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Electronics, Telecommunications, and Information Technology

PhD THESIS

– Abstract –

Theoretical And Experimental Research Of The Propulsion System For An Electric Vehicle

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– Cluj-Napoca –
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2. Motivation

Over time, the number of personal vehicles has grown considerably, currently there are more than two billion vehicles in use around the globe [1]. The most used vehicles, both for personal use and for the transport of goods, are those with a thermal engine, using fossil fuels.

The use of vehicles with a thermal engine causes the generation and release of toxic substances into the air, which are harmful to both human health and the environment [2]. Along with the increase in the number of vehicles, the amount of toxic substances released into the air also increased [3]. Currently, urban areas present high air pollution, due to the use of many vehicles with thermal engines [4]. The presence of harmful substances in the air, also known as greenhouse gases, causes the phenomenon of global warming [2][5][6].

In addition to the problems of air pollution and global warming, the increasing amount of fuels required in the transport sector raises questions about the existing oil resources, which are decreasing, causing prices to rise [2].

All the problems generated by the thermal engine vehicles determined the search for alternative solutions for the transport sector. Thus, an option for transport, which would reduce both the emission of greenhouse gases and the consumption of fossil fuels, is the use of electric vehicles [5][6].

Currently, the use of electric vehicles is no longer a futuristic concept, they are already used in everyday life. However, the purchase price of an electric vehicle, as well as its disadvantages, compared to the classic vehicle with a thermal engine, causes people to be sceptical about buying and using electric vehicles [2][7][8][9].

The main problems of the electric vehicle are the autonomy of the battery and its recharging [7][10]. The time between two charges should be as long as possible, and the charging time as short as possible [7][11]. Thus, the study and use of electric vehicles are subjects of great interest for the automotive industry, first, and then, for users, to determine the full use of electric vehicles, to the detriment of vehicles with a thermal engine.

In this paper entitled "Theoretical And Experimental Research Of The Propulsion System Of An Electric Vehicle", a theoretical study, the implementation and testing of the propulsion system of an electric vehicle was conducted, to identify existing problems and propose solutions.

3. Objectives

This work proposes a theoretical study, modelling, experimental implementation and testing of an electric propulsion system, a system used in an electric vehicle. The main objective of the paper is to determine the existing problems within such a system and to propose some solutions, which will increase the efficiency of the entire system, a reduction in dimensions and costs. All these lead to the development of a compact, low-cost system that would encourage users to purchase such a vehicle.

The main objective was divided into three other objectives:

- making an electric machine control system
- creating an energy storage system
- connect the two subsystems, to build a complete electric propulsion system.

The electric motor and the energy storage system are the main elements of an electric propulsion system. The most efficient implementation of these two elements leads to the efficient implementation of the entire system.

4. Methodology

To achieve the proposed objectives, a research methodology was established, which includes four stages:

- **Documentation And Theoretical Study**

In the first phase, a documentation of the field was carried out, which allowed to create an overview of the electric propulsion system and the elements developed up to this moment. Numerous scientific articles were studied with general information about electric vehicles, then about the electric propulsion system, and, finally, articles about electric machines and their control, respectively specialized books (presented in the Bibliography section of the paper), which describe operation of electric machines and their control; to the same extent, a study of battery types and how to implement a battery pack management system was carried out. This process of study and documentation was carried out continuously during the entire PhD period to always be in contact with the problems under research and with the results obtained. Also, to preserve the degree of novelty of the study, it was considered necessary to know the results already presented in other studies.

- **Research**

- Mathematical Modelling

After the initial documentation of the research field and the identification of the problems that were addressed, the mathematical modelling of the subsystems (that of the electric machine control, respectively that of the energy storage) was carried out to understand better their operation, but also to observe all aspects that influence their behaviour. To work efficiently and quickly, specialised modelling software programmes were used. MATLAB was the main programme used, but Mathcad was also used. The two software programmes provide an easy and reliable way to mathematically model a system.

- Simulation

After the mathematical modelling, the implementation at the simulation level of the systems was carried out, to verify their correct operation, but also to obtain some preliminary results of the proposed implementation methods. Besides, by using simulations, several checks were carried out in a simple, quick way and at a low cost. To simulate the systems proposed in this paper, the following specialised software programmes were used for simulation: PSIM and Simulink MATLAB.

- Experimental Implementation

The electric propulsion system proposed for this study includes the two subsystems, the electric machine control system, and the energy storage system. For both systems, the aspects of interest are the electric machine control, respectively, the management of the energy storage system, and for the entire system, the interaction between the two subsystems is important. Thus, most of the implementation involves the development of several algorithms, for the control of the electric machine, for the management system of the battery, respectively, for the optimal connection of the two subsystems and obtaining a series of results necessary to verify the reliability of the algorithms.

After carrying out the implementations at the simulation level, we moved on to the practical implementation of the system. HIL (hardware in the loop) tests were initially performed using a dSPACE platform. The use of a dSPACE development platform allows a rapid deployment of the system for testing, making it much easier and faster to obtain results that illustrate the system's performance.

- Testing And Validation

The research activity was completed by testing the proposed subsystems, but also the fully implemented system. Each subsystem was tested individually, and in the end, the complete system was tested.

- **Dissemination**

The results obtained from the research were disseminated during the entire period of the doctoral internship by participating in four specialised international conferences and publishing an article in a specialised journal(Q2), all articles being indexed WOS.

5. Thesis Structure

This paper is divided into two main parts: State Of The Art (chapters 1 and 2) and Personal Contributions (chapters 3 – 7).

5.1.State Of The Art

The first part presents the main theoretical elements, currently known, about the addressed subject.

5.1.1. Introduction

Chapter 1, entitled "Introduction", includes general notions about the electric vehicle, a brief history of its appearance and development, the structure of the vehicle (considering the main elements of the electric propulsion system), as well as the types of electric vehicles existing at this time.

5.1.2. Theoretical Fundaments

Chapter 2 represents the "Theoretical Fundaments" of the elements that are presented in detail in the personal contributions section. From the two main elements of the propulsion system (the electric machine and the energy storage system), a study of the two main elements was conducted, considering the solutions existing on the market at this time, the most efficient variants were chosen for the implementation, and are presented in detail in the following chapters.

5.2. Personal Contributions

The second part includes the personal contributions developed during the PhD period. Each element of the propulsion system was studied, analysed, and then implementations were carried out at the simulation level, but also practical implementations of the elements. The operation of the electric machine and its control was the first topic covered. The induction machine and the permanent magnet synchronous machine were studied, respectively, the methods to implement Field-Oriented control for each type of motor. The second topic was the energy storage system, more specifically the battery pack and its management system.

5.2.1. Induction Machine And Its Control

Chapter 3 of the PhD thesis is entitled "The Induction Machine And Its Control" and includes the theoretical study of the operation of the machine and Field-Oriented control of this type of motor.

The induction machine with shorted end rings, also known in the specialized literature as the squirrel cage induction machine, is the most used type of motor because it has a robust construction and a low cost [12].

The operation of this machine is based on the principle of electromagnetic induction. The injection of a three-phase current into the stator windings causes a magnetic field to be generated in the air gap of the motor. The generated magnetic field is sinusoidal and has a frequency equal to that of the injected current, called the synchronous frequency. The generated magnetic field induces a voltage in the rotor, which will cause a current to appear in the short-circuited windings of the rotor. The induced current in the rotor circuit causes a magneto-motive force, which sets the rotor motion in the same direction as the rotating magnetic field. The interaction between the magnetic field generated by the stator and the magneto-motive force determined by the rotor produces the motor torque [12][13].

Field-Oriented or vector control involves an induction machine operating like a separately excited DC motor [12].

In the case of indirect Field-Oriented control, the synchronous rotation angle is calculated based on the sliding pulsation [4], using relation (1):

$$\theta_e = \int \omega_e dt = \int (\omega_{slip} + \omega_r) dt \qquad (1)$$

Indirect vector control is efficient because it ensures the decoupling of flux and torque, the two quantities being each independently controlled, the torque through the current i_q and the flux through the current i_d, according to the relations (5) and (6):

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\frac{L_m}{L_r}\hat{\Psi}_r i_{qs} \qquad (5)$$

$$\hat{\Psi}_r = L_m i_{ds} \qquad (6)$$

Based on the relationships presented previously, the implementation of a vector control for an induction machine can be realised. In Fig. 1 shows the implementation of a vector control system for an induction machine.

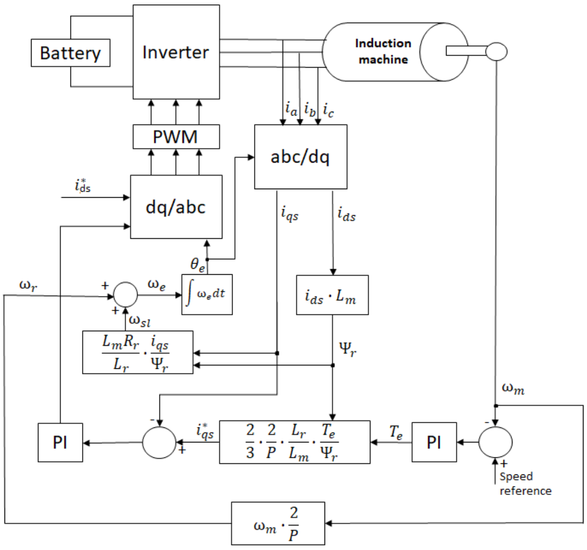


Figure 1. Vector control system of an asynchronous induction machine

Starting from the block diagram in Fig.1 of the vector control system for the motor asynchronously with induction, initially a simulation was developed within Simulink, according to Fig.2.

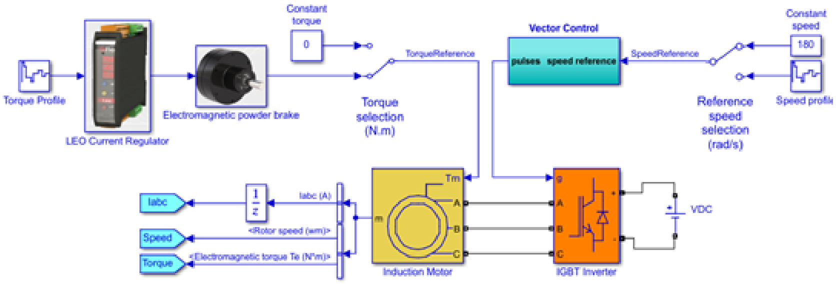


Figure 2.Vector Control System of Induction Motor in Simulink

As well as the implementation at the simulation level, the practical implementation of a small electric propulsion system was also carried out. The system comprises the Lesson 1/3HP, 3450 rpm induction machine, a Danfoss inverter, an EA-PSI 81000-300 power supply, three Lem-HLSR-10-P Hall effect current sensors, a rotary encoder, the electromagnetic powder brake B53, the Leo current regulator, plus the dSPACE MicroLabBox platform, which includes a DS1202 basic computing unit and a DS1302 I/O ports unit. In Fig. 3 shows the block diagram of the vector control system for the induction machine using the dSPACE platform.

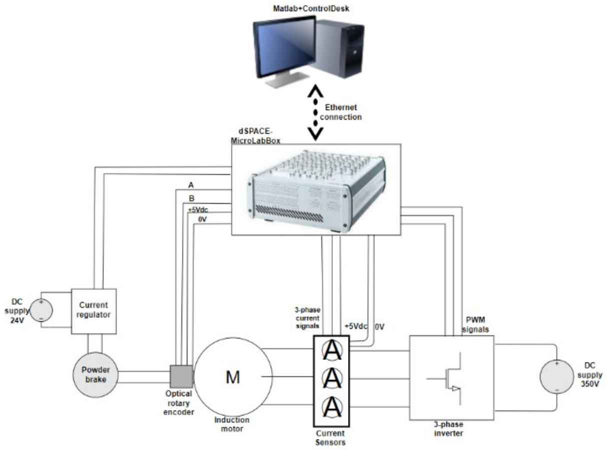


Figure 3. Block diagram of practical vector control system for induction machine

In Fig. 4 and Fig. 5 the practical elements of the small electric propulsion system are presented.

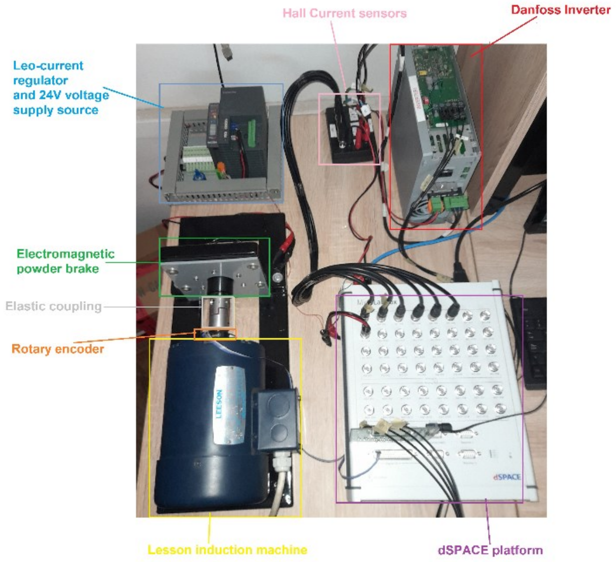


Figure 4. The practical elements of the experimental system

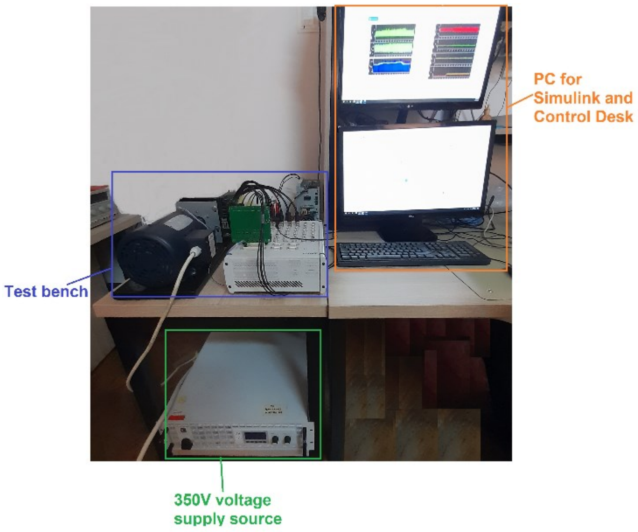
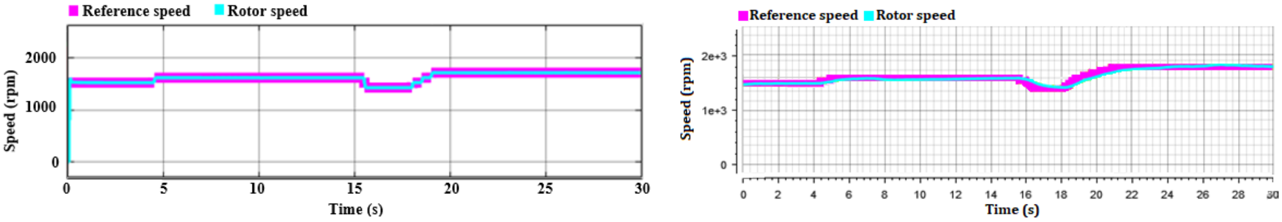


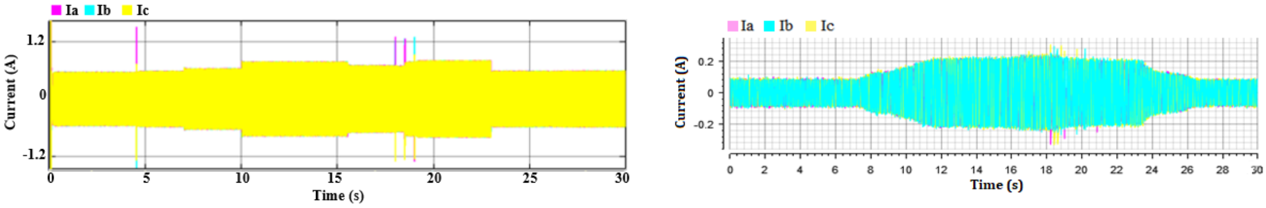
Figure 5.Experimental vector control system

Using the two implementations, practical and simulated, a series of tests were carried out to verify the correct functioning of both the simulated and the practical system. Several scenarios were tested with variations in reference speed and load torque. Next, some of the obtained results are presented:



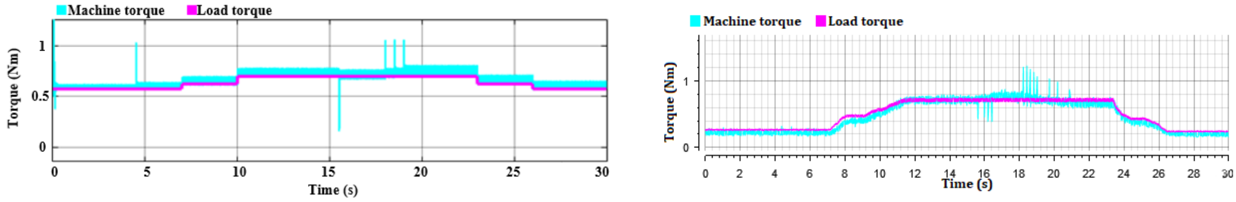
(a) (b)

Figure 6. Motor speed and set speed (a – simulation, b – experimental)



(a) (b)

Figure 7. Stator current (a – simulation, b- experimental)



(a) (b)

Figure 8. Motor torque and load torque (a - simulation, b – experimental)

This chapter covered the study and modelling of the induction machine, the implementation of an indirect vector control for an induction machine, and an electric propulsion system. This system comprises an induction motor, an inverter, an electromagnetic powder brake, a power supply, current and speed sensors, plus an indirect vector control block. The proposed system was tested for both speed variations and load torque variations. The results were obtained validate the proper operation of the control block.

5.2.2. Adaptive Cruise Control In Electric Vehicle With Field-Oriented Control

Chapter 4 of the PhD thesis is entitled "Adaptive Cruise Control Within The Electric Vehicle Using Vector Control" and includes the theoretical study of an Adaptive Cruise Control type system and its adaptation in the case of an electric vehicle.

The Cruise Control type system, popularly known as the tempomat system, allows the driver to set a driving speed, and the system ensures driving at that speed, without the driver having to press the accelerator pedal. However, the driver must remain alert to apply the brakes in case of need [14][15][16].

An improved version of the Cruise Control system is the Adaptive Cruise Control (ACC) system. The Adaptive Cruise Control system acts, not only on the acceleration of the vehicle, to maintain the speed set by the driver, but also to brake the vehicle, ensuring a safe distance from the vehicle in front [17][18].

These systems were created for vehicles with a thermal engine, in which case the throttle had to be controlled, which provides the necessary acceleration. Fig. 9 shows the block diagram of a vehicle with a thermal engine and ACC type system. However, in the case of electric vehicles, the throttle, respectively throttle control, are no longer present, so ADAS-type systems must be adapted to be used in the case of electric vehicles as well. Fig. 10 shows the block diagram of an electric vehicle with an ACC type system.

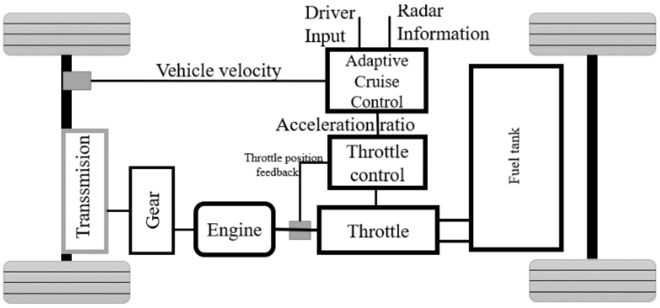


Figure 9. Vehicle with thermal engine with ACC type system

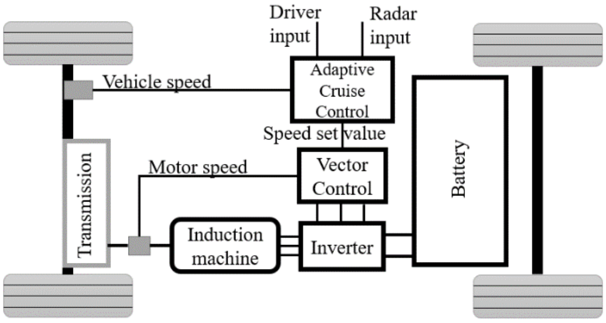


Figure 10. Electric vehicle with ACC type system

In the case of electric vehicles, the Adaptive Cruise Control system must work in conjunction with the electric motor control unit. For integrating the ACC block in an electric vehicle, a cascade control system was proposed, that is, the ACC block performs a closed-loop control, based on the value set by the driver and the measured values, current speed, and relative distance, plus the speed of the tracked vehicle . The signal generated by the ACC block is used as a reference signal for the vector control block, which has as measured values the motor speed and the value of the current through the motor, plus the variation of the motor load torque. Thus, the cascade structure is achieved, having two control loops: the outer loop including the ACC block and the inner loop with the vector control block [19]. Fig. 11 shows the control of an electric vehicle comprising the ACC block and the vector control block.

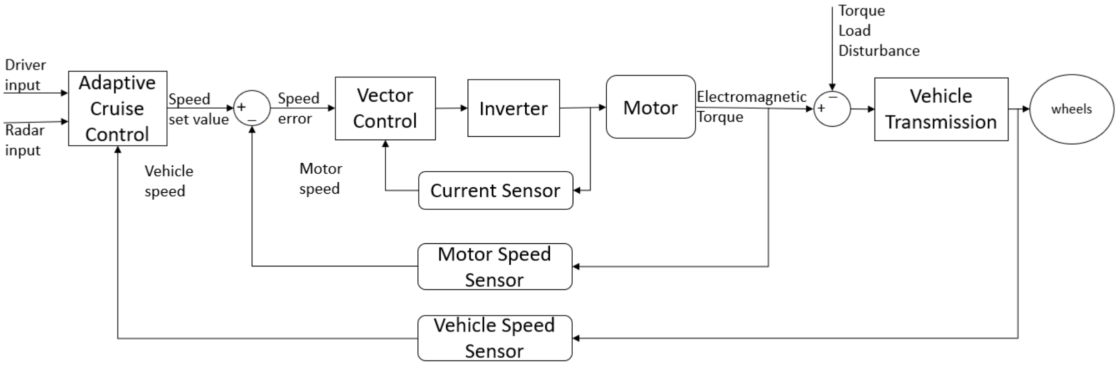


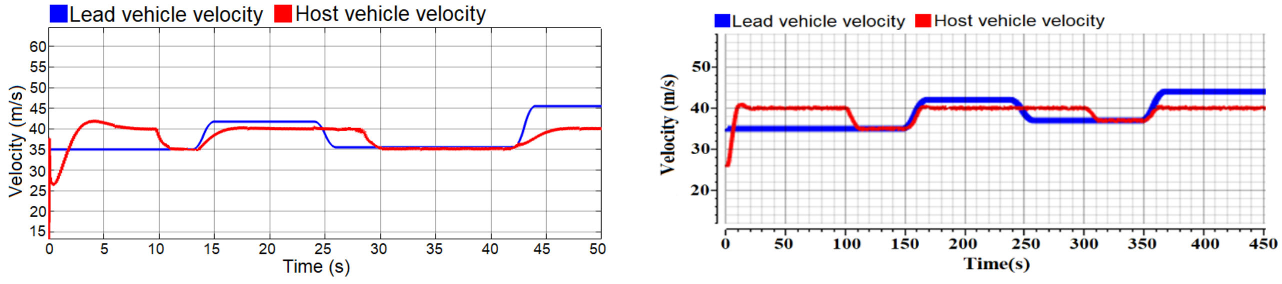
Figure 11. Cascade control for an electric vehicle with ACC type system

Using the vector control system of the induction machine, presented in chapter 3 of the paper, the cascade control structure was made, including the vector control of an induction machine and an ACC type system.

Both at the simulation level and at the practical level, the changes made to the system presented in the previous chapter were only at the control level. It was added an ACC type block and modelled a vehicle that can appear in front of the host vehicle to test safe distance control as well.

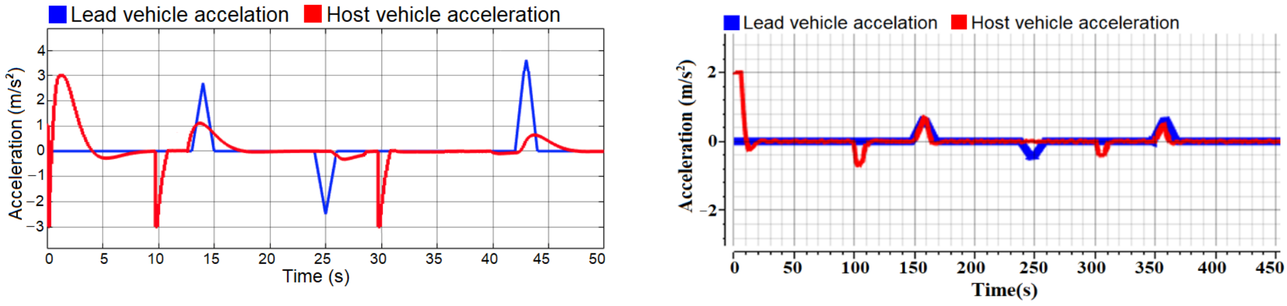
Both simulation-level and practical implementations were used to test and analyse the operation of the ACC block within the electric propulsion system.

For the tests carried out, the speed of the host vehicle was set to 40m/s, so the ACC block generates the required acceleration/deceleration. If no vehicle is detected, the vehicle must run at a set speed regardless of the motor load torque value. In the first part of the scenario, the speed of the tracked vehicle is 35m/s, then the speed increases to 42m/s, then decreases to a value of 36m/s, and finally the speed increases to a value of 45m/s. For each duration that the tracked vehicle has a speed lower than 40m/s, the host vehicle approaches the tracked vehicle, so the ACC block must adjust the speed to maintain a safe distance between the two vehicles. The results obtained from the test are presented below:



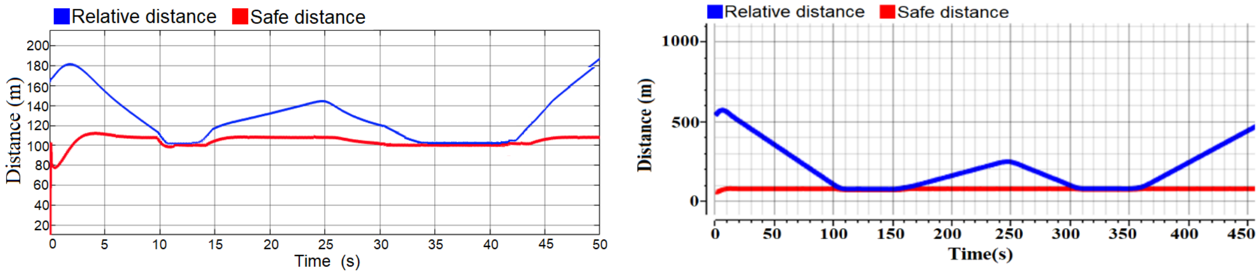
(a) (b)

Figure 12. The speed of the host vehicle and the leading vehicle (a – simulation, b – experimental)



(a) (b)

Figure 13. The acceleration of the host vehicle and the leading vehicle (a – simulation, b – experimental)



(a) (b)

Figure 14. Relative distance between the vehicles and the safe distance (a – simulation, b – experimental)

This chapter presents the concept of an Adaptive Cruise Control system within an electric propulsion system, which includes an electric induction machine, controlled using of an indirect vector control.

The results obtained from the simulation of the system, as well as the experimental results presented, illustrate the proper operation of the system, both when operating in the speed control mode and in the distance control mode, keeping a safe distance from another vehicle present in the face. Thus, it can be stated that an Adaptive Cruise Control type system can be installed and function properly in an electric vehicle, just as in the case of a vehicle with a thermal engine.

5.2.3. Permanent Magnet Synchronous Machine And Its Control

Chapter 5 of the paper is entitled "The Permanent Magnet Machine And Its Control" and includes the theoretical study of the operation of the machine and the vector control of this type of machine.

The synchronous machine is part of the category of AC machines, like the asynchronous machine. Compared to an asynchronous machine, the rotor of the synchronous machine rotates at a speed equal to the synchronous speed corresponding to the frequency of the supply voltage, hence the name synchronous motor [12].

The stator of the synchronous machine has the same construction as the stator of the asynchronous machine: it has three windings, arranged at 120^o from each other, generating a rotating magnetic field [19]. The rotor, however, is different from the asynchronous machine rotor because in a synchronous motor the rotor comprises an electromagnet, which requires a secondary power supply, or comprises permanent magnets [13].

The torque of the synchronous machine is proportional to the product of the amplitude of the flux in the stator and the flux in the rotor and the sine of the angle between the two vectors. The magnetic field generated by the rotor is constant, generated by a direct current or a permanent magnet, and the magnetic field generated by the stator is variable and rotates at synchronous speed. The magnetic field in the rotor aligns with the variable magnetic field generated by the stator and follows its rotational motion, therefore the rotor moves at a speed equal to the synchronous speed [13].

As with the induction machine, vector control ensures high efficiency in the permanent magnet synchronous machine as well.

Vector control of a permanent magnet synchronous machine is like that of an induction machine, but the following points should be considered:

- The slip frequency, ω_{slip}, is zero because the synchronous motor always runs at a synchronous speed;
- The permanent magnets ensure magnetic flux, therefore, the i_d current reference value is set to the value 0;
- The synchronous command frequency is determined using an encoder attached to the motor shaft;
- The control loop implementation does not depend on the machine parameters [12].

Keeping the current reference i_d at zero and the current reference i_q calculated on the basis of relation (40), three implementation variants of a vector control block for a permanent magnet synchronous machine [112] can be developed, shown în Fig. 15, Fig. 16, and Fig. 17.

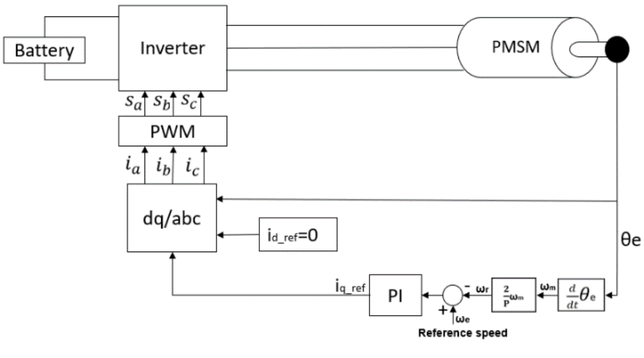


Figure 15. Vector control of a permanent magnet synchronous machine with open loop control i_d and i_q currents

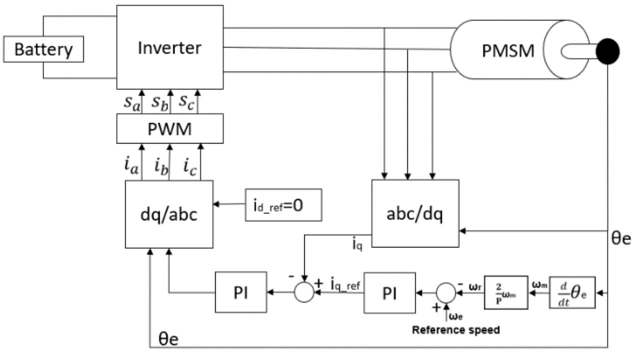


Figure 16. Vector control of a permanent magnet synchronous machine with open loop control for i_d current and close loop control for i_q current

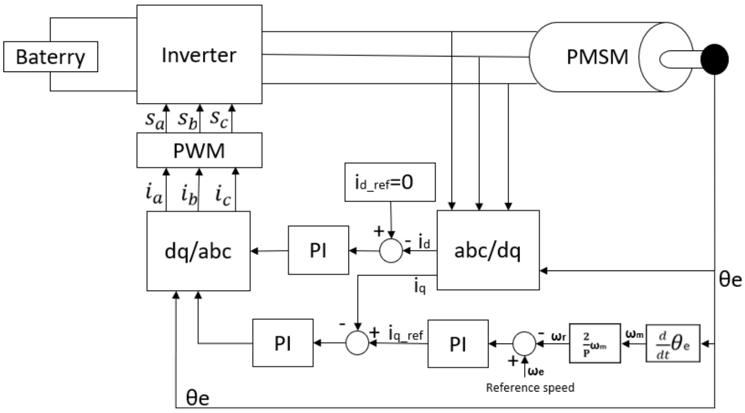


Figure 17. Vector control of a permanent magnet synchronous machine with close loop control i_d and i_q currents

Starting from the system shown in Fig. 15, 16 and 17, a simulation-level implementation was carried out within Simulink, presented in Fig. 18.

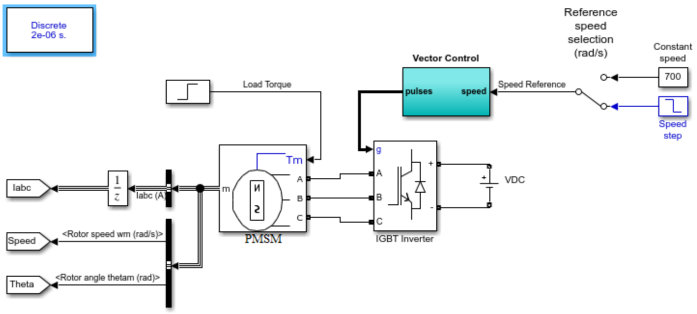


Figure 18. Vector control system of a permanent magnet synchronous machine implemented în Simulink

The system developed within the simulation allowed the testing of the three implementation variants of the vector control block, presented in Fig. 15, 16 and 17.

The practical implementation of a small electric drive system comprising a permanent magnet synchronous machine and vector control was realized using the DMB0224C10002 permanent magnet synchronous machine, a power supply, an inverter, Hall position sensors, an optical encoder rotary, Hall current sensors, the dSPACE platform and a computer to implement the application, more precisely the control block, required for the dSPACE platform. Fig. 19 and Fig. 20 illustrate a block diagram of the practically implemented system, respectively, the practical elements of the system.

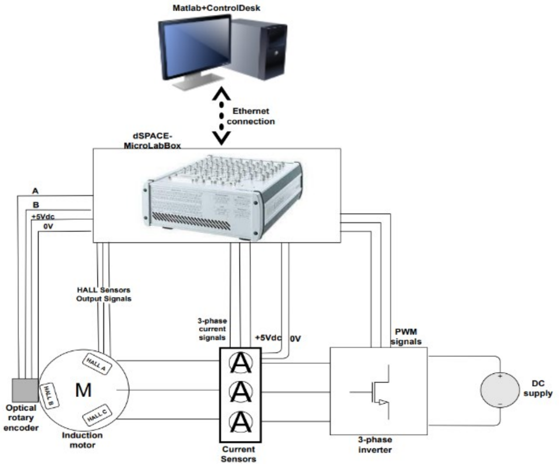


Figure 19. Block diagram of the experimental vector control system for a permanent magnet synchronous machine

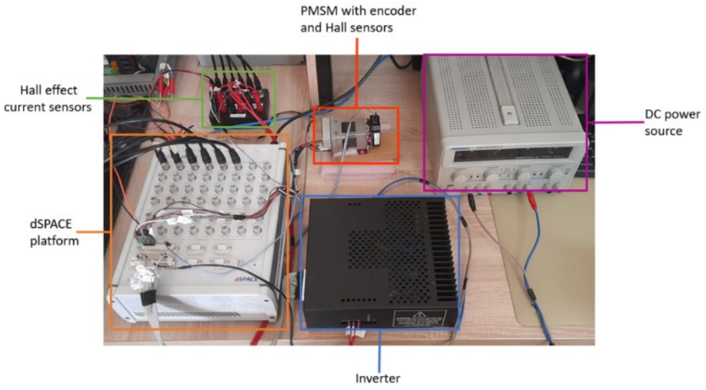
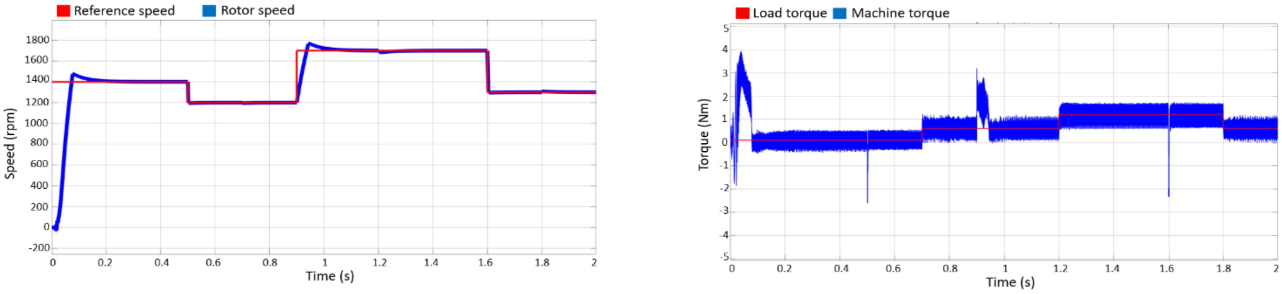


Figure 20. Experimental elements of the vector control system for a permanent magnet synchronous machine

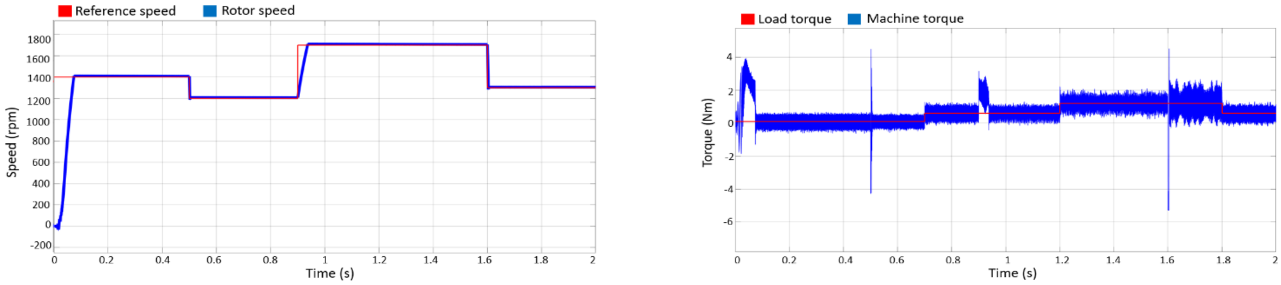
Based on the two implementations of the electric propulsion system a with permanent magnets synchronous machine (the one in the simulation and the practical one) different tests were carried out, which allowed the system performance to be analysed.

The three implementation variants were tested in the simulation, using the same test profile. The results are presented below:



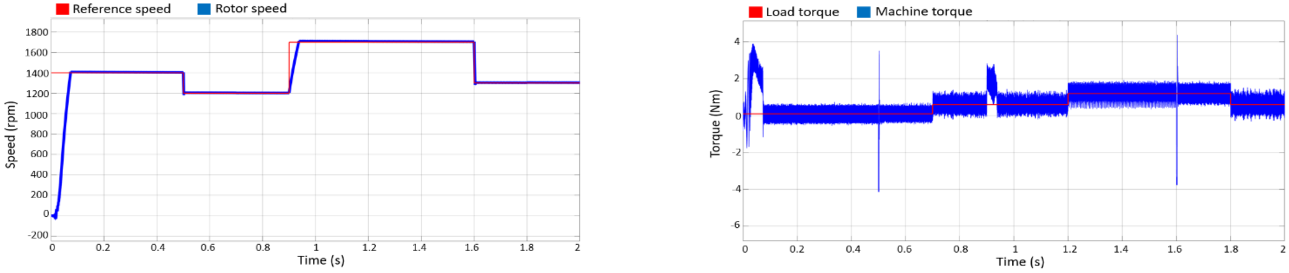
(a) (b)

Figure 21. The system response for the first implementation (a – machine and set speed, b – machine torque and load torque)



(a) (b)

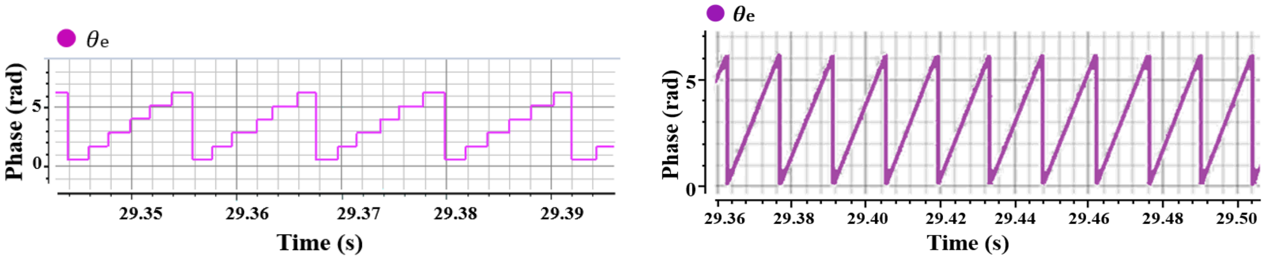
Figure 22. The system response for the second implementation (a – machine and set speed, b – machine torque and load torque)



(a) (b)

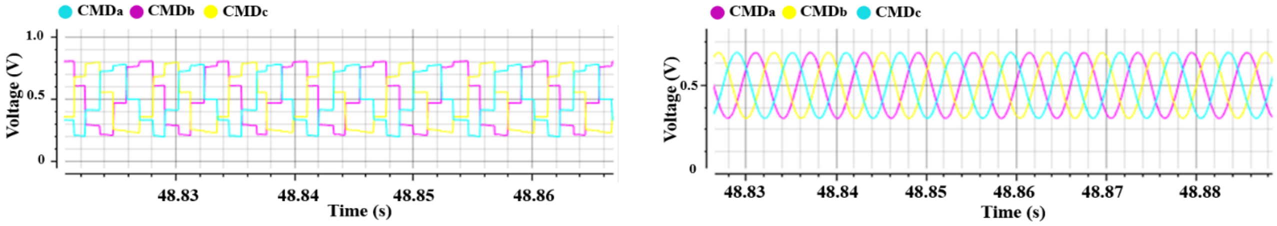
Figure 22. The system response for the third implementation (a – machine and set speed, b – machine torque and load torque)

The practical implementation included both a rotary encoder and Hall sensors to measure the synchronous angle of rotation. A comparison of the operation of the vector control was made when the synchronous angle of rotation is measured with Hall sensors or with the rotary encoder.



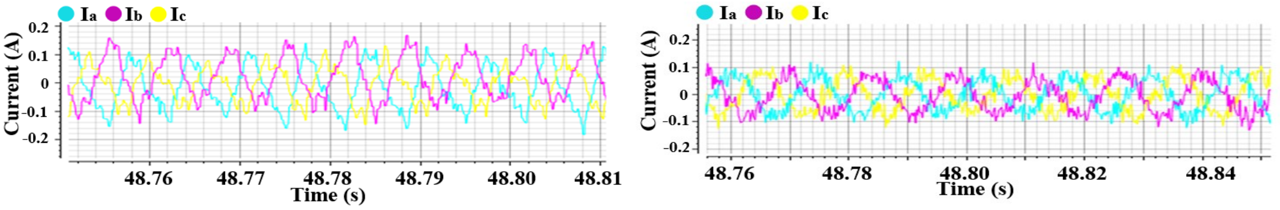
(a) (b)

Figure 23. Synchronous angle (a – measured with Hall sensors, b – measured with an incremental encoder)



(a) (b)

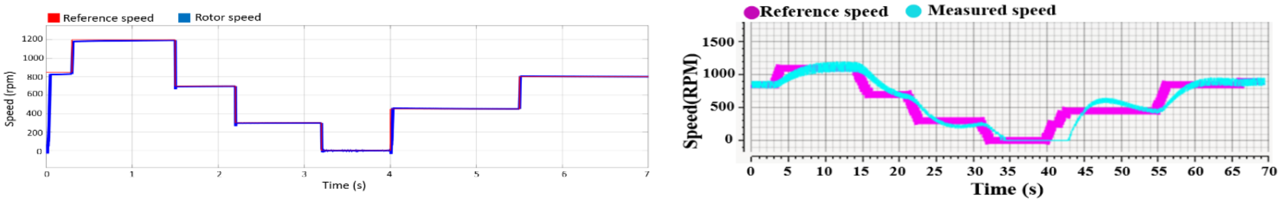
Figure 24. Sinusoidal command signals (a – measured with Hall sensors, b – measured with an incremental)



(a) (b)

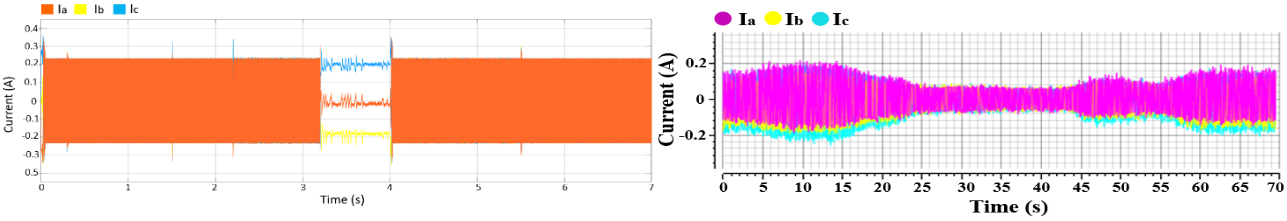
Figure 25. Stator current (a – measured with Hall sensors, b – measured with an incremental)

A dynamic speed variation test was also performed to test the efficiency of the vector control block, both in simulation and in practice. The results are presented below:



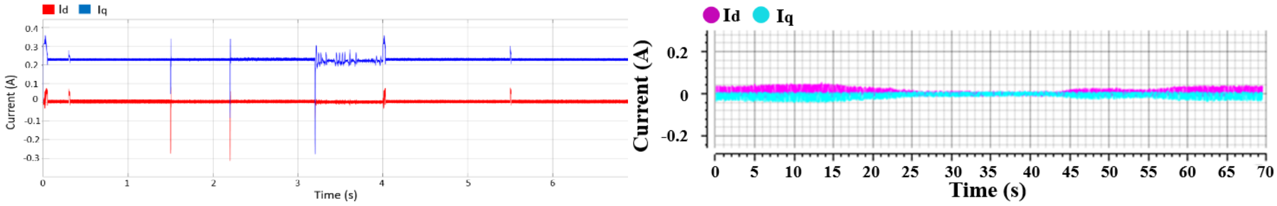
(a) (b)

Figure 26. Machine speed and set speed (a – simulation, b – experimental)



(a) (b)

Figure 26. Stator current (a – simulation, b – experimental)



(a) (b)

Figure 27. I_{ds} and i_{qs} currents (a – simulation, b – experimental)

This chapter presents the operation and modelling of a permanent magnet synchronous motor, the study and implementation of a vector control corresponding to this type of motor and proposed the implementation of an electric propulsion system.

The implementation at the simulation level allowed the testing of three variants of the implementation of the vector control block, and the practical implementation allowed the comparison of the method of measuring the synchronous angle of rotation with Hall sensors or rotary encoder. The obtained results support the efficient operation of the vector control block for a permanent magnet synchronous motor, in case of speed variations.

5.2.4. Battery Pack and Its Management System

In chapter 6 of the paper, entitled "The Battery Pack And Its Management System" a theoretical study, simulation modelling, practical implementation and testing of a battery pack are presented.

In the case of an electric vehicle, the battery is the most important element, along with the electric machine, without which the electric vehicle would not work. In terms of cost, the battery represents about 50% of the initial cost of the vehicle. Therefore, it is of great importance to choose and use the battery in the vehicle, so that it can be functional for a long time. Moreover, the evolution of electric vehicles is based on the evolution of rechargeable batteries [20][21].

Currently, the batteries used in electric vehicles that most satisfactorily meet the requirements of a battery in an electric vehicle are lithium-ion batteries. The main characteristics of lithium-ion batteries, ideal for electric vehicles, are their specific energy and power density higher than those of other existing battery types [22][23][24][25].

However, lithium-ion batteries also have several disadvantages. A major disadvantage is the fact that batteries are easily flammable, which can cause fires or even explosions if they are not used properly [23]. Moreover, lithium-ion batteries have a low operating capacity in cases of abuse (their use in harsh conditions), a fact that causes early damage to the battery [20][22]. Thus, to ensure a good operation, both from the perspective of safety and to avoid premature degradation, a battery pack management system is also necessary in addition to the lithium-ion cell pack [20][22][23].

The management system, within the electric vehicle, must ensure the proper operation of the lithium-ion battery pack, both from a safety perspective, the batteries operate within normal parameters, to avoid the risk of fires or explosions [26], and from the perspective of optimal operation to avoid situations of abuse, which can lead to early battery degradation [22].

The battery of an electric vehicle is a generic notion because in reality, several elements are needed to realize the energy storage system: a battery pack consisting of numerous battery cells, a pack management system, sensors, switches, fuses, communication interfaces and cooling/heating system. In Fig. 28 the block diagram of the energy storage system in an electric vehicle is illustrated.

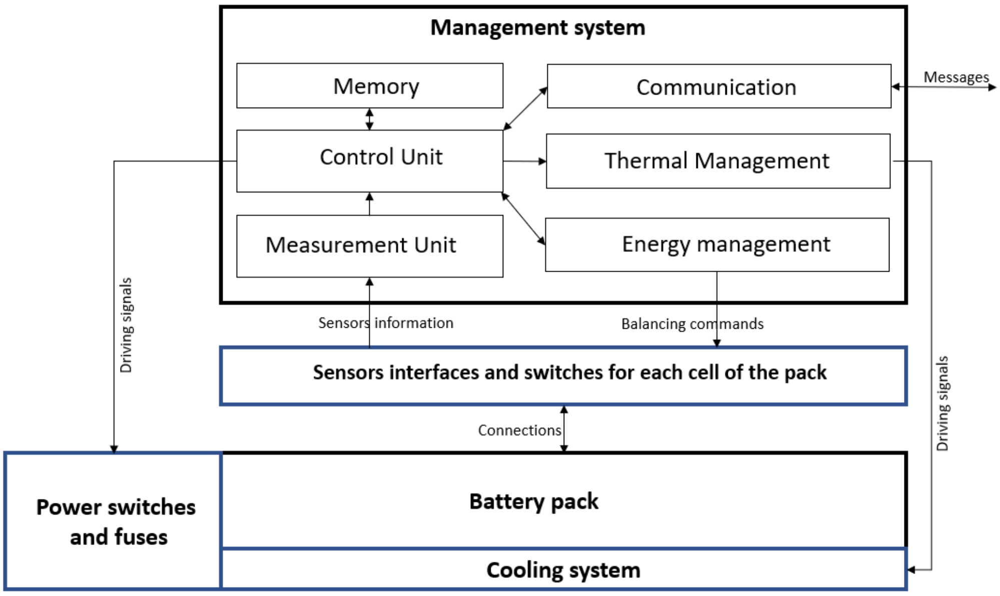


Figure 28. Block diagram of the energy storage system in an electric vehicle

The battery management system performs many functions, but only two functions have been extensively studied in this paper: battery charge state estimation and cell balancing within the pack.

The state of charge is the parameter that provides information about the amount of energy that is stored, relative to the maximum amount that the battery can store [27][28]. Determining the state of charge is an essential function of the battery management system because the optimal use of the battery is based on the correct estimation of the state of charge, even more so in an electric vehicle, whose autonomy is based only on battery power [29].

The state of charge is not a parameter of the battery that can be measured directly, as it depends on several factors, thus several methods have been developed to estimate the state of charge. Within this work, an estimation method based on Coulomb Counting and an estimation method using Kalman filters, more specifically, the Extended and Unscented Kalman filter, were developed at the simulation level.

Given that, within an electric vehicle, the battery pack consists of hundreds of battery cells connected in series and/or parallel, balancing between the cells is mandatory for optimal performance of the pack and extended life [30].

There are two types of balancing that can be used within a battery pack: static balancing and dynamic balancing [28]. Static balancing is performed before the pack is used or outside the pack lifetime[28].

The battery management system performs dynamic balancing and there are two types: passive balancing and active balancing [30][28].

For the implementation of a battery management system, a simulation was carried out in Simulink. Fig. 29 shows the energy storage system, and in Fig. 30 the elements of the battery management system are illustrated. The modelled package comprises 6 cells connected in series.

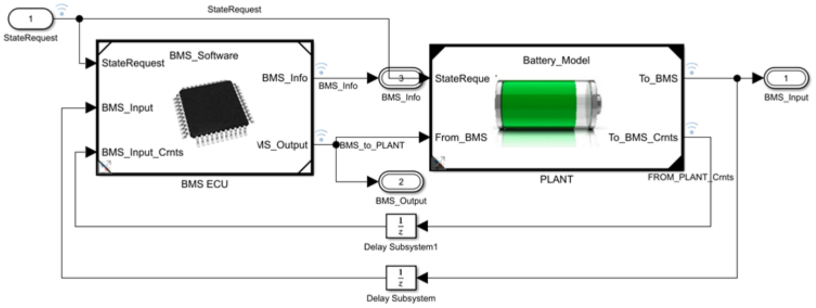


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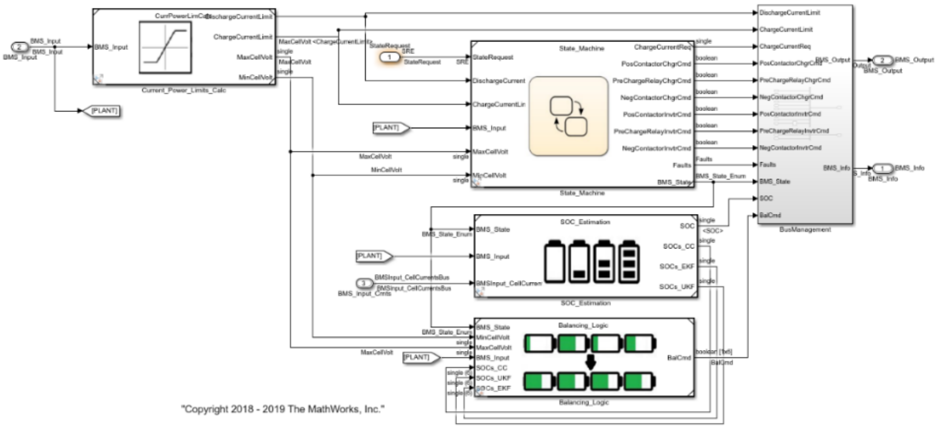
Figure 29. Simulated battery pack in Simulink



"Copyright 2018 - 2019 The MathWorks, Inc."

Figure 30. Battery management system simulated within Simulink

This simulated system was used to implement state-of-charge estimation, Coulomb Counting and Kalman filters (extended and unscented), plus passive swing, using a switched resistor topology, but also active swing, in switched capacitor topology. The obtained results are presented below:

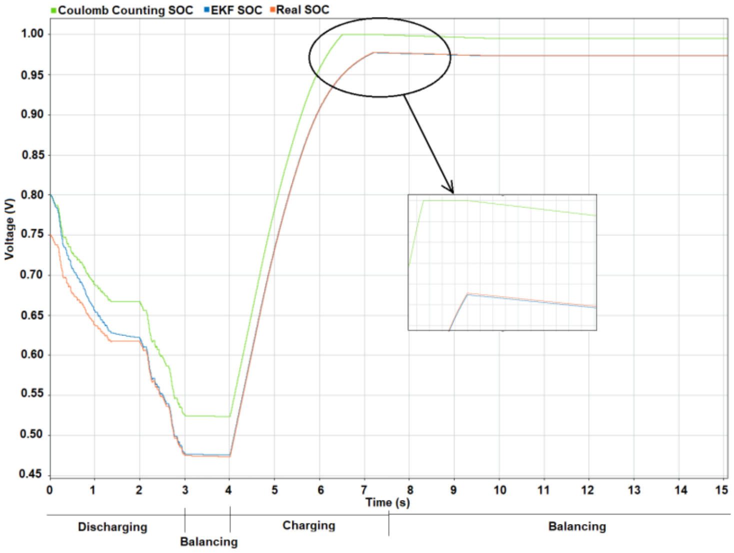
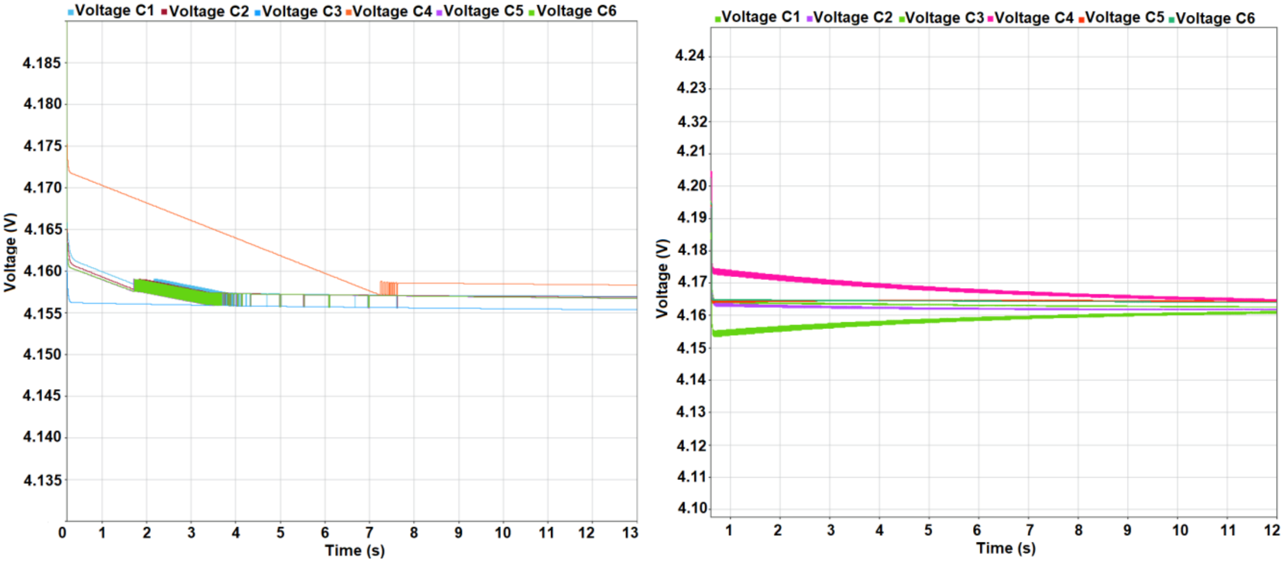


Figure 31. State of charge of cell 1 estimated with Coulomb Counting(green), UKF(pink), EKF(orange) and actual state of charge of cell (blue)



(a) (b)

Figure 32. Cell voltages during the balancing process (a – passive, b – active)

For the practical implementation of the battery pack, specialised integrated circuits have been studied and used for cell monitoring, protection and even balancing. Thus, several integrated circuits and development boards from Analog Devices, specialised for building a battery pack, were used to implement a battery pack.

In the first stage, the EVAL-ADBMS1818 module was used for cell monitoring, which has as its central element the ADBMS1818 circuit, specialised in monitoring 18 battery cells, and allows their passive swing, with a maximum current of 200mA, using PWM signals [145][146]. Fig. 33 shows the structure of the system made with the EVAL-ADBMS1818 module, and in Fig. 34 the practical elements are illustrated.

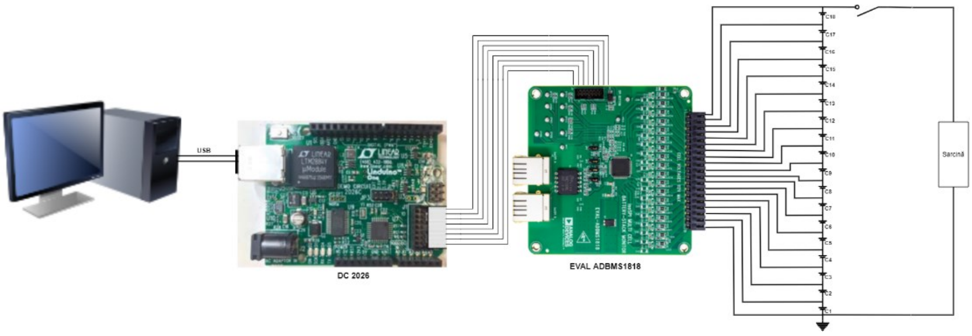


Figure 33. The structure of the battery pack made with the module EVAL-ADBMS1818

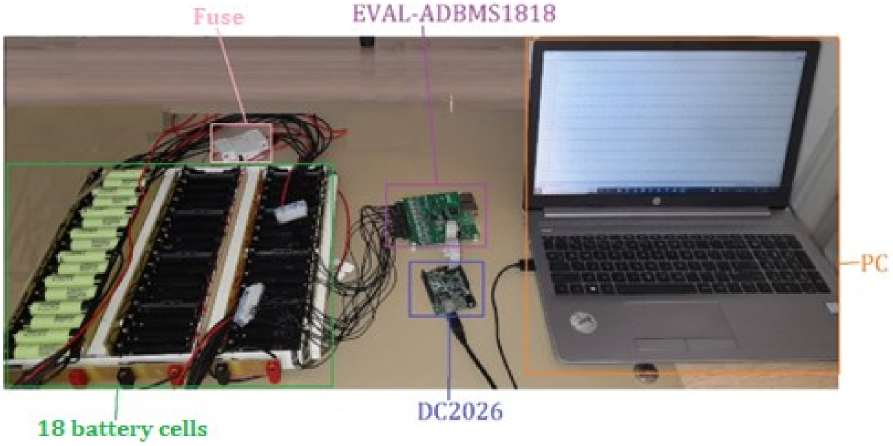


Figure 34. The practical elements of the battery pack made with the module EVAL-ADBMS1818

The system shown in Fig. 34 ensures the formation of a pack of 18 lithium-ion cells, each with a nominal voltage of 3.6V, connected in series, adding up to a total voltage of 64.8V. Fig. 35 illustrates the cell voltage during the passive balancing process.

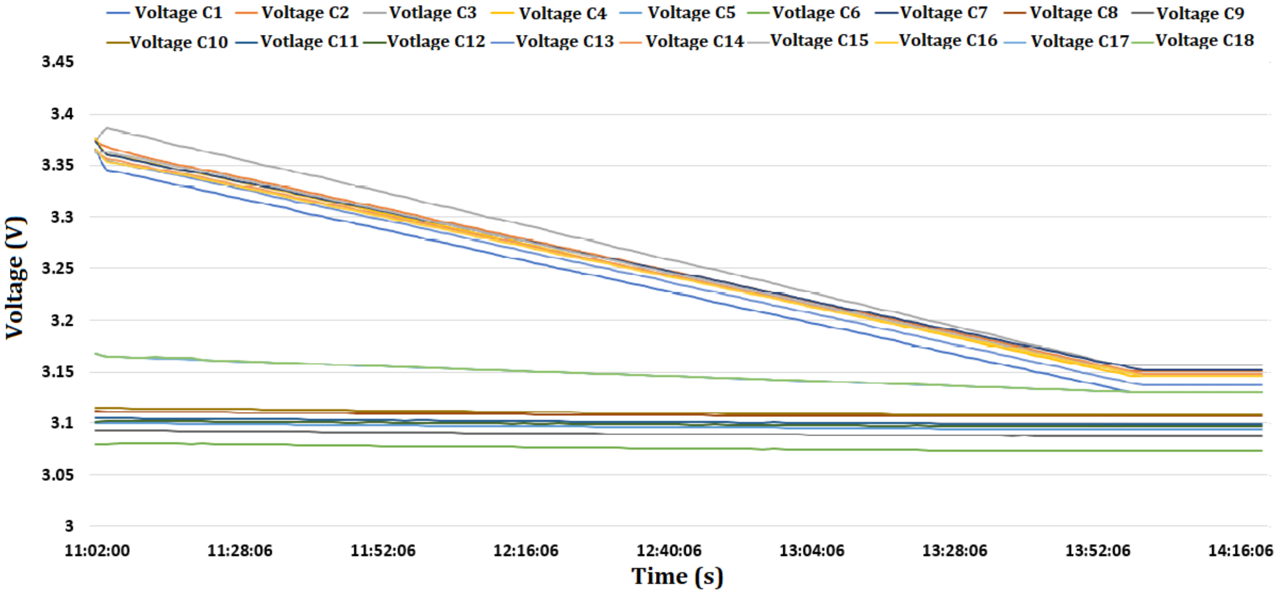


Figure 35. The voltage of the 18 cells during the passive balancing process, with the module EVAL-ADBMS1818

For better efficiency, a 24-cell active monitoring and balancing system was built using the DC2100B-C module and the DC2100B-D module. Fig. 36 illustrates the structure of the implemented system, and Fig. 37 presents the practical elements.

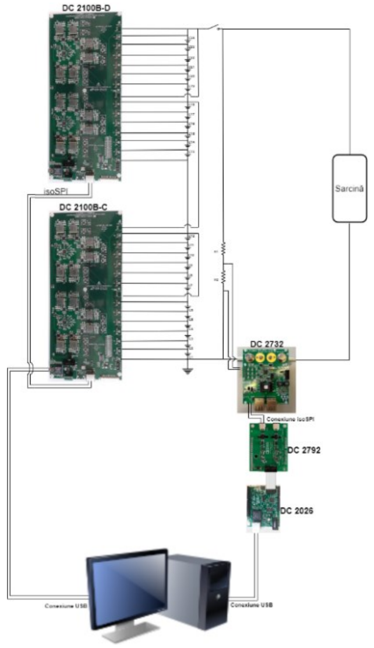


Figure 36. The structure of the battery pack made with the modules DC2100B-C and DC2100B-D

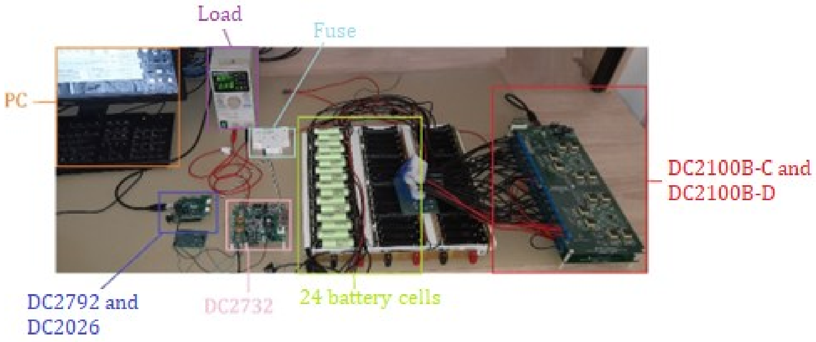


Figure 37. The practical elements of the battery pack made with the modules DC2100BC and DC2100BD

DC2100B modules allow active balancing, by discharging overcharged cells, but also charging weak cells.

The active balancing process involved several consecutive moments of discharging and charging, respectively, for the 12 cells, to reach a balance, at the most appropriate value of the voltages of the 12 cells. Fig. 38 shows the process of active balancing of the 12 cells connected to the DC2100B-C module, and Fig. 39 the active balancing process of the next 12 cells, connected to the module DC2100B-D.

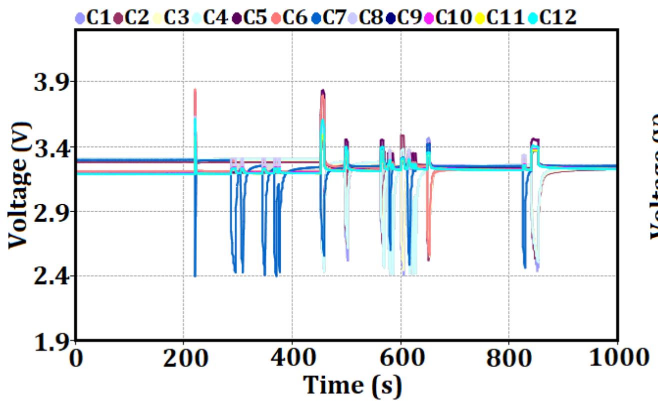


Figure 38. Active balancing for the 12 cells connected to the module DC2100B-C

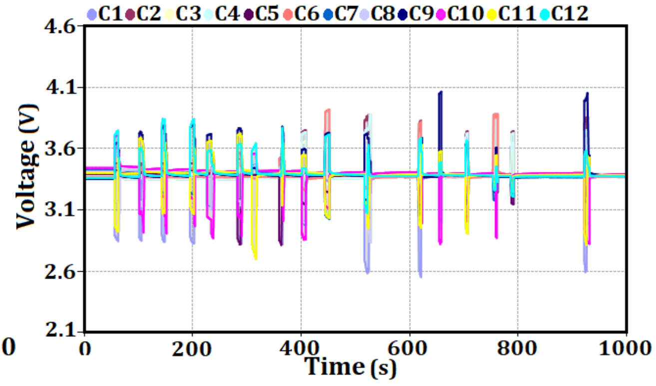


Figure 39. Active balancing for the 12 cells connected to the module DC2100B-D

Chapter 6 presents the theoretical study, simulation and practical implementation of a battery pack, state-of-charge estimation algorithms, and cell balancing methods. Using simulation-level modelling as well as the implementation of a practical battery pack, three state-of-charge estimation methods and passive and active balancing methods were tested to balance the cells within the pack.

5.2.5. Electric Propulsion System

Chapter 7 of this work has the title "Electric Propulsion System" and includes the implementation of an electric propulsion system, made by connecting the subsystems presented in the previous chapters.

The system includes the permanent magnet synchronous motor DMB0224C10002 with the vector control system, presented in detail in chapter 5, but the power supply is provided by a pack of 12 cells of li-ion batteries, monitored with a DC2100B-C module, presented in detailed in chapter 6.

All elements of the vector control subsystem of the permanent magnet synchronous motor were kept the same as in Fig. 20. The only difference is the removal of the laboratory power supply. Power to the inverter is provided by the battery pack, consisting of 12 cells connected in series, actively monitored and balanced with the DC2100B-C module, plus the DC2732 module for current monitoring through the entire pack. Fig. 40 shows the structure of the proposed system, and Fig. 41 the practical elements are presented.

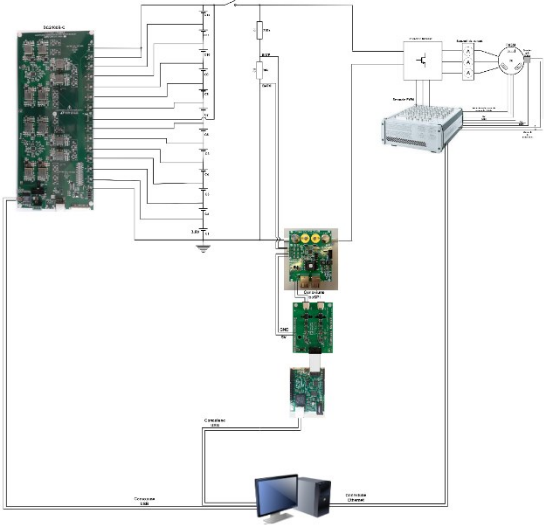


Figure 40. Block diagram of the proposed electric propulsion system

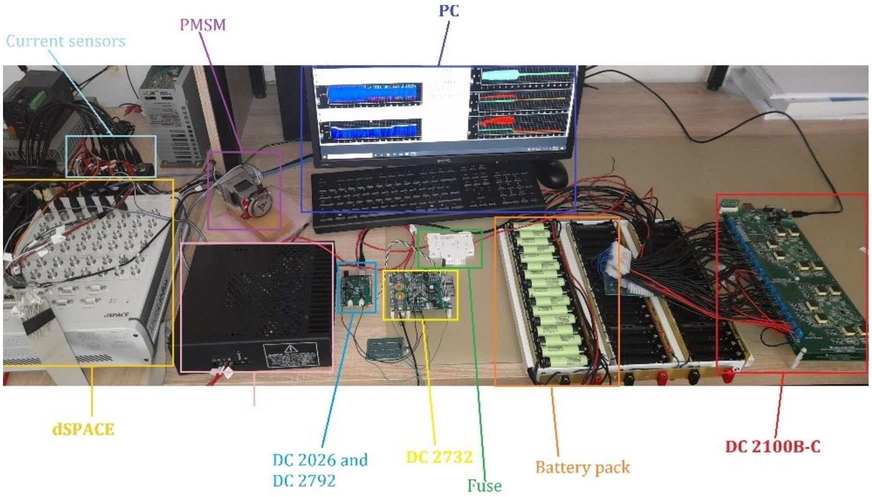


Figure 41. The practical elements of the proposed electric propulsion system

The system shown in Fig. 41 was tested in an engine speed variation scenario, monitoring how the engine speed follows the imposed reference speed, the motor stator current, the current delivered by the batteries and the battery pack voltage. These results validated the appropriate operation of the control unit and battery pack. The results are presented below:

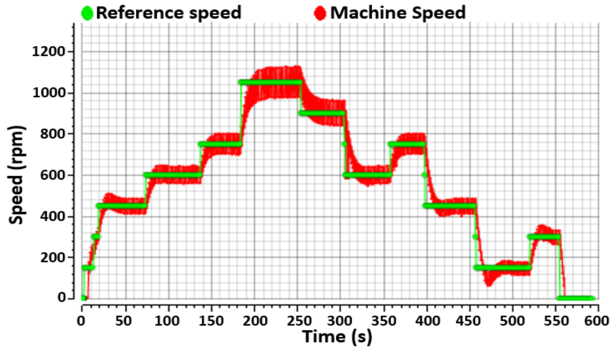


Figure 42. Machine speed and set speed

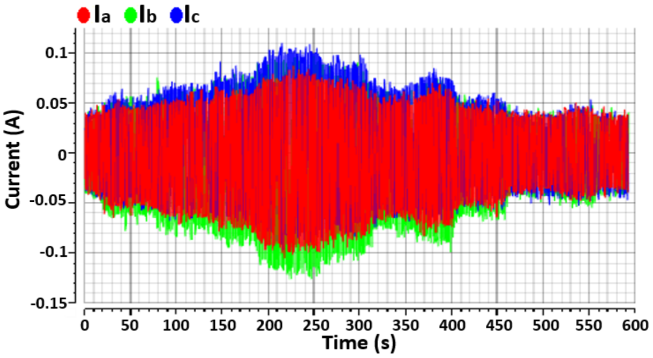


Figure 43. Stator current

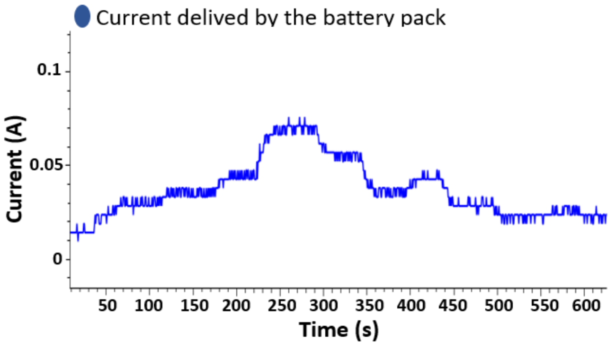


Figure 44. The current delivered by the battery pack

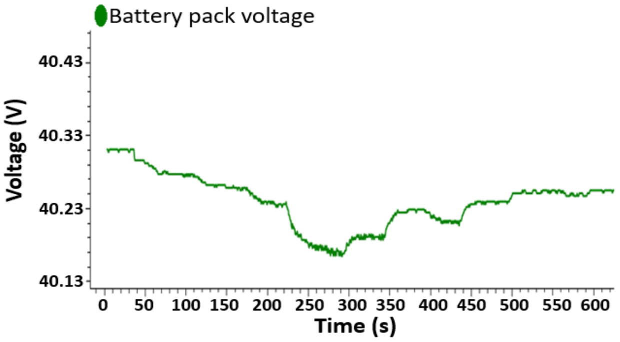


Figure 45. Battery pack voltage

In this chapter, the implementation of a propulsion system that includes both the electric motor and the battery pack that provides power to the motor is presented. The formed system was tested with a reference speed variation profile. Thus, it was analysed how the variation in speed influences the other quantities within the system. The motor stator current and the current supplied by the batteries show the same variation, as does the speed, the battery pack delivering the necessary current, imposed by the control block, for the motor speed to equal the speed imposed by the reference value.

6. Conclusions

This paper aims to study, model and implement an electric propulsion system. The development of electric vehicles is a topic of essential currently in the entire world.

In the first stage, a theoretical study of electric vehicles was conducted, of the main elements of the propulsion system, in chapter 1, and several elements were identified on which improvements can be made, to increase the performance of the entire system.

To be able to determine the elements where innovative contributions can be made, in chapter 2, a detailed study was made of the main elements of the vehicle, the electric motor, with its control, and the electric energy storage system.

In this paper are studied the permanent magnet synchronous machine, which offers the highest efficiency, but at a high cost, and the induction machine, which offers low cost and robust operation, but with lower efficiency.

Within the vector control system for the induction machine, an ACC block was also added, thus a simulation, but also a practical implementation of an electric propulsion system with an ACC system, which provides speed control for a set value, but also speed adaptation to maintain a safe distance from another vehicle in front.

After studying the two types of electric motors used in electric vehicles, a battery pack was study and implemented.

Finally, a complete propulsion system was presented, built by connecting the permanent magnet synchronous motor and the battery pack, forming the propulsion system, like an electric vehicle.

In conclusion, this paper includes a theoretical study of the existing types of electric vehicles and the main elements within an electric vehicle.

7. Originality And Novel Contributions

- The study and implementation of an indirect vector control for an induction machine, for its application in an electric propulsion system.
- The implementation of a digital indirect vector control, using a dSPACE platform, allowed the rapid realisation of a vector control system at the prototype level.
- Study and analysis of the operation of an Adaptive Cruise Control type system in the case of an electric vehicle.
- The adaptation of an Adaptive Cruise Control type system within an electric propulsion system, with an indirect vector control for an asynchronous induction motor.
- The implementation at the practical level of an electric propulsion system comprising an Adaptive Cruise Control type system using a dSPACE platform, which allowed the propulsion system to be tested in the case of an Adaptive Cruise Control mode operating scenario.
- The study and implementation of an indirect vector control for a permanent magnet synchronous machine in three possible variants of the current control.
- Practical implementation of a digital indirect vector control for a permanent magnet synchronous machine using a dSPACE platform.
- Implementation of a battery cell pack at the simulation level, but also practical, which allowed passive swinging, with resistors and switches, and active swinging of the cells, with multiple transformers.
- Use of specialised integrated circuits from Analog Devices for passive and active monitoring and balancing of cells within a battery pack.
- The realisation of a small-scale electric propulsion system comprising a permanent magnet synchronous motor with indirect vector control and a 12-cell pack, actively monitored, and balanced, using specialised modules from Analog Devices.

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9. Dissemination

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