in the equation (2.14):

$$\omega_j = \frac{V_j \cdot i_j}{R_w} \tag{2.14}$$

The torque of the motor will be calculated considering the static torque. Following the previous calculation, diagrams of acceleration, angular speed of the motor shaft and torque where received and are illustrated on the Figure 2.1.

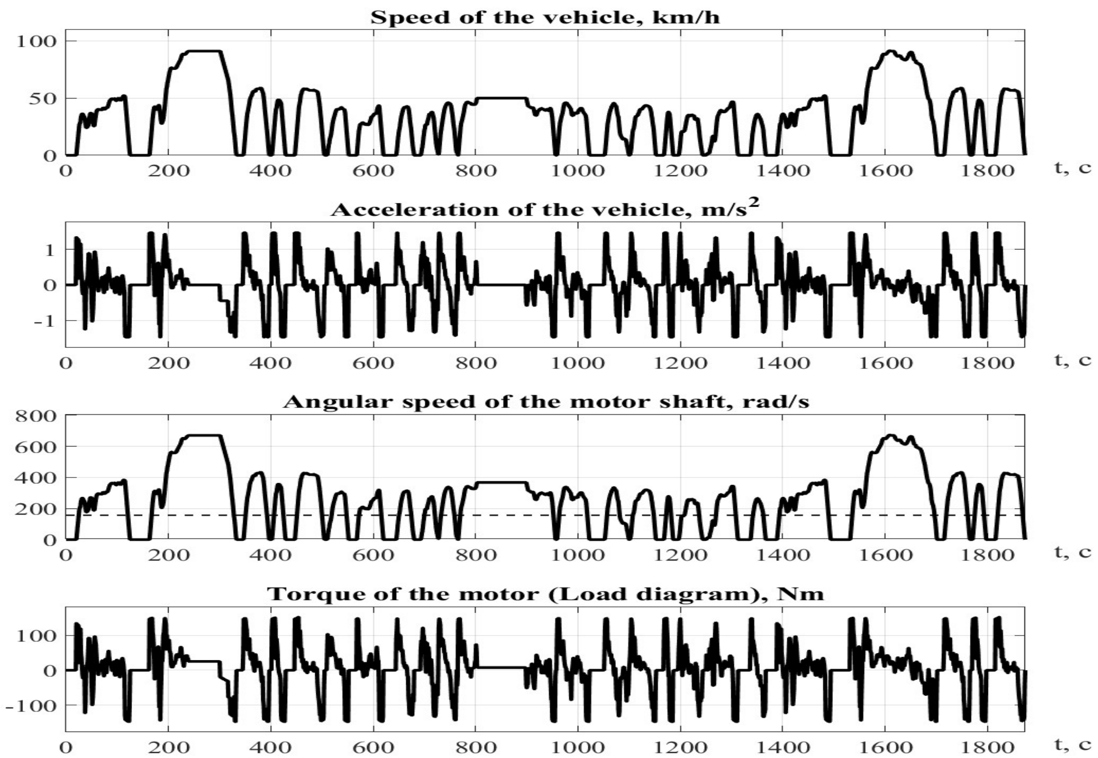

Figure 2.1: Diagram of vehicle speed, acceleration, speed of rotation of the motor shaft and load diagram

As a main parameter for the calculation of our motor power is the equivalent torque on the cycle. It can represent in the equation (2.15):

$$T_e = \sqrt{\frac{1}{T_c}\int_0^{T_c} M^2(t)dt} = 63{,}5385\ N \cdot m \tag{2.15}$$

Then taking into consideration a safety factor of $k_s = 1{,}3$, the nominal speed of rotation of the motor shaft (considering the flux weakening) $\omega_n = 157\frac{rad}{s}$ and the previously calculated equivalent torque, the power of the electric motor can be calculated as in the formula (2.16):

$$P_m = k_s \cdot T_e \cdot \omega_n = 1{,}3 \cdot 66{,}4311 \cdot 157 = 12{,}9\ kW \tag{2.16}$$

The nearest motor will be chosen.

2.2. Calculus of the parameter of the motor in nominal mode

Table 2.1: Characteristics of the motor Marelli 160L4

Nominal Power	$P_{2n} = 15\ kW$
Nominal line stator voltage	$U_{1n} = 380\ V$
Number of pole pairs	$p_n = 2$
Moment of inertia	$J_m = 0{,}075$
Efficiency	$\eta = 0{,}9$
Power coefficient	$cos\varphi = 0{,}8$
Overload capability	$\lambda = 2{,}4$
Nominal slip	$S_n = 0{,}026$

Critical slip	$S_c = 0{,}12$
Nominal stator voltage frequency	$f = 50\ Hz$
Stator resistance	$R_s = 0{,}2147$
Rotor resistance	$R_r = 0{,}2205$
Stator inductance	$L_s = 0{,}06518$
Rotor inductance	$L_r = 0{,}06518$
Mutual inductance	$L_\mu = 0{,}06419$

Parameters as stator and rotor resistance, stator and rotor inductance and the mutual inductance were taken from a motor with equal parameters of power and pole pairs, nominal line voltage [30]. The table 2.1 shows us the motor parameters.

The angular speed of the stator voltage is represented in the equation (2.17):

$$\omega_{on} = 2\pi f = 2 \cdot 3{,}14 \cdot 50 = 314 \frac{rad}{s} \tag{2.17}$$

Ideal idle speed of the motor is represented in the equation (2.18):

$$\omega_{is} = \frac{\omega_{on}}{p_n} = \frac{314}{2} = 157 \frac{rad}{s} \tag{2.18}$$

Nominal speed of the motor represented in the equation (2.19):

$$\omega_n = \omega_{is}(1 - S_n) = 157 \cdot (1 - 0{,}026) = 152{,}996 \frac{rad}{s} \tag{2.19}$$

Nominal torque is represented in the equation (2.20):

$$T_n = \frac{P_{2n}}{\omega_n} = \frac{15 \cdot 10^3}{149{,}996} = 98{,}042\ N \cdot m \tag{2.20}$$

Critical torque, considering the overload capability of the motor is represented in the equation (2.21):

$$T_{cr} = \lambda \cdot T_n = 2{,}4 \cdot 98{,}042 = 235{,}3009\ N \cdot m \tag{2.21}$$

Nominal value of the phase voltage is represented in the equation (2.22):

$$U_{1nf} = \frac{U_{1n}}{\sqrt{3}} = \frac{380}{\sqrt{3}} = 220\ V \tag{2.22}$$

Nominal value of the stator current is represented in the equation (2.23):

$$I_{1n} = \frac{P_{2n}}{\sqrt{3} \cdot \eta \cdot U_{1n} \cdot cos\varphi} = \frac{15 \cdot 10^3}{\sqrt{3} \cdot 0{,}9 \cdot 380 \cdot 0{,}8} = 31{,}56\ A \tag{2.23}$$

Amplitude value of the stator current is represented in the equation (2.24):

$$I_{1na} = \sqrt{2} I_{1n} = \sqrt{2} \cdot 31{,}65 = 44{,}76\ A \tag{2.24}$$

Amplitude value of the stator flux in idle mode is represented in the equation (2.25):

$$\psi_{1i} = \frac{U_{1na}}{\omega_{on}} = \frac{311}{314} = 0{,}99\ Wb \tag{2.25}$$

Calculation of parameters in the equation (2.26-2.34) $\alpha, \alpha_1, \beta, \beta_1, \gamma, \gamma_1, \gamma_2, \sigma, \sigma_1$:

$$\alpha = \frac{R_r}{L_r} = 3{,}38\ \frac{Ohm}{H} \tag{2.26}$$

$$\alpha_1 = \frac{R_s}{L_s} = 3{,}29\ \frac{Ohm}{H} \tag{2.27}$$

$$\sigma = L_s \left(1 - \frac{L_\mu^2}{L_s \cdot L_r}\right) = 0{,}002\ H \tag{2.28}$$

$$\sigma_1 = L_r \left(1 - \frac{L_\mu^2}{L_s \cdot L_r}\right) = 0{,}002\ H \tag{2.29}$$

$$\beta = \frac{L_\mu}{\sigma \cdot L_r} = 501{,}1856 \frac{1}{H} \tag{2.30}$$

$$\beta_1 = \frac{L_\mu}{\sigma \cdot L_s} = 501{,}1856 \frac{1}{H} \tag{2.31}$$

$$\gamma = \frac{R_s}{\sigma} + \alpha \cdot L_\mu \cdot \beta = 218{,}097 \frac{Ohm}{H} \tag{2.32}$$

$$\gamma_1 = \frac{R_r}{\sigma_1} + \alpha_1 \cdot L_\mu \cdot \beta_1 = 218{,}186 \frac{Ohm}{H} \tag{2.33}$$

$$\gamma_2 = \frac{R_s}{\sigma} + \alpha \cdot L_\mu \cdot \beta + \alpha = 221{,}48 \frac{Ohm}{H} \tag{2.34}$$

The table 2.2 show us the full motor parameters.

Table 2.2 - Full parameters of the motor

P_{2n}, kW	15	R_s, Ohm	0,2147
ω_{is}, rad/s	157	R_r', Ohm	0,2205
$\omega_n, rad/s$	153	L_s, H	0,06518
T_n, Nm	98.042	L_r, H	0,06518
T_{cr}, Nm	235.3	L_μ, H	0,06419
λ	2.4	$\alpha_1, Ohm/H$	3,29
I_{1na}, A	31.57	$\alpha, Ohm/H$	3,38
ψ_{1i}, Wb	0.99	$\beta, 1/H$	501,1856
η	0.9	$\gamma, Ohm/H$	218,097
$cos\varphi$	0.8	σ, H	0,002
$J_m, kg \cdot m^2$	0.075		

2.3. Calculus of the battery

The calculation of the required characteristics of the battery will be performed using the parameters mentioned in the table 2.3.

The calculus is performed using the algorithm from [31].

Table 2.3: Data used for calculation of the battery

Maximum mass of the vehicle, kg	2500
Friction coefficient on asphalt f_r	0.012
Flow rate of the air ξ	1.225
Aerodynamical coefficient C_w	0.8
Frontal area A_f, m^2	4.5

The calculation is made basing on the graph of motion of our vehicle, that is shown on the figure number 2.2.

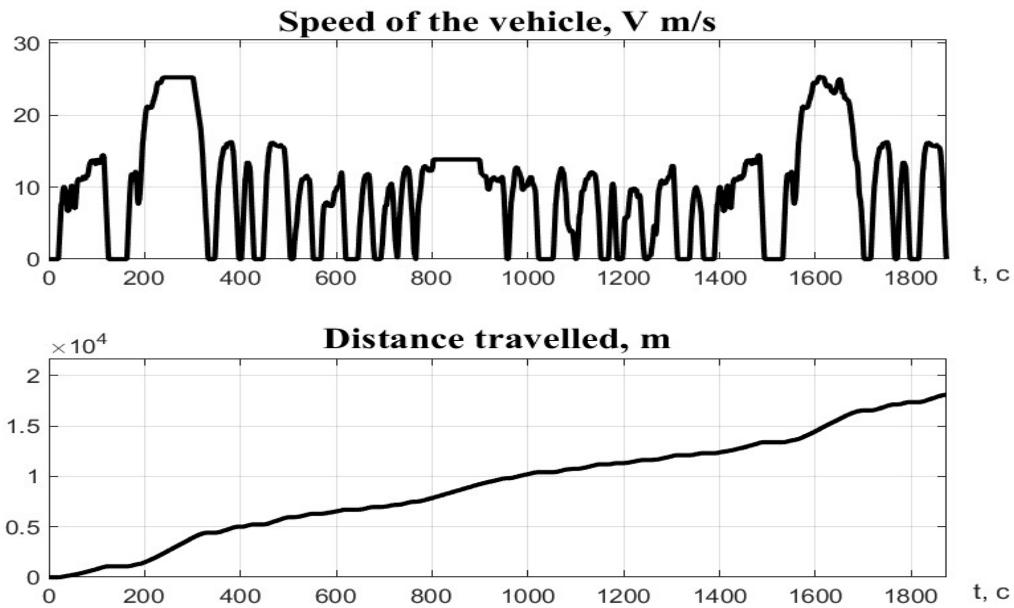

Figure 2.2: Speed of the vehicle and travelled distance

The total travelled distance by the vehicle can be received by integrating the trajectory of speed. The graph of distance path is shown on figure 2.2.

The energy used by the vehicle can be divided into two main parts:

- Energy wasted while converting electric energy into kinetic and vice-versa.
- Energy wasted on friction and aerodynamic resistance.

So, the energy needed for the battery of our vehicle is represented in the equation (2.35):

$$W_{battery} = W_{fr} + W_e \qquad (2.35)$$

where W_{fr} – energy waste, consists of friction losses and aerodynamic resistance; W_e – losses while converting electric energy into kinetic one. Using the formula for calculating power we can write the equation (2.36):

$$W_{fr} = \frac{1}{T}\int_0^T \left(mgf_r + \frac{1}{2}\xi C_w A_f V^2\right) \cdot Vdt \qquad (2.36)$$

Where $T = 1875\ s$ – full time of the cycle; $g = 9{,}81\ {}^{m}/_{s^2}$ – acceleration of free fall.

When converting electric energy from the battery into kinetic energy, its way pass through the converter, electric motor and reducer. Let's take, that the efficiency of the converter is $\eta_{conv} = 0{,}97$; the efficiency of the motor as mentioned previously $n_m = 0{,}9$; efficiency of the reducer $n_{red} = 0{,}98$. So, the sum of all the efficiency will be $\eta_\Sigma = \eta_{conv} \cdot n_m \cdot n_{red} = 0{,}97 \cdot 0{,}9 \cdot 0{,}98 = 0{,}86$. So, the energy, wasted for converting electric energy into kinetic one can represented in the equation (2.37):

$$W_e = (1 - \eta_\Sigma \ ) \cdot \frac{1}{T}\int_0^T m\frac{dV}{dt} \cdot Vdt \qquad (2.37)$$

Substituting known parameters into two previous equation and integrating, will be calculated with equation (2.38) the energy required for travelling 250 km.

$$W_{250} = \frac{W_{battery} \cdot 250}{S} = 251{,}86\ MJ \tag{2.38}$$

where $W_{battery} = 17{,}89\ MJ$ – for a cycle of $S = 18{,}08\ km$.

So, the charge of the battery needed to travel for 250 km for this vehicle, considering, that the DC voltage of the battery is $V_{dc} = 540\ V$, is represented in the equation (2.39)

$$Ih = \frac{W_{250}}{3600 \cdot V_{dc}} = \frac{251{,}86 \cdot 10^6}{3600 \cdot 540} = 129{,}557\ A \cdot h \tag{2.39}$$

For our practical realization will be chosen the element of type L135F72, parameters are mentioned in [32]. To reach our needed parameter, it is needing to connect 169 elements in series, and two lines of 169 elements in parallel. The total mass would be of 642.2 kg, and the approximately value – 16 100 $ ≈ 14 000 € [33]

3 Developing of the torque control system of the motor

3.1. Mathematical model of the asynchronous motor

Shown below is the mathematical model of Asynchronous motor in the reference frame d-q with the equation (3.1):

$$\begin{aligned}
\dot{\theta} &= \omega, \\
\dot{\omega} &= \mu(\psi_{2d} i_{1q} - \psi_{2q} i_{1d}) - \frac{T_l}{J} - \nu\omega, \\
\dot{i}_{1d} &= -\gamma i_{1d} + \omega_0 i_{1q} + \alpha\beta\psi_{2d} + \beta p_n \omega \psi_{2q} + \frac{1}{\sigma} u_{1d}, \\
\dot{i}_{1q} &= -\gamma i_{1q} - \omega_0 i_{1d} + \alpha\beta\psi_{2q} - \beta p_n \omega \psi_{2d} + \frac{1}{\sigma} u_{1q}, \\
\dot{\psi}_{2d} &= -\alpha\psi_{2d} + \omega_2 \psi_{2q} + \alpha L_m i_{1d}, \\
\dot{\psi}_{2q} &= -\alpha\psi_{2q} - \omega_2 \psi_{2d} + \alpha L_m i_{1q}, \\
\dot{\varepsilon}_0 &= \omega_0, \varepsilon_0(0) = 0,
\end{aligned} \tag{3.1}$$

Where, ω_0 – angular speed of the reference frame (d-q), ε_0 – angular position of the reference frame (d-q) related to the fixed stator reference frame (a-b), $u_1 = (u_{1d}, u_{1q})^T, i_1 = (i_{1d}, i_{1q})^T, \psi_2 = (\psi_{2d}, \psi_{2q})^T$ – vectors of stator voltages and currents and rotor flux, ω – angular rotor speed, T_l – load torque, $\omega_2 = \omega_0 - p_n\omega$ – slip frequency, p_n – number of pole pair.

Also, we have our continuous parameters, related to electrical and mechanical parameters of the asynchronous motor, and can be calculated as follow:

$$\alpha = \frac{R_2}{L_2}, \gamma = \frac{R_1}{\sigma} + \alpha L_m \beta, \sigma = L_1\left(1 - \frac{L_m^2}{L_1 L_2}\right), \beta = \frac{L_m}{L_2 \sigma}, \mu = \frac{1}{J}\frac{3}{2} p_n \frac{L_m}{L_2}$$

Where, R_1, R_2, L_1, L_2 – stator and rotor active resistance and inductance, L_m – mutual inductance, J – full moment of inertia, $\nu = \frac{\nu_1}{J}$; $\nu_1 > 0$ – viscous friction.

In the model represented by formulas (3.1) the measurable vector of variables $y = (\theta, \omega, i_{1d}, i_{1q})^T$, but at the same time the rotor flux is not measured, so the vector control of the asynchronous motor is defined as a control task of measuring the vector y.

In general formulation of vector control of the torque and module of the rotor flux the output variables, that must be worked out, are defined as non-linear function of time in the equation (3.2):

$$y_1 = \begin{bmatrix} \frac{3}{2}\frac{L_m}{L_2}(\psi_d i_q - \psi_q i_d) \\ (\psi_d^2 + \psi_q^2)^{\frac{1}{2}} \end{bmatrix} \triangleq \begin{pmatrix} T \\ |\psi| \end{pmatrix} \tag{3.2}$$

Let's look at the main features of implementation of vector control with orientation on the field of the asynchronous motor. In the ideal case, when the angular position of the rotor flux vector ε_ψ (Figure 3.1) is known, the condition $\varepsilon_0 = \varepsilon_\psi$ means that the axis d of the reference frame (d-q) coincides with the direction of the rotor flux vector, that is represented in the equation (3.3):

$$\begin{gathered} \psi_d = |\psi| \\ \psi_q \equiv 0 \end{gathered} \tag{3.3}$$

By the condition (3.3) is determined the ideal orientation by the rotor flux vector, and the reference frame (d-q) is called oriented by the rotor flux vector.

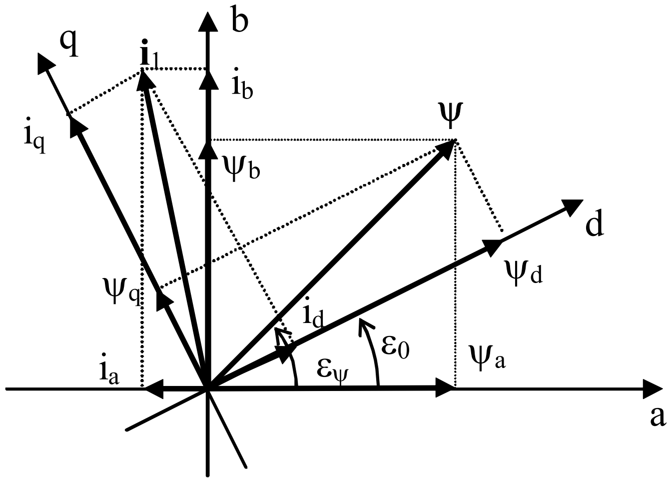

Figure 3.1: Position of the vectors in (d-q) reference frame

Then determining in the model, the change rule of the control actions as in the equation (3.4):

$$\begin{pmatrix} u_d \\ u_q \end{pmatrix} = \sigma \begin{pmatrix} -\omega_0 i_q + v_d \\ \omega_0 i_d + v_q \end{pmatrix}, \tag{3.4}$$

we have our asynchronous motor dynamic equation in the reference frame (d-q), that is oriented on the rotor flux vector:

$$\begin{gathered} \dot{\theta} = \omega \\ \dot{\omega} = \frac{1}{J}(T - T_c) \\ T = \frac{3}{2}\frac{L_m}{L_2}|\psi| i_q \\ i_{1q} = -\gamma i - \beta\omega|\psi| + v_q \end{gathered} \tag{3.5}$$

The equation system (3.5) is describing the electromechanical subsystem of the asynchronous motor due to the action of a non-linear regulator oriented on the field of the machine. The equation (3.5) is identical to the equation in the case of a DC motor.

$$|\dot{\psi}| = -\alpha|\psi| + \alpha L_m i_d$$
$$i_d = -\gamma i_d + \alpha\beta|\psi| + v_d \tag{3.6}$$

$$\dot{\varepsilon}_0 = \omega_0 = \omega + \alpha \mathrm{L_m} \frac{\mathrm{i_{1q}}}{|\psi_2|} \tag{3.7}$$

The equations (3.6), (3.7) determines the asynchronous motor dynamics of the electromagnetic subsystem. The equation (3.6), that describes the dynamic behavior of the rotor flux, is a second order linear system completely decoupled from the electromechanical subsystem. The equation (3.7), that determines the dynamics of the angular position of the rotor flux vector and is a known equation for the synchronous field speed of the asynchronous motor according to $\omega_0 = \omega + \omega_2$, where $\omega_2 = \alpha \mathrm{L_m} \frac{\mathrm{i_q}}{|\psi|}$ – slip frequency.

So, the regulator, based on the reference frame change $\varepsilon_0 = \varepsilon_\psi$ and (3.4), can be written as in the equations (3.8 – 3.10):

$$\begin{pmatrix} u_a \\ u_b \end{pmatrix} = e^{J\varepsilon_0} \left[\sigma \begin{pmatrix} -\omega_0 i_q + v_d \\ \omega_0 i_d + v_q \end{pmatrix} \right] \tag{3.8}$$

$$\begin{pmatrix} i_d \\ i_q \end{pmatrix} = e^{-J\varepsilon_0} \begin{pmatrix} i_a \\ i_b \end{pmatrix} \tag{3.9}$$

$$\cos\varepsilon_0 = \frac{\psi_a}{|\psi|}$$
$$\sin\varepsilon_0 = \frac{\psi_b}{|\psi|} \tag{3.10}$$

where, ψ_{2a}, ψ_{2b} – components of the rotor flux vector in the reference frame (a-b), $|\psi_2| = (\psi_{2a}^2 + \psi_{2b}^2)^{\frac{1}{2}}$.

3.2. Developing of the DTC and flux algorithm using a decoupled reduced order observer

Let's determine $\psi^* > 0$ as a set value of the module of the rotor flux, a limited function with limited first and second time derivative. We need to develop a two-dimensional vector $v = (v_d, v_q)^T$ that can guarantee the asymptotic working out of the output regulated value in (3.2), that is, to have conditions as in equation (3.11):

$$\lim_{t\to\infty} \tilde{T} = 0, \qquad \lim_{t\to\infty} \tilde{\psi} = 0, \tilde{\psi} = |\psi| - \psi^*, \tag{3.11}$$

Where, $\tilde{T} = T - T^*$ - the error on torque working out, T^*- the setted up torque trajectory of the asynchronous motor.

Let's write the working out errors of stator currents in the equation (3.12):

$$\tilde{i}_d = i_d - i_d^*, \qquad \tilde{i}_q = i_q - i_q^*. \tag{3.12}$$

And, the algorithm of torque control as the equation (3.13)

$$i_q^* = \left(\frac{3}{2}\frac{L_m}{L_2}\right)^{-1} \frac{T^*}{\psi^*} \tag{3.13}$$

Equations (3.5), (3.6) considering errors can be represented as:

$$\tilde{T} = \frac{3}{2}\frac{L_m}{L_2}\psi^* \tilde{i}_q + \frac{3}{2}\frac{L_m}{L_2}\tilde{\psi}\tilde{i}_q + \frac{3}{2}\frac{L_m}{L_2}\tilde{\psi} i_q^*, \qquad \dot{\tilde{i}}_q = -\gamma \tilde{i}_q - \beta\omega|\psi| - \gamma i_q^* - \dot{i}_q^* + v_q, \tag{3.14}$$

$$\dot{\tilde{\psi}} = -\alpha\tilde{\psi} + \alpha L_m \tilde{i}_d - \alpha\psi^* + \alpha L_m i_d^* - \dot{\psi}^*, \qquad \dot{\tilde{i}}_d = -\gamma \tilde{i}_d + \alpha\beta|\psi| - \gamma i_d^* - \dot{i}_d^* + v_d, \tag{3.15}$$

Let's write the control action v_q in (3.14) as the equation (3.16):

$$\begin{aligned} \dot{x}_q &= k_{iiq}\tilde{\imath}_q, \\ \nu_q &= x_q, \\ v_q &= -k_{iq1}\tilde{\imath}_q - \nu_q + \gamma i_q^* + \beta\omega|\psi| + i_q^*. \end{aligned} \tag{3.16}$$

Where, $(k_{iq} \ , k_{iiq}) > 0$ – coefficient of the proportional and integral part of the current regulator on the axis (q).

For the electromagnetic subsystem (3.15) under the condition that the rotor flux vector is measured:

- Regulator of the flux module is represented in the equation (3.17)

$$\begin{aligned} \dot{x}_\psi &= k_{\psi i}\tilde{\psi}, \\ i_d^* &= \frac{1}{\alpha L_m}\left(\alpha\psi^* + \dot{\psi}^* - k_\psi\tilde{\psi} - x_\psi\right). \end{aligned} \tag{3.17}$$

- Regulator of the current vector of the stator current i_d

$$\begin{aligned} \dot{x}_d &= k_{iid}\tilde{\imath}_d, \\ v_d &= -k_{id1}\tilde{\imath}_d - x_d + \gamma i_d^* - \alpha\beta|\psi| + i_d^*. \end{aligned} \tag{3.18}$$

where $(k_\psi, k_{\psi i}) > 0$ – proportional and integral coefficient of the rotor flux regulator, $(\mathrm{k}_{id1}, \mathrm{k}_{iid}) > 0$ - proportional and integral coefficient of the current regulator on the axis (d) represented in the equation (3.18)

After substituting from (3.16) and (3.17), (3.18) in (3.14), (3.15), we have the dynamic equation of errors working out in the equation (3.19):

- Torque of the asynchronous motor

$$\begin{aligned} \tilde{T} &= \frac{3}{2}\frac{\mathrm{L_m}}{\mathrm{L_2}}\left(\psi^*\tilde{\imath}_q + \tilde{\psi}\tilde{\imath}_q + \tilde{\psi}i_q^*\right), \\ \dot{x}_q &= k_{iiq}\tilde{\imath}_q, \\ \dot{\tilde{\imath}}_q &= -k_{iq}\tilde{\imath}_q - x_q. \end{aligned} \tag{3.19}$$

- Module of Flux is written as:

$$\dot{x}_\psi = k_{\psi i}\tilde{\psi},$$
$$\dot{\tilde{\psi}} = -(\alpha + k_\psi)\tilde{\psi} - x_\psi + \alpha L_m \tilde{i}_d. \tag{3.20}$$

$$\dot{x}_d = k_{iid}\tilde{\imath}_d,$$
$$\dot{\tilde{\imath}}_d = -k_{id}\tilde{\imath}_d - x_d. \tag{3.21}$$

The two subsystems in the electromechanical subsystem (3.19) and electromagnetic (3.20), (3.21) are linear, fully decoupled, and asymptotically stable, so:

$$\lim_{t\to\infty} x_2 = \lim_{t\to\infty}\left(x_\psi, \tilde{\psi}, x_d, \tilde{i}_d\right)^T = 0, \tag{3.22}$$

$$\lim_{t\to\infty} x_1 = \lim_{t\to\infty}\left(x_q, \tilde{i}_q\right)^T = 0. \tag{3.23}$$

Combining conditions (3.22) and (3.23) we have from (3.19), that:

$$\lim_{t\to\infty}\tilde{T} = 0$$

exponentially going to zero. So, the task of working out the torque and the flux module of the asynchronous motor in condition of measuring the rotor flux vector is globally guaranteed. Note also, that the initial condition in system (3.19) – (3.21) usually occur due to the formation $\psi^* > 0$.

And from the equation (3.19) we have the condition as in equation (3.24):

$$\lim_{t\to\infty} T = T^*$$

if

$$\lim_{t\to\infty} x = 0 \tag{3.24}$$

where, $x = (x_1^T, x_2^T)^T$.

The global asymptotic stability of the algorithm gives us the possibility to pass from the non-linear control of measurable vector of state variables to the control by vector variables $y = (\theta, \omega, i_d, i_q)^T$. Then taking the non-measurable variables $|\psi|$, ψ_a, ψ_b in the control algorithm (3.8) – (3.10) and (3.13), (3.16) – (3.18) and changing them by $|\hat{\psi}|$, $\hat{\psi}_a, \hat{\psi}_b$ obtained from a non-linear asymptotic flux observer. Let's have a look to a simple rotor flux observer with equation in stator reference frame (a-b) as in equation (3.25).

$$\begin{aligned} \dot{\psi}_a &= -\alpha\psi_a - \omega\psi_b + \alpha L_m i_a, \\ \dot{\psi}_b &= -\alpha\psi_b + \omega\psi_a + \alpha L_m i_b. \end{aligned} \tag{3.25}$$

Let's suppose that the signals ω, i_a, i_b in (3.25) are limited, so the observer for the system (3.25) will be as in equation (3.26):

$$\begin{aligned} \dot{\hat{\psi}}_a &= -\alpha\hat{\psi}_a - \omega\hat{\psi}_b + \alpha L_m i_a, \\ \dot{\hat{\psi}}_b &= -\alpha\hat{\psi}_b + \omega\hat{\psi}_a + \alpha L_m i_b. \end{aligned} \tag{3.26}$$

The errors of observing the flux are represented in equation (3.27):

$$\tilde{\psi}_a = \psi_a - \hat{\psi}_a, \tilde{\psi}_b = \psi_b - \hat{\psi}_b \tag{3.27}$$

Their dynamics considering (3.25) and (3.26) is represented in (3.28):

$$\begin{aligned} \dot{\tilde{\psi}}_a &= -\alpha\tilde{\psi}_a - \omega\tilde{\psi}_b, \\ \dot{\tilde{\psi}}_b &= -\alpha\tilde{\psi}_b + \omega\tilde{\psi}_a. \end{aligned} \tag{3.28}$$

To analyze the stability of the system (3.27) let's use the Lyapunov function that is represented in equation (3.29):

$$V = \frac{1}{2}\left(\tilde{\psi}_a^2 + \tilde{\psi}_b^2\right) \tag{3.29}$$

The derivative with respect to (3.27) in the equation (3.30):

$$\dot{V} = -\alpha\left(\tilde{\psi}_a^2 + \tilde{\psi}_b^2\right) = -2\alpha V \tag{3.30}$$

From (3.28) and (3.29) the use of Lyapunov theorem tells us, that $\left(\tilde{\psi}_a, \tilde{\psi}_b\right)^T = 0$ is globally exponentially stable. Moreover, (3.29) give us a stricter form of the equation (3.31):

$$e_\psi(t) \leq \left\| e_\psi(0) \right\| e^{-\alpha t} \tag{3.31}$$

where

$$e_\psi = \left(\tilde{\psi}_a^2 + \tilde{\psi}_b^2\right)^{\frac{1}{2}}$$

So, the module of the error $e_\psi(t)$ exponentially goes to zero with a speed that is determined by the parameter α. If $e_\psi(0) = 0$, then $e_\psi(0) \equiv 0, \forall t \geq 0$.

To develop our vector control algorithm let's change in (3.3), (3.8) – (3.10) the real value of flux with the estimated values are represented in the equation (3.32).

$$\begin{aligned} \cos\varepsilon_0 &= \hat{\psi}_a \left|\hat{\psi}\right|^{-1}, \\ \sin\varepsilon_0 &= \hat{\psi}_b \left|\hat{\psi}\right|^{-1}. \end{aligned} \tag{3.32}$$

where $\left|\hat{\psi}\right| = \left(\hat{\psi}_a^2 + \hat{\psi}_b^2\right)^{\frac{1}{2}} > 0$.

The mathematical model of the asynchronous motor considering (3.7), and the equation of the observer (3.26) will be described as in the equation (3.33):

$$\begin{gathered} \dot{\theta} = \omega, \\ \dot{\omega} = J^{-1}(T - T_c), \\ T = \frac{3}{2}\frac{L_m}{L_2}\left(\psi_d i_q - \psi_q i_d\right), \\ i_d = -\gamma i_d + \alpha\beta\psi_d + \beta\omega\psi_q + v_d, \\ i_q = -\gamma i_q + \alpha\beta\psi_q - \beta\omega\psi_d + v_q, \\ \dot{\psi}_d = -\alpha\psi_d + (\omega_0 - \omega)\psi_q + \alpha L_m i_d, \\ \dot{\psi}_q = -\alpha\psi_q - (\omega_0 - \omega)\psi_d + \alpha L_m i_q, \\ \\ \left|\dot{\hat{\psi}}\right| = -\alpha\hat{\psi} + \alpha L_m i_d, \\ \dot{\varepsilon}_0 = \omega_0 = \omega + \alpha L_m i_q \left|\hat{\psi}\right|^{-1}. \end{gathered} \tag{3.33}$$

Let's replace in the torque control algorithm (3.13), (3.16) and flux control (3.17), (3.18) the real flux vector module $|\psi|$ with its estimated value $|\hat{\psi}|$, and the real error of the flux module $\tilde{\psi}$ with the error of working out of the estimated value of the flux $\tilde{\tilde{\psi}}$, that can be defined as in the equation (3.34):

$$\tilde{\tilde{\psi}} = |\hat{\psi}| - \psi^* \tag{3.34}$$

Asymptotically linearizing regulator in the equations (3.35-3.37):

$$\begin{pmatrix} u_a \\ u_b \end{pmatrix} = e^{J\varepsilon_0} \begin{pmatrix} u_d \\ u_q \end{pmatrix},$$
$$\begin{pmatrix} i_d \\ i_q \end{pmatrix} = e^{-J\varepsilon_0} \begin{pmatrix} i_a \\ i_b \end{pmatrix}',$$

$$e^{J\varepsilon_0} = \begin{bmatrix} \cos\varepsilon_0 & \sin\varepsilon_0 \\ -\sin\varepsilon_0 & \cos\varepsilon_0 \end{bmatrix}, \tag{3.35}$$

$$\begin{pmatrix} u_d \\ u_q \end{pmatrix} = \sigma \begin{pmatrix} -\omega_0 i_q + v_d \\ \omega_0 i_d + v_q \end{pmatrix}, \tag{3.36}$$

$$\dot{\varepsilon}_0 = \omega_0 = \omega + \alpha L_m i_q |\hat{\psi}|^{-1}. \tag{3.37}$$

Rotor flux observer is represented in the equation (3.38):

$$\begin{pmatrix} \cos\varepsilon_0 \\ \sin\varepsilon_0 \end{pmatrix} = \frac{1}{|\hat{\psi}|} \begin{pmatrix} \hat{\psi}_a \\ \hat{\psi}_b \end{pmatrix}, |\hat{\psi}(0)| > 0, |\hat{\psi}(0)| > 0, \tag{3.38}$$

$$\begin{aligned} \dot{\hat{\psi}}_a &= -\alpha\hat{\psi}_a - \omega\hat{\psi}_b + \alpha L_m i_a, \\ \dot{\hat{\psi}}_b &= -\alpha\hat{\psi}_b + \omega\hat{\psi}_a + \alpha L_m i_b. \end{aligned} \tag{3.39}$$

Algorithm of torque working out is represented in the equation (3.40):

$$i_q^* = (\mu_1 \psi^*)^{=1} T^*; \tag{3.40}$$

where $\mu_1 = 1.5L_m L_2^{-1}$.

Algorithm of current regulator on axis (q) in the equation (3.41 – 3.42):

$$\begin{gathered}\dot{x}_q = k_{iiq}\tilde{i}_q, \\ v_d = -k_{iq1}\tilde{i}_q - x_q + \gamma i_q^* + \beta\omega|\hat{\psi}| + i_q^*,\end{gathered} \tag{3.41}$$

$$i_q^* = \frac{1}{\mu_1}\left(\frac{\dot{T}^*}{\psi^*} - \frac{T^*\dot{\psi}^*}{\psi^{*2}}\right). \tag{3.42}$$

Algorithm of flux module regulator in the equation (3.43):

$$\begin{gathered}i_d^* = (\alpha L_m)^{-1}\left(\alpha\psi^* + \dot{\psi}^* - k_\psi\tilde{\tilde{\psi}} - x_\psi\right), \\ \dot{x}_\psi = k_{\psi i}\tilde{\tilde{\psi}}.\end{gathered} \tag{3.43}$$

Algorithm of current regulator on axis (d) in the equations (3.44 – 3.45):

$$\begin{gathered}\dot{x}_d = k_{iid}\tilde{i}_d, \\ v_d = -k_{id1}\tilde{i}_d - x_d + \gamma i_d^* - \alpha\beta|\hat{\psi}| + i_d^*,\end{gathered} \tag{3.44}$$

$$i_d^* = (\alpha L_m)^{-1}\left\{\alpha\dot{\psi}^* + \ddot{\psi}^* - \alpha L_m k_\psi \tilde{i}_d + \left[k_\psi(\alpha + k_\psi) - k_{\psi i}\right]\tilde{\tilde{\psi}} - k_\psi x_\psi\right\}. \tag{3.45}$$

On the figure 3.2 we can se the structural scheme of our control system.

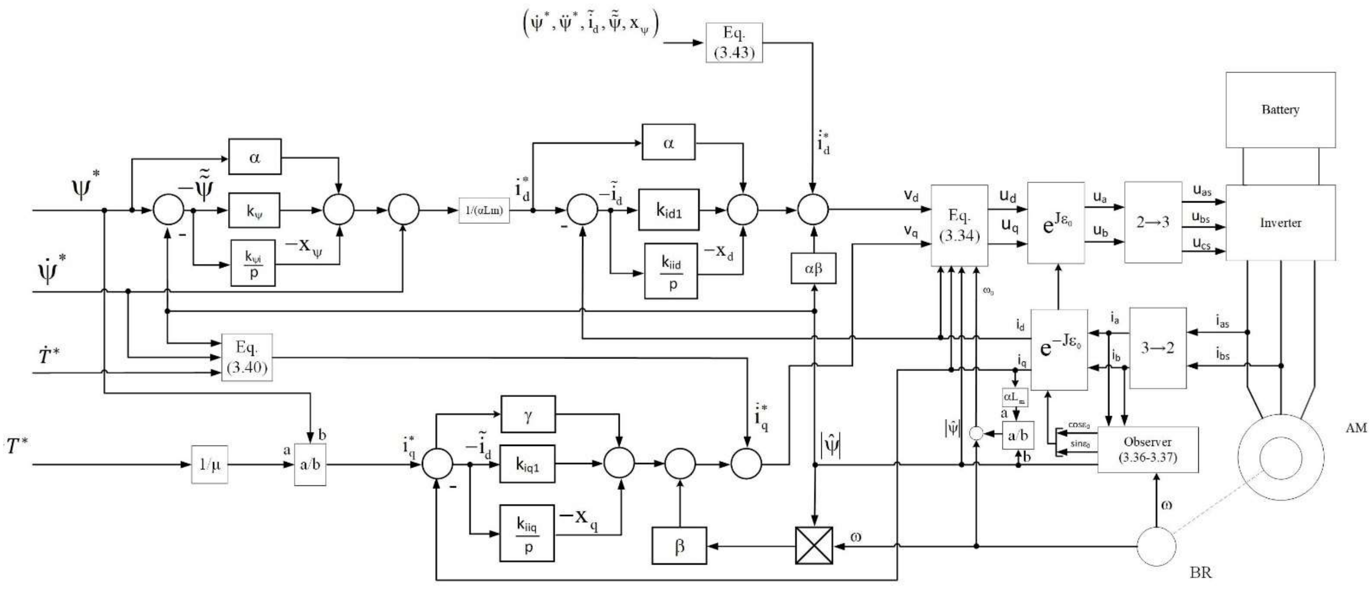

Figure 3.2: Structural scheme of the control system

4 Matlab simulation with various input tracks and analysis of results

Case 1: To ensure the operation of the DTC and flux control, it will be worked out a given trajectory of the torque, and a given trajectory of the flux. The time to reach nominal torque will be set as 0,5 s, and its nominal value will be acting for 2 s. The nominal torque was calculated previously in point 2.1 using the formula 2.20. Motor excitation is performed in the interval of time between 0 and 0.25 s.

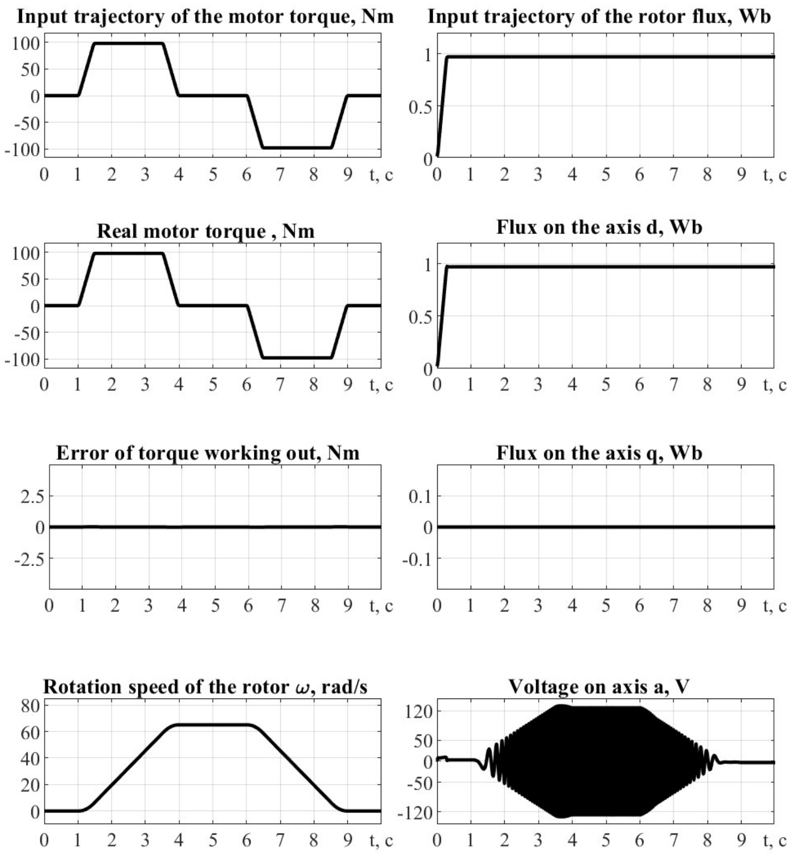

Figure 4.1: Transients in the first test

From the results shown on figure 4.1, several conclusions can be stated:

1) In this vector control system, the rotor flux on the axis q is equal to 0, so the condition $\lim_{t\to\infty}\psi_q = \lim_{t\to\infty}\tilde{\psi}_q = 0$ is maintained, as we can see from the graph on the figure 4.1;
2) The trajectory of the torque working out is free of dynamic error, because a compensation of input torque derivative is present in the system.

As a sum up of the first test – the algorithm of vector control work correctly.

Case 2: The motor was accelerated to a speed higher than the nominal speed. At a speed higher than the nominal one, the motor must work with constant power, so the torque must be limited (to avoid overheating) and weaken the flux (to avoid limitation of voltage). To realize a switch was introduced in the system, it will work when the nominal speed will be reached.

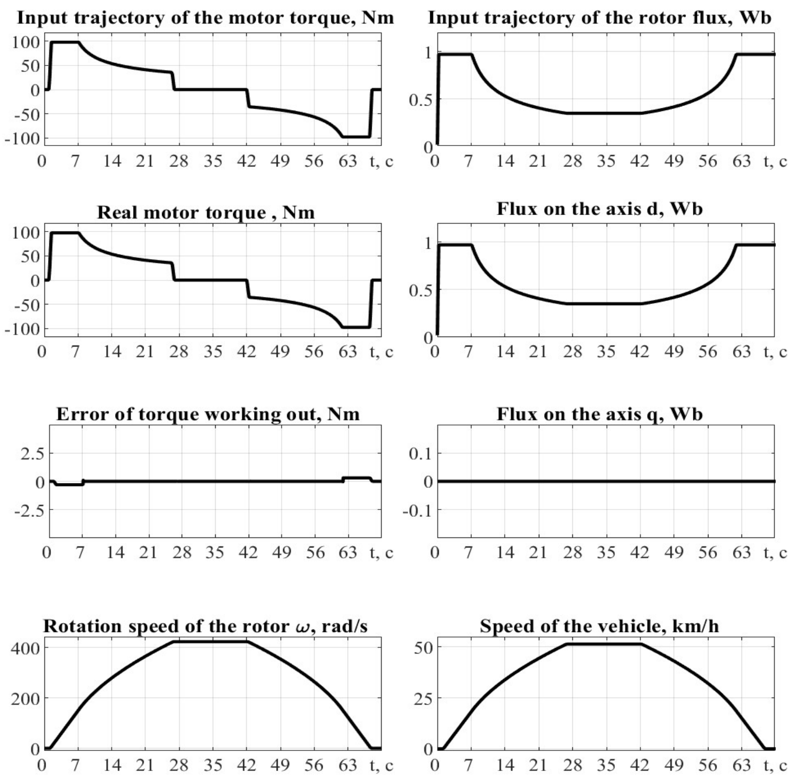

Figure 4.2: Transients in the second test

From the results shown on the figure 4.2, several conclusions can be stated:

1) When the motor reaches its nominal speed of 153 rad/s it activates the switch and a limitation is introduced in the system – the input flux and torque decrease inversely proportional to the speed. So, the motor starts working in the second zone with constant power.
2) It is present a small dynamic error in the torque working out, approximately 0.2 Nm, it is present because we are limiting only the torque and not limiting the derivative.

Case 3: Now it is possible to model the real working cycle from the previously obtained trajectory of the vehicle. Then the results will be analyzed, and an evaluation of the system will be performed.

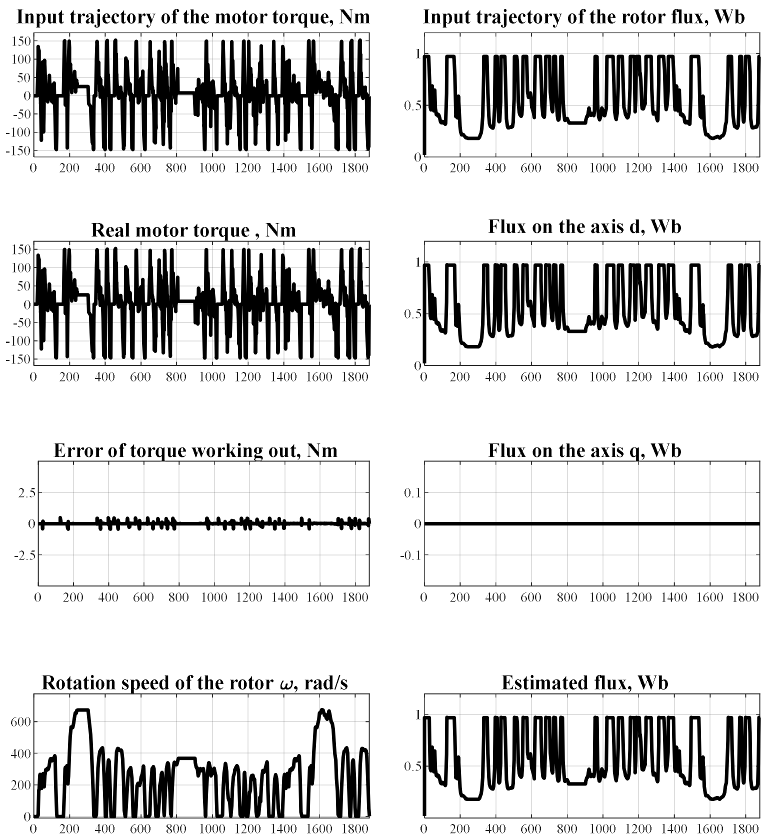

Figure 4.3: Transients in the third test

From the results shown on figure 4.3 several conclusions can be made:

1) In this vector control system, the rotor flux on the axis q is equal to 0, so the condition $\lim_{t\to\infty}\psi_q = \lim_{t\to\infty}\tilde{\psi}_q = 0$ is maintained, as we can see from the graph on the figure 4.3;
2) The torque is worked out with a high precision.
3) The trajectory of motion coincides with the previously obtained in the paragraph 2.1.

Now it is possible to calculate the energy consumed by the vehicle in this cycle. The result is shown on the figure 4.4.

In the following cycle the total consumed energy reach 12.7806, so we can calculate the maximum distance that our vehicle can travel using the following equation (4.1):

$$S_{max} = \frac{W_{250} \cdot S_t}{W_t} = \frac{252 \cdot 18.08}{12.7806} = 356.40\ km \tag{4.1}$$

The figure 4.4 show us the consumed energy on the cycle.

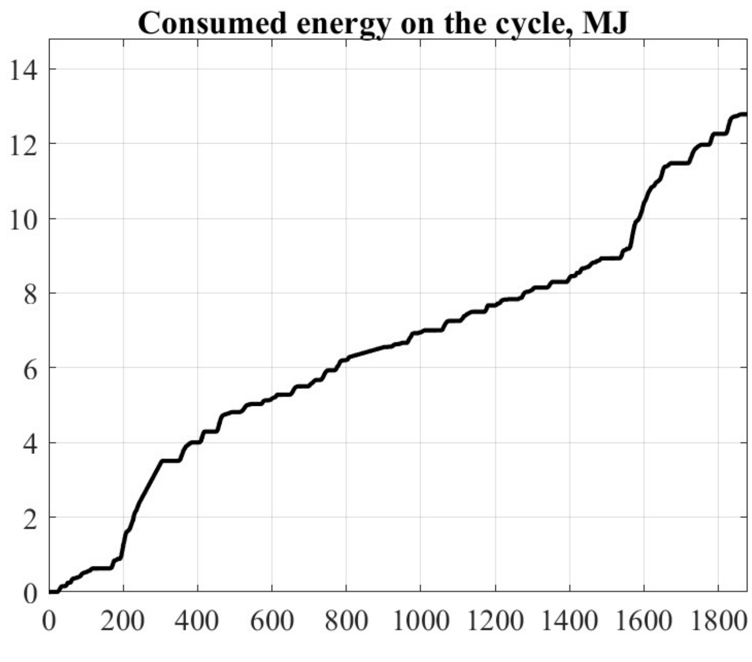

Figure 4.4: Consumed energy during the cycle

5 Functional scheme and economical calculation

5.1. Calculation and selection of main components

The figure 5.1 is showing the functional scheme of an electric drive.

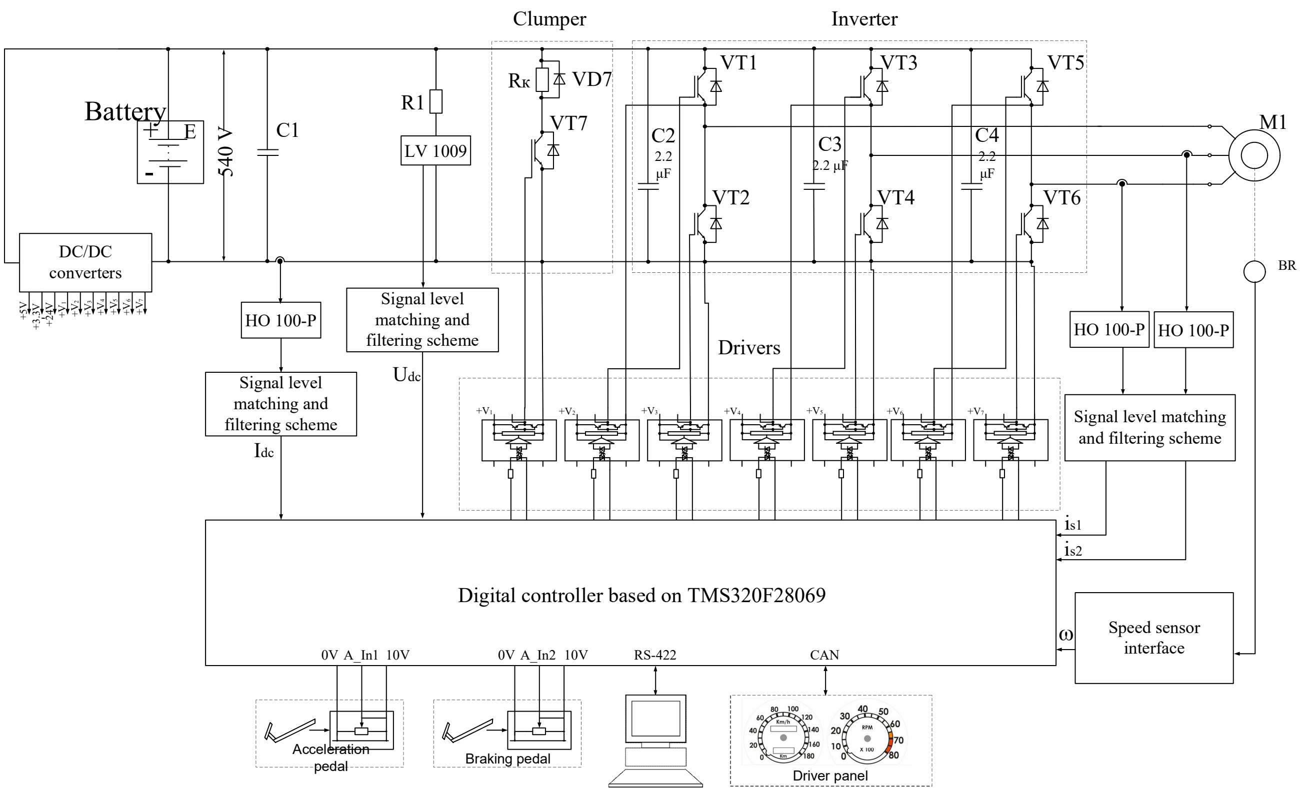

Figure 5.1: Functional scheme of the electric drive

From previous calculation we know that the amplitude value of the stator current is equal to 45 A. And considering an overload capability of the drive of our electric vehicle of $k_{ovl} = 2$, we can calculate the maximum current on the exit of our inverter as in the equation (5.1):

$$I_{max} = k_{ovl} \cdot I_{1na} = 2 \cdot 45 = 90\ A \tag{5.1}$$

While choosing IGBT their maximum U_{CE} must be 1.5 higher than the maximum voltage in the DC part and can be calculated as in the equation (5.2). The maximum voltage in the DC part of our vehicle is limited by the maximum Voltage of the battery, that is equal to 540 V.

$$U_{CE} = 1.5 \cdot 540 = 810\ V \tag{5.2}$$

The selection of IGBT will be performed using the following parameters. As in equation (5.3) and (5.4)

$$U_{CEmax} > U_{CE} \tag{5.3}$$

$$I_C > I_{max} \tag{5.4}$$

From the catalogue we can choose the following IGBT module SEMiX106GD12T4p, with the following parameters:

$$U_{CE} = 1200\ V, I_C = 100\ A$$

The main difference in the selection of capacitors for industrial converters and for electric vehicle is that the selection of the capacitors for electric vehicles is based on the current consumed by the battery and not on the pulsation of voltage [34]. Based on those considerations were chosen a capacitor B32678 with parameters: 120 μF and maximum pulsing current 90A.

With orientation on Idc a current sensor HO 100-P, with nominal current 100 A, and with a range of measurement of 250 A was chosen.

To measure the speed of rotation of the motor will be used an encoder H20DB-37.

For processing input signals from sensors and further forming control signals on IGBT, standing to the algorithm, a microcontroller is needed. For those purposes the TMS320F28069 is chosen. The scheme of the microcontroller is shown on the figure 5.2.

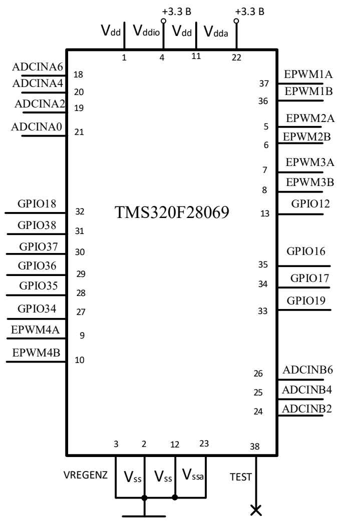

Figure 5.2: Scheme of microcontroller TMS320F28069

5.2. Calculation and selection of main components

To calculate the cost of our modernization we need to evaluate the value of components that were chosen before, they are shown on the table 5.1.

Table 5.1: Components of the electric vehicle

Component	Quantity	Value
IGBT module		
SEMiX106GD12T4p [35]	1	**100 €**
Capacitor		
B32678 [36]	1	**15 €**

Current sensor		
HO 100-P [37]	3	**51 €**
Voltage sensor		
LV 1009 [38]	1	**64 €**
Encoder		
H20DB-37 [39]	1	**400 €**
Microcontroller		
TMS320F28069 [40]	1	**300 €**
Battery		
L135F72	338	**14 000 €**
AC Motor		
Marelli 200LA2	1	**1000 €**
Total value		**15 970 €**

After calculating the value of our components, we need to determine the duration of payback of our modernization. To do this, we must calculate the operating costs of a standard Iveco Daily with an internal combustion motor and compare them with the one that mount an electric motor. Considering the cost of gasoline that is around 1,65 € [41], taking into account the medium consumption of fuel on 100 km, that is near to 15 l, and the cost of a new Iveco Daily – near to 32 000 € [42]. The calculation will be performed in a time period of 10 year. In order to calculate the cost of operating the vehicle with an electric motor we will use the cost of 1kW*h, that is around 0.18 € for business [43], the consumption of electric energy in medium per day is 26kW*h. Another important cost for the calculation is the cost of 1km travelled by the vehicle, it includes the costs of maintenance, tires, repairs. For an electric vehicle it is about 0,31 € and for an ICE is higher and it is equal to 0,4 €. The graph with the operating costs of two type of Iveco Daily is shown on figure 5.6.

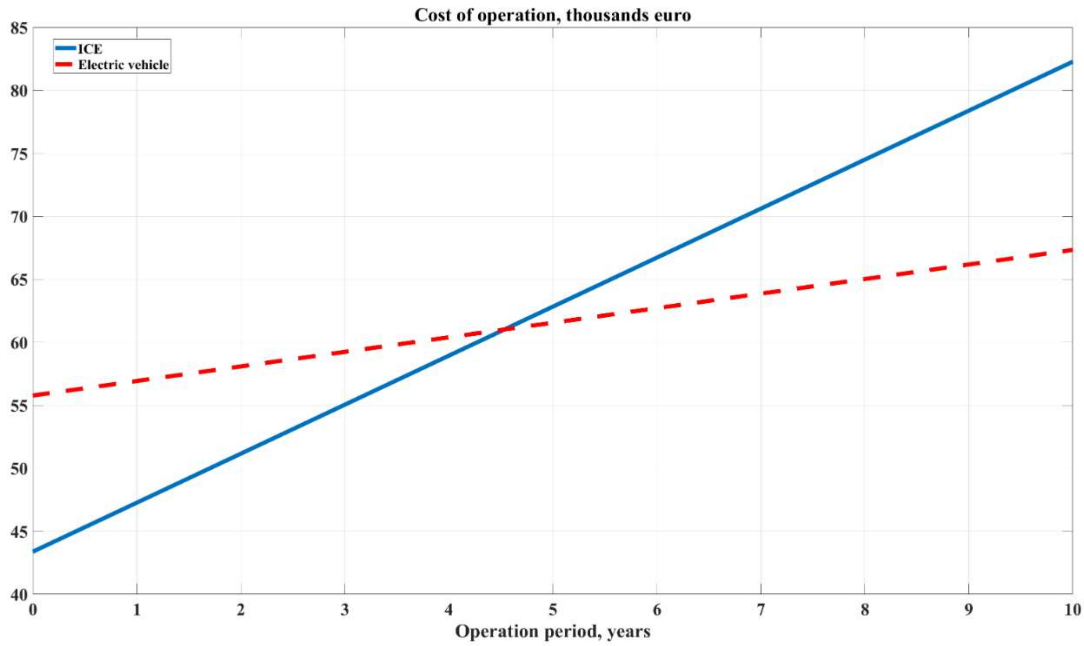

Figure 5.3: Operational costs of two types of vehicle

Analyzing the graph of operation of our vehicle with ICE and with an electric motor it is easy to see, that at a first time the cost of a model with an electric engine is higher than the one with ICE more than 1.5 times. The reason is that the vehicle with an electric engine contains in its value the cost of the standard model vehicle and the value of components used for the modernization. The steep increase in the operating cost of the ICE variant is connected to the high value of fuel and to the consumption of the last, but not only, also the maintenance cost plays a big role in the cost of operating the ICE variant.

A conclusion can be made from the graph – the operating cost of the electric model reach the cost of operating of the ICE model in 4.5 years.

6 Conclusion and future development

In this thesis work was developed an electromechanical system of an electric vehicle based on the chassis of Iveco Daily. As a motor was used an asynchronous motor (because of its reliability and energy efficiency).

After the calculation of the power needed for our cycle it was selected a motor of Italian production - Marelli 200LA2. Also using the experimental cycle, it was obtained that we need a battery of $W_{250} = 252\ MJ$ to travel 250 km.

To control the torque of our electric motor, it was developed an DTC algorithm. Using mathematical modelling it was checked the working capability of our model, reliability, precision. The result of modelling shown us, that the system works out perfectly our trajectory. Because of the speed going moreover the nominal one, a flux weakening is provided in our system. The decreasing of the flux is provided proportionally to the increase of the speed.

As a last part of the work, it was calculated the main parameters of the power part and the controller. Economical calculation was performed to argument that a modification like this can be useful and economically reasonable in the real world. As we can see in 4.5 year our modification can fully reach the cost of using a standard ICE vehicle.

As a future development it can be substituted the asynchronous motor with other type of motors and maybe another battery cell type can be used.

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Variable	Description	SI unit
θ	Angular position of the rotor	rad
ω_n	Nominal angular speed of the motor	rad/s
ω	Angular speed of the rotor	rad/s
T	Torque of the rotor	Nm
T^*	Input torque of the rotor	Nm
$\tilde{T}$	Error of torque working out	Nm
T_c	Static torque	Nm
T_e	Equivalent torque	Nm
D	Weakening coefficient	
$\lvert\psi\rvert$	Module of rotor flux	Wb
$\lvert\hat{\psi}\rvert$	Estimated rotor flux	Wb
$\tilde{\psi}$	Error of rotor flux working out	Wb
R_S	Stator Resistance	Ohm
$R`_r$	Rotor Resistance	Ohm
L_S	Stator Inductance	H
L_r	Rotor Inductance	H

L_m	Mutual inductance	H
p_n	Number of pole pairs	Qt
$\left(i_d^*, i_q^*\right)$	Input currents on axis d and q	A
(k_{id1}, k_{iid})	Proportional and integral part of current regulator on axis d	
(k_{iq1}, k_{iiq})	Proportional and integral part of current regulator on axis q	
$(k_{\psi}, k_{\psi i})$	Proportional and integral part of flux regulator	
Ih	Battery charge	$A \cdot h$
A_f	Vehicle frontal area	m^2
C_w	Aerodynamical coefficient	
ξ	Air flow rate	
f_r	Friction coefficient on asphalt	
P_{2n}	Nominal power of the motor	kW
λ	Overload capacity	
I_{1na}	Nominal current of the motor	A
η	Motor efficiency	%
J_m	Motor inertia	$kg \cdot m^2$