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# Ph.D. THESIS
# SUMMARY

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METODE DE ÎMBUNĂTĂȚIRE A CONSUMULUI DE ENERGIE PENTRU AUTOVEHICULE

METHODS OF IMPROVING ENERGY CONSUMPTION FOR MOTOR VEHICLES

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# Content

# Chapter 1

# Introduction

The problem of global warming and car pollution, especially in urban areas, has been known for decades, but no significant progress has been made in the last ten years to slow it down, even though regulations have been around for about half a century.

With the development of relatively affordable battery packs capable of delivering energy densities large enough to allow electric vehicles to reach a range of hundreds of kilometers, the entire automotive industry has diverted much of its resources to these types of alternative powertrains that are, at least apparently, environmentally friendly.

On the other hand, hydrocarbon resources are becoming increasingly difficult to exploit, which will lead to a significant increase in the price of fossil fuels in the not too distant future, if oil consumption trends continue to grow.

Therefore, it is becoming increasingly clear that vehicles powered by conventional internal combustion engines which we have been accustomed to for over a hundred years will have to be equipped with electric motors, the latter being much more efficient.

However, the rapid transition to electric vehicles has many drawbacks, due to the fact that they currently have a significantly higher weight compared to conventional ones, the charging time required for the battery is significant and the range is mostly insufficient for long trips. Moreover, recycling as well as the exploitation of lithium reserves are harmful to the environment, the infrastructure available in many countries is poorly developed, and perhaps most importantly, a significant part of electricity is currently produced by burning coal and hydrocarbons, which means that the pollution is only moved from the cities to the surrounding areas, where the thermal power plants are built.

Given the above statements, until truly globally feasible solutions are found, the transition should take place slowly, in a few decades (most likely), with the help of hybrid powertrains, which offer both the advantages of conventional heat engines (increased range and short refueling times), as well as those of electric motors (high instantaneous power, increased efficiency and zero pollutant emissions, respectively).

## 1.1 Presentation of the field of the doctoral thesis

The field covered in this thesis includes both electronics used in the automotive industry and power electronics, respectively, in other words, methods of sizing the main components of vehicles equipped with hybrid powertrains, along with power management algorithms and circuits, but also active cell-balancing circuits developed for the rechargeable batteries used by cars, as well as auxiliary storage systems that allow to improve the energy consumption for motor vehicles. It is well known that the car industry has recently focused on the development of both hybrid and electric vehicles, primarily due to increased air pollution and the declining hydrocarbon resources. Because in many geographical areas the direct transition from conventional to electrically powered vehicles is almost impossible (both due to infrastructure deficiencies and due to the high cost of acquisition and low range), combining the advantages of both aforementioned powertrains represents the ideal compromise for the transition period, which can last between 30 and 40 years (at least in Romania). Also, the development of electricity conversion systems, rechargeable batteries, as well as electric motors plays a very important role in maximizing the efficiency of modern powertrains.

## 1.2 Scope of the doctoral thesis

This paper contributes to the sizing of the main components for the various hybrid powertrains, as well as to the methods used for controlling the distribution of energy during the driving of the vehicle. These methods deal with different hybrid powertrain architectures, including the series-hybrid, as well as the parallel-hybrid configuration, and are mainly based on measurements performed on a conventional powertrain, when traveling on public roads, in different regimes of speed and acceleration, in various weather conditions, at multiple altitudes, as well as during different seasons, using two types of tires (summer and winter, respectively). Each of the two architectures studied has both advantages and disadvantages, compared to a conventional powertrain, but also to a fully electric one, powered exclusively by rechargeable batteries or fuel cells. On the other hand, this thesis proposes an active system for balancing the charging voltages of the cells used within the high voltage batteries, that are used to power the traction electric motor, which allows to optimize the electricity consumption of the vehicle. In addition, this thesis proposes the development and use of auxiliary systems for storing electric energy, in order to reduce and optimize fuel consumption, both for the heat engine and for the auxiliary systems of the vehicle.

## 1.3 Content of the doctoral thesis

Chapter 1 presents the field of the doctoral thesis, the purpose of the thesis, as well as its content.

Chapter 2 briefly describes the problems caused by air pollution, how energy is being generated, and the conversion of energy used mainly to power vehicles. Moreover, the exploitation potential of current energy resources is assessed, in order to find out if it can ensure the actual consumption from renewable sources.

Chapter 3 presents the implications of transitioning to environmentally friendly powertrains, especially in Romania, and then a brief feasibility study is conducted, with regards to the correct choice of powertrain type, depending on different constraints.

Chapter 4 is dedicated to hybrid electric vehicles, starting with a classification of hybrid powertrains used in industry, in terms of their architecture.

In this chapter, a series of improvements are proposed for the most important components of the hybrid powertrains, starting with the internal combustion engine, continuing with the electric traction motor, the electric generator and the corresponging power converters, ending with the drivetrains and the energy storage devices, respectively.

This chapter concludes with a review of current technologies used in the industry, as well as a list of several car models which are currently in production in Europe.

In Chapter 5, the author proposes a simple and very inexpensive method of measuring in real time the parameters of the powertrain for a conventional car, equipped with a heat engine and automatic transmission. The main purpose of this method is to facilitate the design and sizing of the main components of hybrid electric powertrains. Data collection was performed using a computerized diagnostic interface, the accuracy of which was verified both by mathematical calculations and by computer-assisted simulations.

In Chapter 6, the author proposes a methodology for designing and sizing the main components of a series-hybrid powertrain, as well as the development of an energy management algorithm, which were obtained based on the data collected using the aforementioned interface, while driving the car on public roads.

Chapter 7 deals with the development of parallel-hybrid powertrains, using the same method of real-time collection of the parameters for a conventional propulsion system, while driving the vehicle on public roads.

Firstly, the author proposes a hybrid powertrain with a parallel configuration, which is able to match the performance and technical specifications (torque and maximum power curves) of a conventional powertrain featuring a higher engine displacement.

Then, based on this architecture, it was developed an algorithm that allows the vehicle to travel using either the energy provided by fossil fuel, through the heat engine, or the energy stored within the high voltage battery of the proposed system (using the electric traction motor ), or a combination of the two energy sources, thus enabling achieving improved fuel consumption, as well as reducing the quantity of pollutant emissions.

As a result, the energy storage element (battery pack) will have different characteristics compared to the high-voltage battery that is used for the plug-in hybrid system that only matches the performance of a conventional engine.

At the end of each subchapter from Chapter 7 are presented the experimental results obtained by the author in order to develop the parallel-hybrid type of powertrains that have been proposed.

In Chapter 8, the author proposes an efficient method of designing electronic call-balancing circuits for high-voltage battery packs, also presenting a series of practical results obtained during the development of these systems.

Chapter 9 proposes an auxiliary energy storage system which allows the optimization of consumption for vehicles by using specific elements that are able to harvest energy from different sources. Also, based on measurements made while driving the car on public roads, the sizing for this auxiliary system was performed, which can be used in combination with Start-Stop systems.

Chapter 10 contains the conclusions of this thesis, starting with the results obtained, continuing with the presentation of the original contributions, the list of original publications, ending with the development perspectives.

This chapter is followed by a number of 13 Annexes (A.1 - A.13), whose role is to clarify and complement the information presented in this thesis.

The last section is represented by the Bibliography, which concludes the doctoral thesis and which includes a number of 183 bibliographical references that also included the personal publications of the doctoral student, detailed in subchapter 10.3 of this thesis.

# Chapter 2

# The current energy situation and the motivations for the transition to less polluting vehicles

The problem of pollution, especially within congested cities is indeed a very important environmental and public health concern and conventional vehicles will have to be replaced or adapted to alternative propulsion systems, but it is essential that this transition to be achieved in a sustainable way.

Air pollutants include primary pollutants, which are emitted directly from sources (PM, $SO_2$, $NO_x$, HC, VOC, CO, $NH_3$), and secondary pollutants, which are generally produced by the chemical reactions of two or more primary pollutants [1].

Global warming, resulting from the greenhouse effect, which is induced by the presence of carbon dioxide ($CO_2$) in the atmosphere, is accelerated by the burning of fuels used to generate electricity, to power heat engines and to heat buildings [1], [2].

Today, most vehicles rely on the combustion of hydrocarbon (HC) fuels to obtain the energy needed to power them, and improving fuel economy has a significant impact on the amount of GHGs produced within cities, where population density is very high. Currently, the most promising technologies aimed at reducing pollutant emissions are implemented on hybrid-electric or all-electric vehicles which are equipped with fuel cells or rechargeable batteries.

It should be noted, however, that greenhouse gases are produced by both natural causes (approximately 44.6% of the total) and anthropogenic causes (approximately 55.4% of the total), and the transition to non-gas-emitting vehicles can reduce pollution by up to 4% while driving [3], [4].

Regarding the energy, it must be produced from sources that already exist in nature, such as fossil fuels, nuclear fuels or forms of renewable energy. Instead, the sources of energy supply are represented by the primary ones (which can be consumed directly), the secondary ones (refined petroleum products, biofuels, etc.) or the tertiary ones (electricity), the last two categories being used directly for powering vehicles [5].

Energy conversion is usually done through thermal power plants, which convert kinetic energy into electricity using generators, but there are also other direct conversion methods [5].

Regarding the alternative sources available on Earth, the incident solar radiation generates a total amount of energy which is over 100 million times higher than the total energy used by Earth inhabitants within a year. This immense quantity of energy free, distributed almost evenly, and available to all nations and inhabitants of the planet [5].

On the other hand, just over 2% of the total solar energy received by the Earth is transformed into wind energy, which is over two million times higher than the total energy that was used by the human population in 2010. Wind energy is one of the most benign and environmentally friendly forms of electricity production, as it does not involve chemicals and does not produce harmful emissions or heat pollution [5].

Another very important renewable source for the production of electricity, that is currently used, is hydroelectric energy, which is harnessed with the help of hydropower plants [5].

In addition to the aforementioned renewable energy sources, biofuels (methanol, ethanol and biodiesel) can be used directly to power the internal combustion engines of motor vehicles, being very important, as they help supporting the transition to "green" cars.

However, it should be kept in mind that the timeframe for this transition to less polluting vehicles may differ both depending on the geographical area and on the economic potential of each country.

# Chapter 3

# Implications of the transition to less polluting vehicles

This chapter is intended to expose the implications of the transition to less polluting vehicles, and in this regard, it was made an analysis on the energy production in our country, as well as the operating costs of vehicles, depending on the type of powertrain they are equipped with.

As mentioned at the end of the previous chapter, the transition period to less polluting vehicles will differ depending on the geographical area, but especially depending on the economic potential of each state. In addition, it should be kept in mind that the average price of a barrel of oil (in recent decades) was around $60, which makes conventional vehicles still attractive and relatively inexpensive to operate [6].

In Romania there is a potential for the exploitation of energy from renewable sources of approximately 144 TWh/year, given that the final energy consumption for 2018 was 175 TWh (excluding the transport and agriculture sectors) [7].

For the last years, the annual average electricity production from different sources has decreased, while the consumption has increased, the balance registering a decrease from 829 MW to -307 MW. Out of a total of 6,549 MW (at the level of 2021), hydrocarbons and coal are still the main source for 36% of the average national electricity production amount [8].

If only 7.5% of the car fleet at the level of 2021 (approximately 550,000 units) would be fully electric cars, which would need simultaneous charging (within 8 hours), this will generate an average hourly power requirement of 3,960 MW, which is about 60% of the national daily production, from June 2020 to May 2021. If these vehicles were to be recharged quickly (150 kW, average hourly power), production should be increased at 82,500 MW, which is about 1,250% of the current average [8], [9].

On the other hand, if the same percentage would be represented by plug-in hybrid cars, the numbers presented above would be reduced tenfold, which is a feasible alternative for Romania and other countries.

Given that over 76% of cars on the streets in our country are older than 12 years, it is expected that the transition to fully electric vehicles will take place over several decades [9].

The chapter includes a series of studies on operating costs for cars equipped with different types of powertrains (conventional, hybrid-electric, and all-electric, respectively), and it was concluded that for frequent use of the vehicle over a long period of time (8 years and 240,000 km), hybrid or all-electric models become more convenient to operate financially, if the basic model is purchased.

However, especially in the case of fully electric cars, it should be borne in mind that the price of a kilowatt-hour paid at fast charging stations is two or maybe three times higher than at home, which leads to an increase of the total operating costs for this type of vehicles [10].

On the other hand, if the car is purchased based on a fixed budget, Diesel models, as well as hybrid electric ones require lower total operating costs than petrol variants, even for moderate operation (60,000 km, within 4 years).

In order to make a correct comparison, both the price of electricity and fossil fuels should be constantly monitored, because at the end of 2021 electricity cost 1.51 lei/kWh, while standard gasoline and diesel fuel had related costs of 6.10 lei/liter and 6.07 lei/liter, respectively, which further disadvantages fully electric cars.

Thus, the costs associated with fuel and/or electricity necessary to travel a distance of 100 kilometers, using different types of powertrains, are as follows: 40.32 lei for the Volkswagen Golf 7 1.4TSI Comfortline model, powered by gasoline, 33.62 lei for the Golf 7 1.6TDI Comfortline model, powered by diesel fuel, 38.94 lei for the hybrid model (petrol/electricity), Golf 7 GTE and 26.12 lei for the fully electric model, e-Golf 7.

Regarding the list price of a car that could be equipped with a parallel-hybrid type of powertrain which includes a compression ignition engine, 1.6TDI, and a battery with a capacity of 4.3 kWh, it would be about €37,000, a value very close to that of the current hybrid model, which is powered by gasoline and electricity (Volkswagen Golf 7 GTE).

Regarding the weight of such a diesel-hybrid model, it could weigh 169 kg more than the Volkswagen Golf 7 GTD model, which was in production in 2018 and offers similar performance, but this difference can be reduced substantially by using state-of-the-art composite components and materials.

# Chapter 4

# Hybrid electric vehicles

This chapter presents a classification of powertrains that are part of hybrid vehicles, along with certain control strategies that can be applied to them, depending on different constraints (costs, complexity, type of application, etc.), each with both advantages, as well as specific disadvantages.

According to the definition, a hybrid vehicle is a vehicle that has two or more propulsion systems. A hybrid vehicle that also includes an electric propulsion system is called a Hybrid Electric Vehicle (HEV) [2].

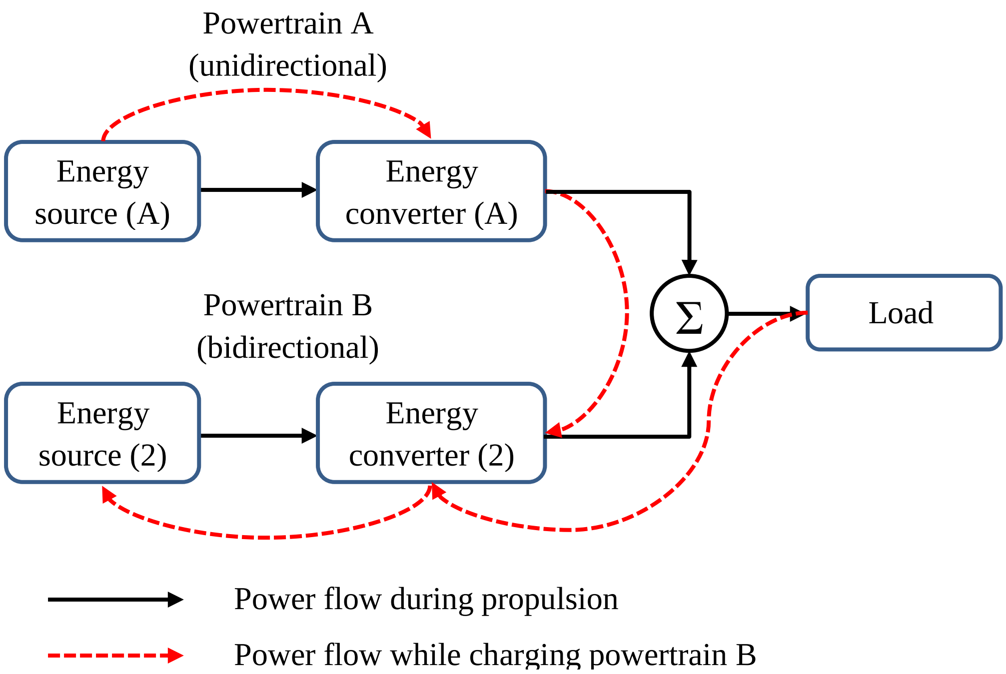



***Figure 4.1*** *Hybrid electric powertrain [2].*

In most cases, both in terms of complexity and size, but especially in terms of cost, hybrid vehicles combine at most two propulsion systems. In order to recover the braking energy, which is dissipated in the form of heat (in the case of conventional vehicles, equipped only with internal combustion engines), the hybrid powertrains (consisting of the propellers and the drivetrain) also have a propulsion system that allows bidirectional energy flow [2].

On the other hand, for each important component of the hybrid powertrain (heat engine, electric motor/generator, power converters, transmission systems, energy storage devices), a number of improvements have been proposed, which mainly help to reduce both energy consumption and pollutant emissions. All these subassemblies can be chosen from a diverse range, current technologies offering multiple solutions to manufacturers in the automotive industry.

A graphical representation of the Volkswagen Golf 7 GTE hybrid electric model, together with the hybrid powertrain is shown in Figure 4.21.


***Figure 4.21*** *Volkswagen Golf 7 GTE hybrid electric model [11].*

Regarding the models of hybrid electric and fully electric vehicles that were in production in 2021, the offer is varied, both in terms of the configuration of the powertrain, the power source that feeds the heat engine, and the capacity of the high voltage battery, respectively. Thus, a list of some of the most important models that are marketed in Europe has been elaborated.

Therefore, recent developments show that vehicles equipped with hybrid or all-electric powertrains have a high potential for further development and will most likely be able to replace conventional ones during the upcoming decades.

# Chapter 5

# Measuring the parameters of a conventional powertrain using a computerized diagnostic interface

This chapter proposes a very simple method of collecting in real time the parameters of the conventional powertrain of a car, by using a cheap diagnostic tool, in order to facilitate the development of alternative architectures, with which hybrid or electric vehicles are equipped.

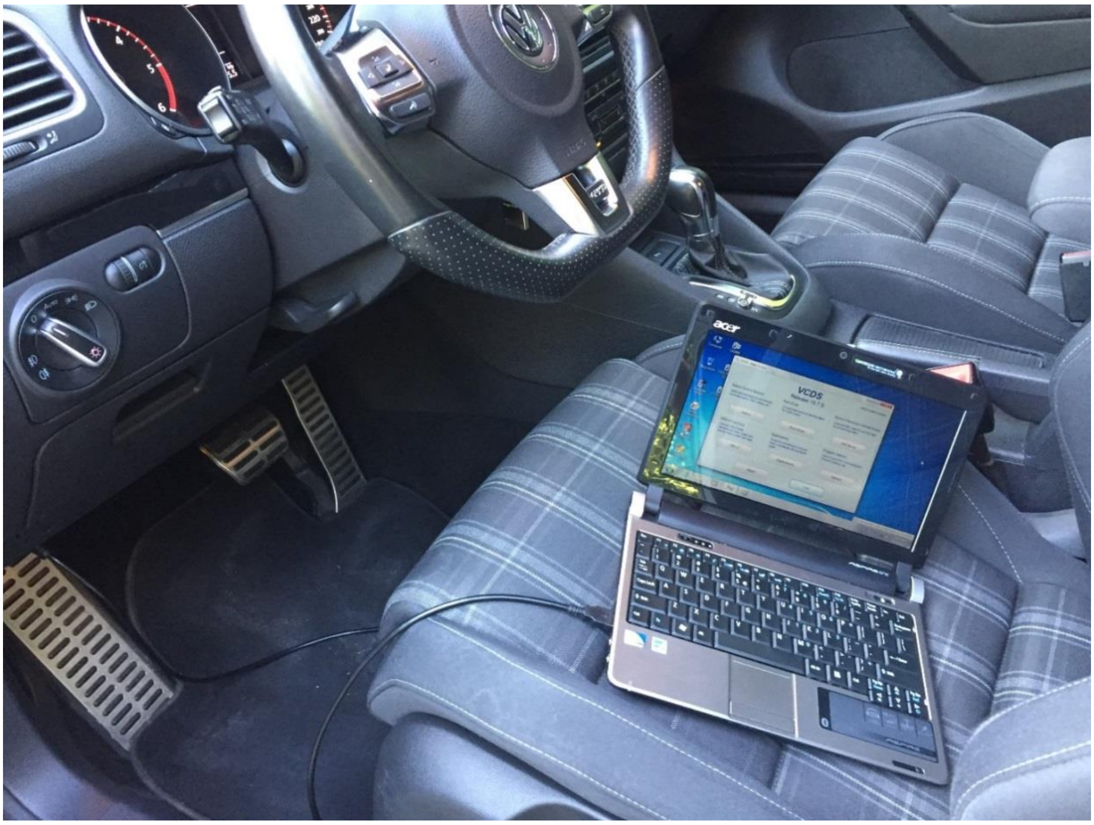


***Figure 5.1*** *The setup connection between the car, OBD-II interface and VCDS GUI.*

To collect all the necessary parameters from the vehicle's powertrain, the VCDS software, version 15.7.0, has been used, as also proposed in [12] – [16]. This tool is a Windows-compatible application that was developed to emulate the functionality of original Volkswagen Group diagnostic equipment, such as VAS or ODIS [17].

Apart from the graphical user interface (GUI), in order to be able to connect the computer to the vehicle, a special hardware interface was used, which communicates through the OBD-II port, the complete configuration being described in Figure 5.1.

In addition to data collection, they were compared with both mathematical calculations and computer-assisted simulations, in order to validate the proposed method. Based on several parameters, such as the torque developed by the heat engine and its speed, the instantaneous power required for the vehicle to travel at a certain speed can be easily determined. This is a very important information, as it allows designing the hybrid or electric powertrains in a very simple way, using the parameters collected through the OBD-II port of the vehicle.

Moreover, these measurements can be performed in a real environment, on any road, without the need to use expensive equipment, such as dynamometers, which can only be operated indoors, when the vehicle is stationary.

The most important factors contributing to the total forward resistance for a vehicle traveling at a constant cruising speed are the rolling resistance ($F_{roll}$), the aerodynamic resistance ($F_{aero}$) and the tilting resistance ($F_{tilt}$). According to [18], the formulas for each of the three forces are (5.1) – (5.3):

$$F_{roll} = \mu \cdot m \cdot g \tag{5.1}$$

$$F_{aero} = \frac{1}{2} \cdot \rho \cdot c_W \cdot A \cdot (v + v_0)^2 \tag{5.2}$$

$$F_{tilt} = m \cdot g \cdot sin\alpha \tag{5.3}$$

Therefore, the maximum force (in Newtons) required to move the vehicle at a certain speed (in km/h), in steady state, is given by (5.4):

$$F_{traction} = F_{roll} + F_{aero} + F_{tilt} \tag{5.4}$$

Turning this traction force into power shows that the total rolling resistance power is described by (5.5), as follows:

$$P_{traction} = \frac{F_{traction} \cdot v}{3600}, \tag{5.5}$$

where $P_{traction}$ is expressed in kW, $F_{traction}$ is expressed in N and $v$ (which represents vehicle speed) is expressed in km/h.

To validate the results obtained through mathematical calculations, a series of computer-assisted simulations were performed using the MATLAB Simulink program (which includes dedicated tools for this type of application); the simulation configuration is described in Figure 5.7. Therefore, the simulations were performed in order to determine the power required to move a vehicle at a constant cruising speed on a flat road, according to reference [16] (original paper).

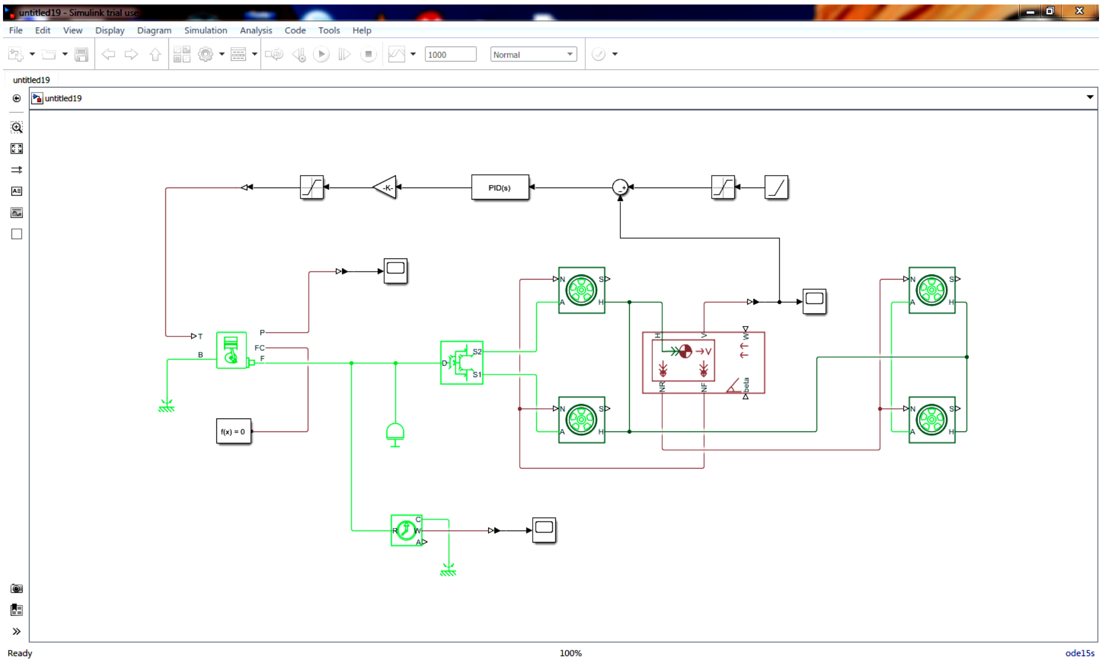


***Figure 5.7*** *MATLAB Simulink setup used for simulating the conventional powertrain of a vehicle.*

The conventional powertrain that was simulated consists of an ICE, a differential, two traction wheels (at the front of the vehicle), two other wheels, connected to the rear axle, a vehicle body and a PID controller, used to control the engine throttle valve, in order to achieve the desired travel speed.

As for the actual measurements, they were collected under driving conditions, in a manner similar to that described in [12] – [16] (references from the list of original publications), their main purpose being to verify the accuracy of the diagnostic tool, as well as to create a database that was later used for designing the proposed hybrid-series or hybrid-parallel powertrains.

The output power delivered by the internal combustion engine (which was calculated based on the measured torque and engine speed values) for a 40 minutes journey (approximately) is shown in Figure 5.14.

From the aforementioned graph it can be seen that the engine provides about 14 kW of power during downhill (inclination of about -0.5° of the road) and about 23 kW, during the climb (about +0.5° road inclination), respectively, at a constant vehicle speed of 101 km/h. This highlights the fact that the result mentioned above corresponds to both mathematical calculations and computer-assisted simulations, thus consolidating the effectiveness of the methodology proposed in this thesis.

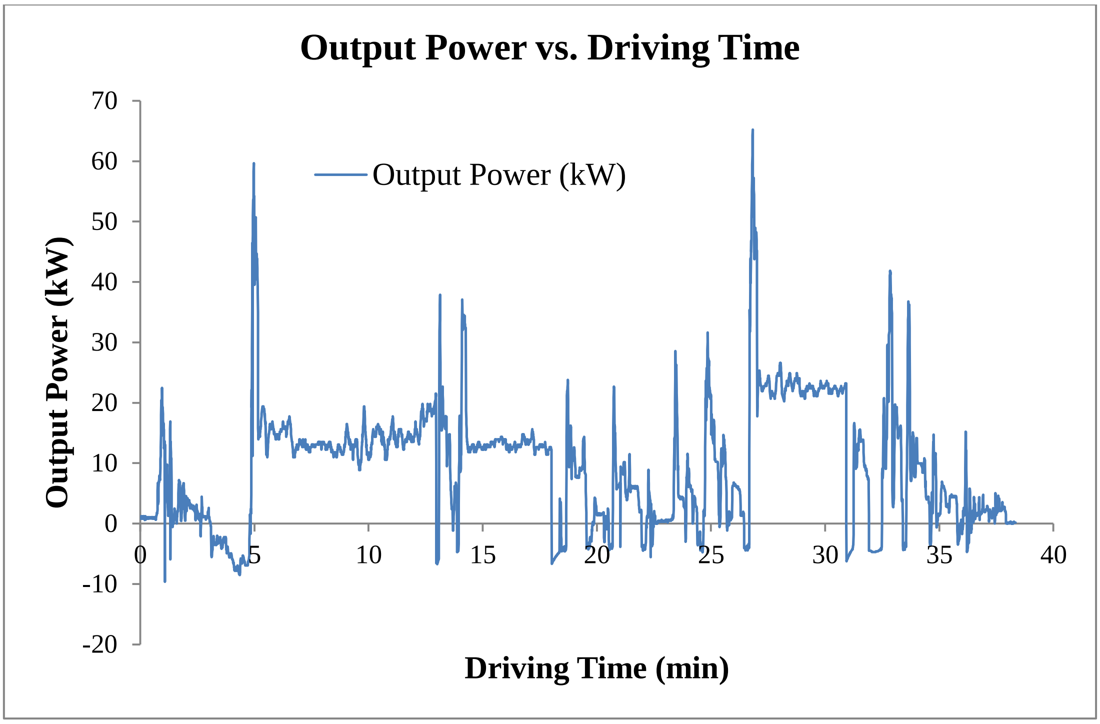



***Figure 5.14*** *The power developed by the internal combustion engine over time, for a journey of about 40 minutes.*

The obtained results show a very close correlation between mathematical calculations, computer-assisted simulations and measurements performed during real road driving conditions, the difference between them being less than 12%, for speeds up to 100 km/h, thus validating the proposed method. It should be noted, however, that not all the auxiliary equipment of the car (exterior lighting, air conditioning system, infotainment system, power steering, electric windows, etc.), nor headwind speed, were taken into account in both the calculations and the simulations.

In addition, it was measured the power required to ride the vehicle (which includes the consumption of the ICE's auxiliary equipment, as well as the mechanical efficiency of the transmission) at a constant speed of approximately 100 km/h, resulting in approximately 14 kW during a slight descent and about 23 kW, during an ascent (on the same part of the road, but in the opposite direction), respectively.

At the end of this chapter, two general methods of improving the energy efficiency of motor vehicles were presented, which could reduce the power required to drive them by about 15%.

# Chapter 6

# Design of series hybrid powertrains

Given the current global situation, personal transport plays a very important role in slowing down the spread of the pandemic and also increases the sense of security for car owners; however, today's conventional vehicles are inefficient and environmentally harmful, while their electric counterparts are expensive and offer insufficient range for people's emerging mobility needs.

Figure 6.1 shows a comparison between a conventional powertrain and the proposed series-hybrid architecture.

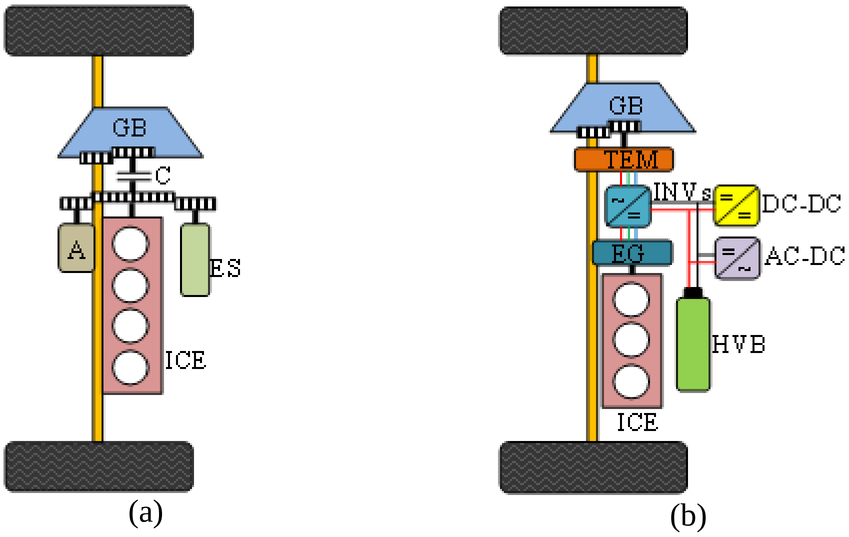



***Figure 6.1*** *Comparison between a conventional powertrain (a) and the proposed series-hybrid architecture (b).*

The purpose of this subchapter is to provide guidance on several design considerations for series-hybrid vehicles, which are mainly based on actual measurements and mathematical calculations (which are used to dimension the components of the powertrain).

Compared to other papers, which rely on using standard driving cycles [19], [20], such as the new European Driving Cycle (NEDC) and/or the Worldwide Harmonized Light Vehicle Test Procedure (WLTP), this thesis proposes hybrid architectures that are dimensioned based on real measurements performed in multiple weather conditions, in several ambient temperature ranges and at various altitudes, as well as during the use of different types of tires (summer/winter tires) [12] – [16].

Based on this data, it has been developed a very simple (rules-based) algorithm that manages the power generated by the heat engine, in order to obtain a high-efficiency series-hybrid powertrain, while maintaining the overall performance of a compact car equipped with 2-liter diesel engine, capable of producing a maximum output power of 125 kW. The algorithm used for managing the proposed series hybrid powertrain is illustrated in Figure 6.8.

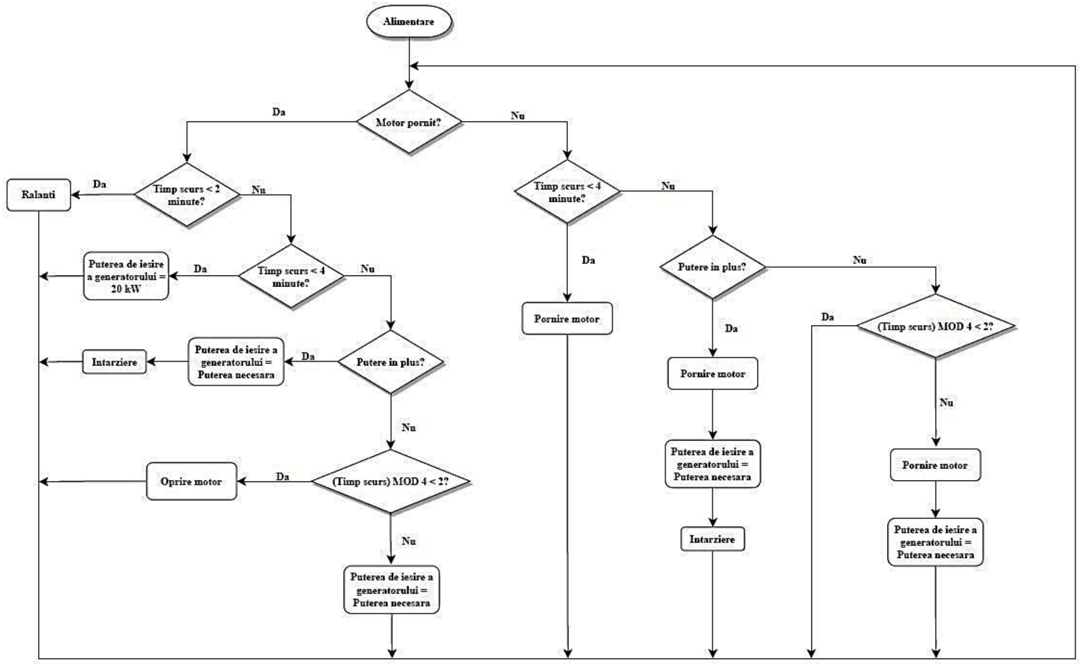



***Figure 6.8*** *The algorithm used for managing the proposed series-hybrid powertrain.*

This chapter provides some specific guidance on designing the powertrain for series-hybrid electric vehicles, based mainly on actual measurements collected while driving on public roads, which were supplemented by mathematical calculations. Moreover, compared to other papers, which propose sophisticated algorithms based on artificial intelligence and which require greater computing power, the algorithm presented in this thesis is very simple and rule-based.

Even if, at first glance, the efficiency of using a series type of hybrid powertrain seems rather low, due to the need to convert mechanical energy (produced by the ICE) into electrical energy (via the electric generator) that must then be converted back into mechanical energy (by means of the electric traction motor, which drives the wheels of the vehicle), the mathematical calculations showed the opposite. Thus, by applying the appropriate algorithm for a plug-in series-hybrid architecture (that can be charged from the mains), which includes a high-voltage battery (with a predefined capacity), its efficiency is higher (under certain conditions) compared to a conventional propulsion system (consisting only of an internal combustion engine).

Specifically, by combining a compression ignition engine with a relatively small displacement of 1.2 liters (capable of producing a maximum output power of 55 kW), which is used to drive a 50 kW (nominal power) electric generator, together with a lithium-based high-voltage battery pack with a capacity of 20 kWh (allowing a maximum depth of discharge rate of 50%), coupled to an electric traction motor with permanent magnets of 125 kW (peak power), an average fuel consumption of about 3.53 liters/100 km can be obtained. Basically, this proposed configuration uses almost 38% less fossil fuel compared to a conventional powertrain (which consumes, on average, around 5.62 liters/100 km).

The resulting fuel consumption corresponds to a vehicle range of approximately 97 km in hybrid mode, for an average speed of 42.69 km/h (being very close, but lower than the combined speed of the WLTP cycle). This means that the average time for which the car can be driven in hybrid mode is 2.29 hours or about 137 minutes.

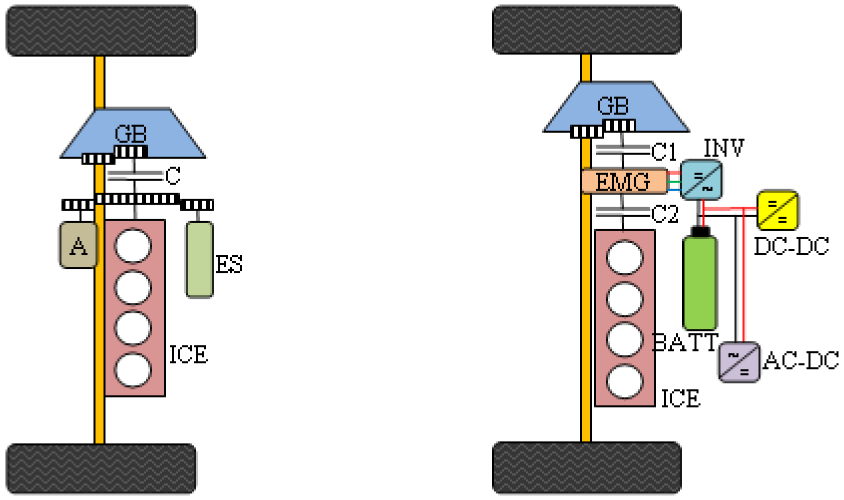
For further development directions, both the algorithm and the components of the powertrain can be customized according to the specifics of the application (public transportation, passenger cars, vans, trucks, etc.). At the same time, they can be adapted according to the characteristics of the heat engine (maximum output power, displacement, the characteristics of its cooling system, etc.), depending on weather conditions or even depending on the driver's wish, in order to improve the overall efficiency of the plug-in hybrid system. Therefore, by applying the proposed methodology, this study can be easily extended to any other type of hybrid or electric vehicle. However, in this case, it is necessary to scale all the components of the powertrain and to modify the control strategy depending on the targeted power requirements and energy consumption.

# Chapter 7

# Design of parallel hybrid powertrains

This chapter provides an insight into several design and sizing considerations for parallel-hybrid powertrains that allow the batteries to be charged from the mains, along with a few simple strategies for managing their power flow.

In order to match the performance of a conventional internal combustion engine with the aid of a parallel mild-hybrid propulsion system, it is necessary to have a preliminary knowledge of the two architectures, a comparison between them being illustrated in Figure 7.1.




(a) (b)

***Figure 7.1*** *Comparison between a conventional powertrain (a) and the proposed parallel-hybrid architecture (b).*

As this system is mainly based on reducing the displacement of the internal combustion engine, two Turbocharged Direct Injection (TDI) Diesel engines were considered, the basic specifications of which are given in Table 7.1, together with the proposed hybrid configuration.

*Table 7.1* *Proposed powertrains specifications [21], [22].*

| Power train | Maximum power (kW) / Engine speed (RPM) | Maximum torque (N·m) / Engine speed (RPM) | Engine displacement (cm³) |
|---|---|---|---|
| 1.6TDI | 77/4,400 | 250/1,900 – 2,500 | 1,598 |
| 2.0TDI | 125/4,200 | 350/1,750 – 2,500 | 1,968 |
| 1.6TDI Hybrid | 125/4,200 | 350/1,750 – 2,500 | 1,598 |

The output power of the hybrid powertrain versus the engine and electric motor speed, $P_{OUT\_HYB}(\omega)$, can be determined as follows:

$$P_{OUT_{HYB}}(\omega) = \begin{cases} P_{ICE_{1.6TDI}}(\omega), when\ P_{ICE_{1.6TDI}}(\omega) \in \\ [0, 0.8 \cdot P_{ICE_{1.6TDImax}}(\omega)] \\ P_{ICE_{1.6TDI}}(\omega) + \left(\frac{P_{ICE_{1.6TDI}}(\omega)}{P_{ICE_{1.6TDImax}}(\omega)} - 0.8\right) \\ \cdot 10 \cdot P_{EMmax}(\omega), when\ P_{ICE_{1.6TDI}}(\omega) \in \\ \left(0.8 \cdot P_{ICE_{1.6TDImax}}(\omega), 0.9 \cdot P_{ICE_{1.6TDImax}}(\omega)\right] \\ P_{ICE_{1.6TDI}}(\omega) + P_{EMmax}(\omega), when\ P_{ICE_{1.6TDI}} \in \\ \left(0.9 \cdot P_{ICE_{1.6TDImax}}(\omega), P_{ICE_{1.6TDImax}}(\omega)\right] \end{cases} \quad (7.5)$$

Initially, a hybrid powertrain that matches the dynamic performance of a larger displacement internal combustion engine is proposed. This can be achieved by using an AFPM electric motor capable of developing a maximum power of 55 kW, together with a 1.2 kWh lithium-based high voltage battery (or a combination of batteries and ultracapacitors), capable of deploying high power densities at very high discharge rates (above 45C, at 185V), from time to time. Moreover, the proposed hybrid powertrain also includes a 1.6-liter diesel engine, which will be assisted by the electric traction engine, according to the proposed control strategy.

In addition to the benefits of reducing the displacement of the internal combustion engine by about 19% (from 1,968 cm³ to 1,598 cm³), which leads to lower operating costs, fuel consumption, as well as the amount of $CO_2$ emitted can also be reduced by 4.5% (on average) in real travel conditions. Moreover, $NO_x$ emissions can be reduced by a certain percentage, while all these improvements are made without compromising the vehicle's performance, such as the maximum speed or acceleration it can reach.

In the second part of this chapter is proposed a plug-in parallel-hybrid powertrain, but which, in addition to matching the performance of a 2-liter heat engine, it allows the vehicle to travel in a fully electric mode (at low speeds ). Thus, the second configuration reduces fuel consumption by 15% (on average, compared to an internal combustion engine featuring a higher displacement), while $CO_2$ and $NO_x$

emissions can be completely eliminated, under certain conditions (at low speeds) and at the same time, the dynamic performance of the vehicle is improved.

The graph illustrating the performance of the electric motor, both when it provides an additional boost for the hybrid powertrain (by assisting the internal combustion engine) and when it drives the transmission alone (in fully electric mode), is shown in Figure 7.10, below:

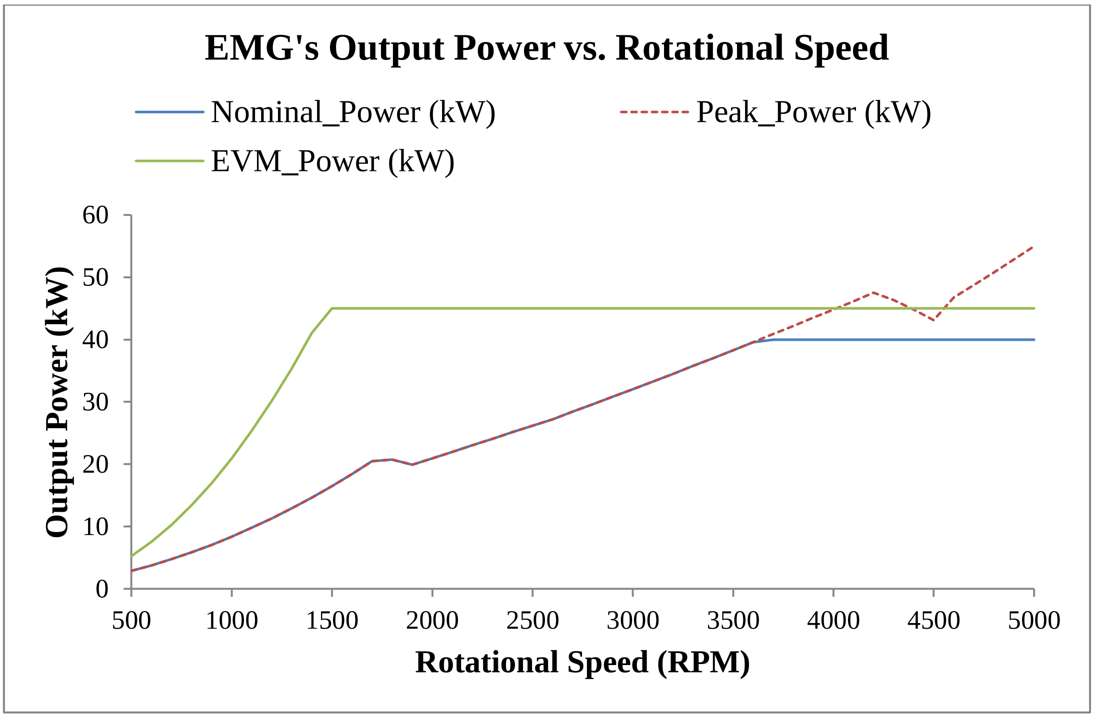



***Figure 7.10*** *The power developed by the electric motor versus its speed.*

A simplified flowchart of the control strategy which has been designed for the proposed hybrid powertrain and which manages the ICE is shown in Figure 7.11.

The main goals of a hybrid powertrain are to increase efficiency, reduce fuel consumption and emissions, but also improve dynamic performance. Therefore, after analyzing and processing a large volume of data (measured under real driving conditions), similar to what was presented in the original paper [13], it was concluded that the power management method proposed in subchapter 7.2 is suitable for several driving styles and traffic situations, bringing significant benefits, mainly for urban driving or traffic jams, but not only.

Thus, from a design point of view, the main difference between the two proposed systems is the value of the nominal capacity of the high voltage battery, which is 4.3 kWh. Also, the new battery must withstand current discharge rates above 12C, at 185V, for short periods of time. On the other hand, the main difference from a functional point of view is the control strategy of the powertrain, which, compared to the first one described above, this allows the implementation of a fully electric mode of travel for the car, as previously mentioned.

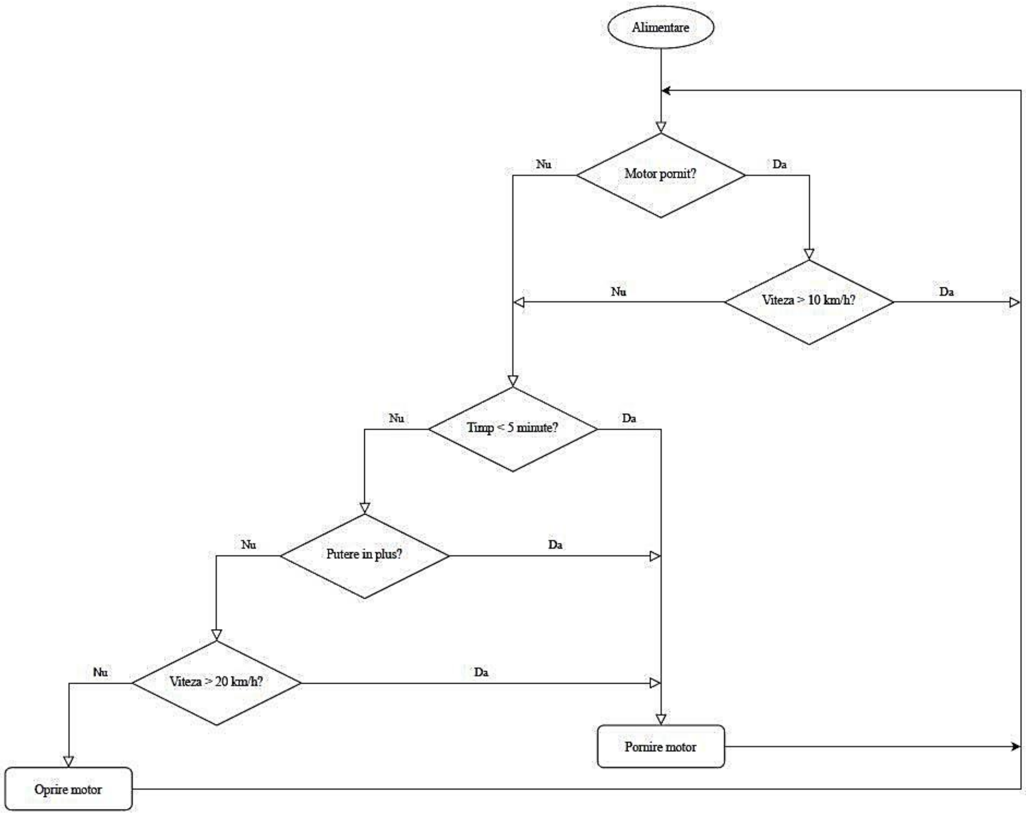



***Figure 7.11*** *The algorithm used for managing the proposed parallel-hybrid powertrain.*

Therefore, the concepts, methods and results presented in this chapter can be implemented on a compact vehicle equipped with a parallel-hybrid powertrain, but these can be extended to other types of vehicles, as well. In addition, the algorithms can be adapted for applications that use heat engines powered by various types of fossil fuels, the necessary changes being minor, in this case. Moreover, depending on the targeted performance and costs, they can be adapted so that the use of electricity may vary, compared to the proposals set out in this thesis.

# Chapter 8

# Design of electronic cell balancing circuits for high voltage battery pack

This chapter presents both the simulation results and the practical implementation of a standalone analog active cell-balancing circuit for automotive battery management systems, which offers the advantage of using it independently, but also the possibility to be modularized, thus communicating with various devices.

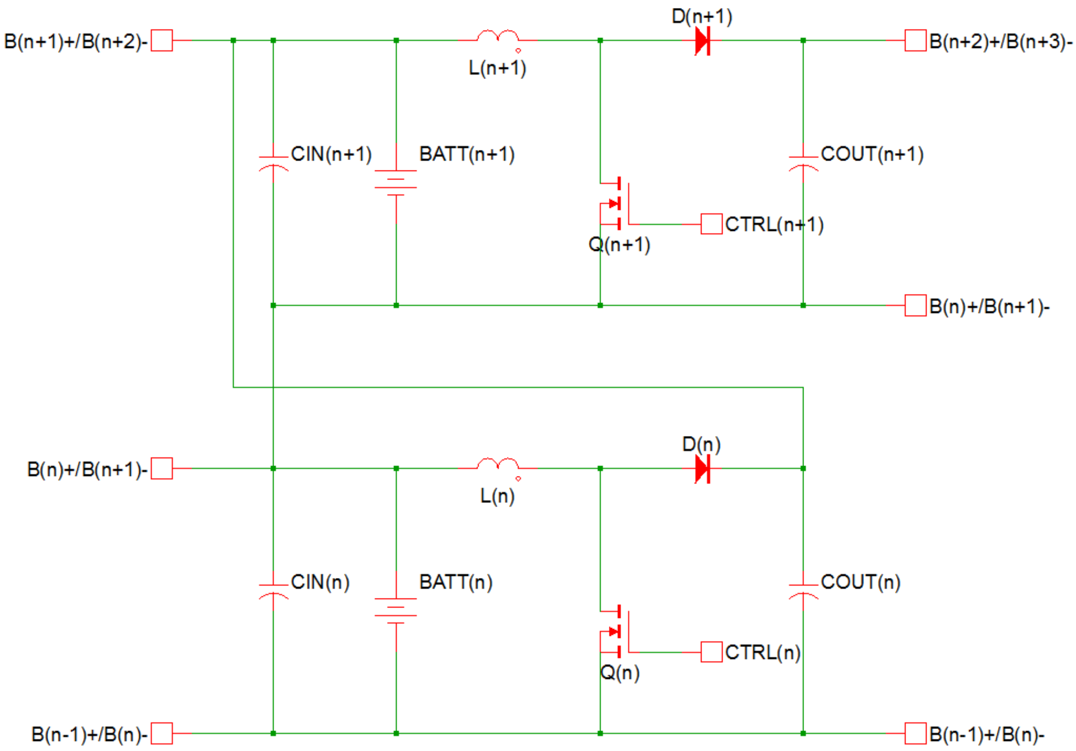



***Figure 8.4*** *Example of an active cell balancing circuit designed with Boost switching voltage regulators, having the load connected between the output and the input.*

The active cell balancing circuit proposed in this chapter, as well as in [23] (reference from the list of original publications), is shown in Figure 8.4 and its operating principle is based on the transfer of excess energy from the lower cell to the upper neighboring cell.

In order to validate the functionality of the proposed circuit, firstly, a series of computer-assisted simulations were performed, similar to what was proposed in [23] (original paper). All simulations presented in this chapter were performed using SIMPLIS, which is a simulation tool dedicated to analog switched-mode power supplies (SMPS).

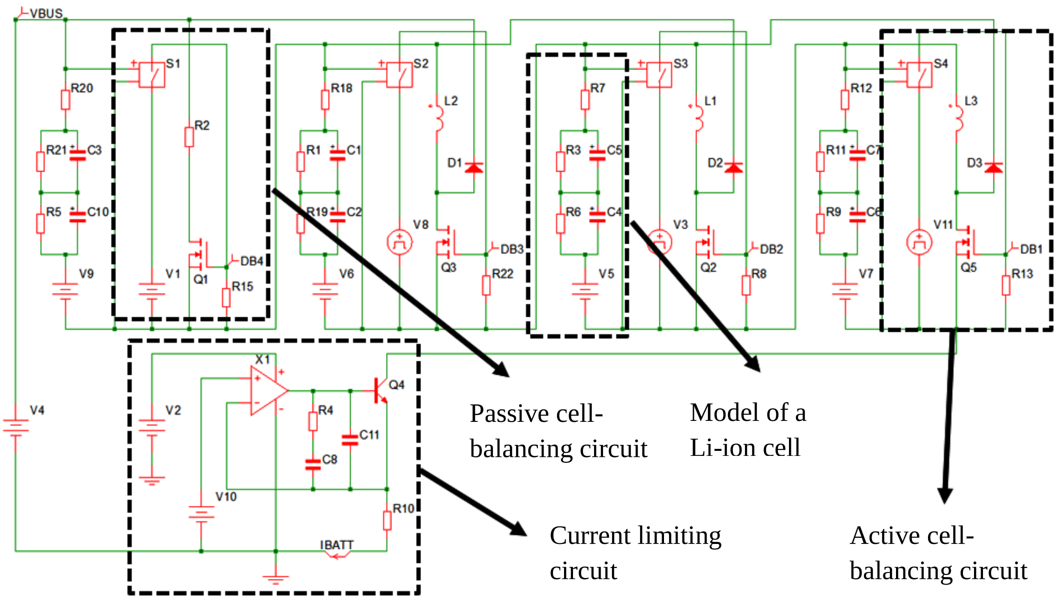



***Figure 8.6*** *Simplified electronic schematic of the active cell balancing circuit.*

After running the simulations, it resulted the output voltages (each with a nominal value of 4.15V and a hysteresis of ± 30 mV) for each cell (VB1, VB2, VB3 and VB4), during the charging and balancing phases, all these being shown in Figure 8.8.

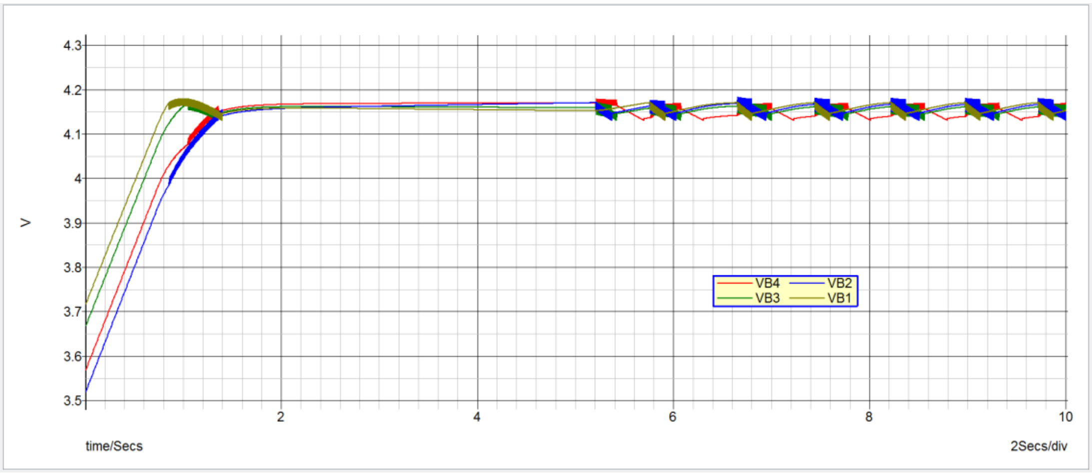



***Figure 8.8*** *The corresponding waveforms for the cells connected in series during the charging and balancing phase.*

For the practical implementation of the proposed cell balancing circuit, the computer program named Altium Designer was used, which is dedicated to the design of electronic schematics as well as printed circuit boards (PCB).

The charging circuit for the series-connected lithium-based cells, which has been designed and tested, is composed of three active circuits (implemented using simple DC-DC switching regulators), represented by asynchronous Boost converters operating at a fixed frequency (as opposed to other papers, which propose a more complex variable switching frequency control), together with a passive circuit (which uses load resistors) for the last cell at the top. The charging current for the entire string was set to 300 mA, while the constant voltage level for each cell was set to 4.15V, with a hysteresis of ±30 mV.

After selecting four used lithium-ion batteries (each with a nominal capacity of 2,200 mAh), which had different voltage levels, they were connected to the charging and balancing circuits shown in Figure 8.13.

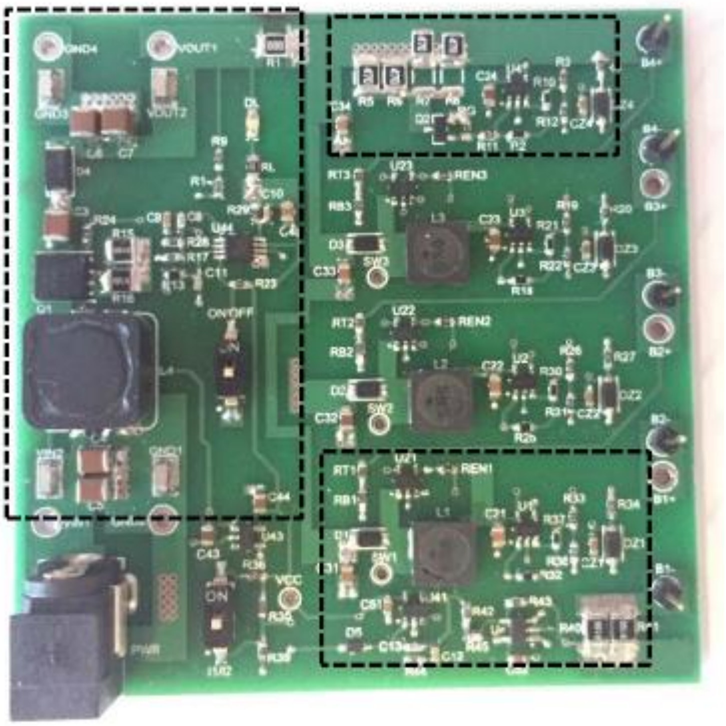



***Figure 8.13*** *Hardware implementation overview, consisting of the battery charger, 3 active cell balancing circuits and a passive cell balancing circuit.*

As expected, depending on the charge level of each lithium-ion cell, the corresponding balancing circuit alternately activates and deactivates (for a certain period of time) the corresponding switching voltage stabilizer (or MOSFET used for the passive circuit), in a manner similar to the simulated circuit, as can be seen in Figure 8.15.

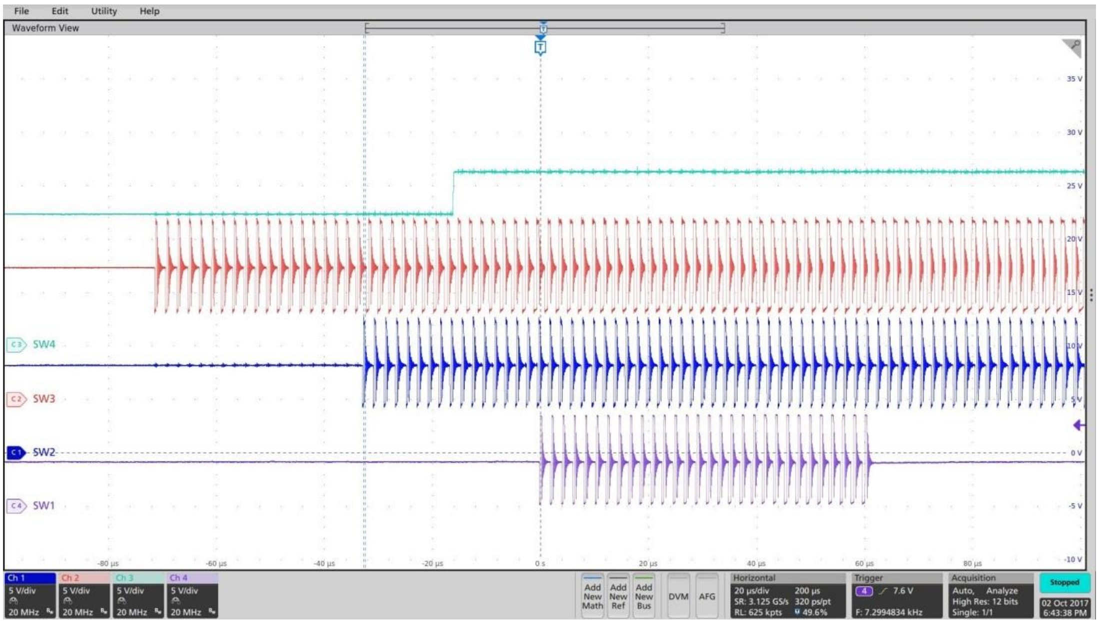



***Figure 8.15*** *Measured waveforms for series-connected cells during the charging and balancing phases.*

The design proposed in this thesis offers the possibility to balance the charge level of any cell in an efficient way, maximizing the life of the battery pack, as well as the total amount of useful energy stored, because the power conversion efficiency for active circuits is about 85%.

Depending on the targeted precision for the charging level (during the constant voltage phase) of each cell, dedicated comparators with integrated references (such as the MCP65R46) may be required and the hysteresis that causes the alternating activation and deactivation of the switching regulators may be reduced (from 60 mV to a lower value, for example, 30 mV), as this directly affects the maximum imbalance between batteries.

For optimal balancing performance, the switching regulators must be chosen according to their switching current limit and it is necessary to correlate it with the value of the charging current set for the entire rechargeable battery pack.

# Chapter 9

# Improving the energy consumption for motor vehicles by means of auxiliary energy storage systems

This chapter offers a collection of methods whose main purpose is to optimize the energy consumption of cars, and which is mainly based on the use of energy harvesting elements, combined with dedicated storage devices, in Start-Stop systems. The elements that allow the storage of electricity are made up of a pack of 4 Li-ion cells, connected in series, each with a capacity of 3,000 mAh, together with a bank of 6 supercapacitors, which have a capacity of 1,200F each.

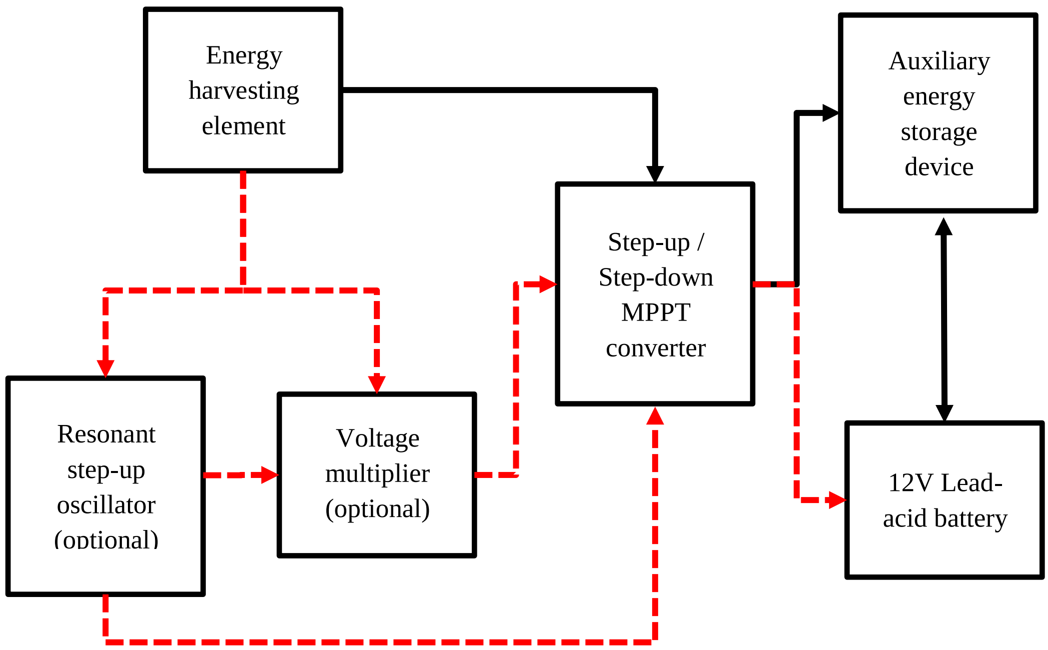



***Figure 9.2*** *Overview of the proposed energy harvesting system.*

The proposed system must be able to harvest energy from different sources (both when the vehicle is parked and when it is moving or stationary with the engine running), therefore the block diagram of the entire system is shown in Figure 9.2.

Because some energy harvesting sources (such as electromagnetic radiation or heat flux) provide small amounts of electricity at a low output voltage, it should be stepped up to about a few volts to allow current electronic circuits to operate correctly, therefore, an additional conversion stage is required. To this end, a series of tests were performed to validate the previous statement (as in [24]) using SIMPLS, which is a simulation program dedicated to switched-mode power supplies (SMPS).

The results of the computer-assisted simulations show that the output voltage of the energy harvesting element can be increased from about 50 mV to 1.4V in about 1 second, as shown in Figure 9.4.

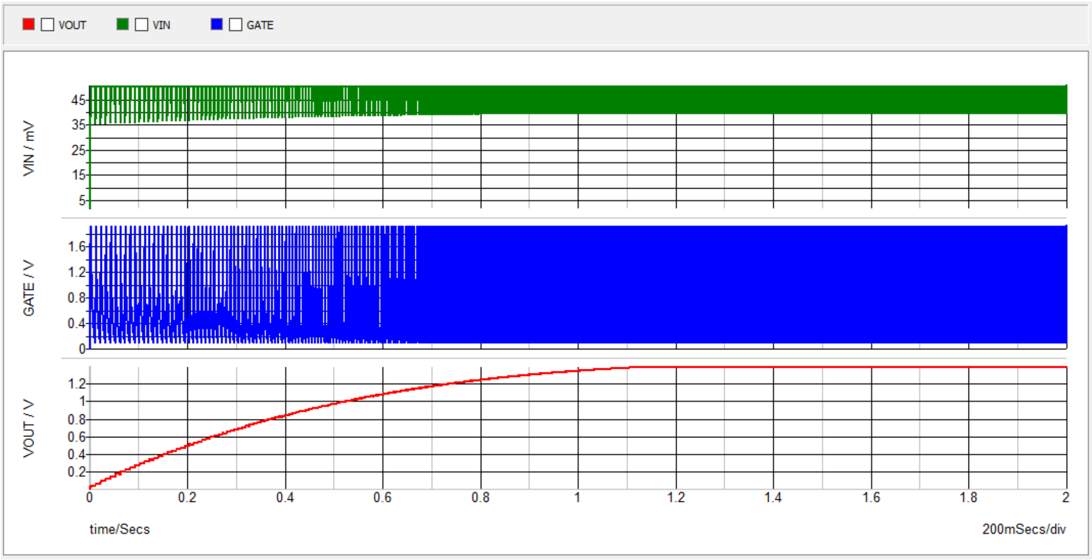



***Figure 9.4** Simulated waveforms for high voltage self-oscillating resonant converter.*

Figure 9.7 shows an overview of the circuit that has been physically created and can be used in energy harvesting applications, powered by photovoltaic cells, thermoelectric generators or even electromagnetic radiation.

Therefore, starting from certain available energy harvesting sources, various computer-assisted simulations were performed, as well as an experimental setup, to evaluate the feasibility of these auxiliary storage systems in the automotive industry.

Moreover, based on the actual measurements collected while driving in various heavy traffic situations (including traffic jams), a number of theoretical estimations have been developed, with regards to the amount of energy required to restart the heat engine whenever is necessary, by using a BSA as an important element of the Start-Stop system.

In addition, some mathematical calculations were performed in order to determine the amount of energy that can be harvested using a panoramic sunroof equipped with photovoltaic cells.

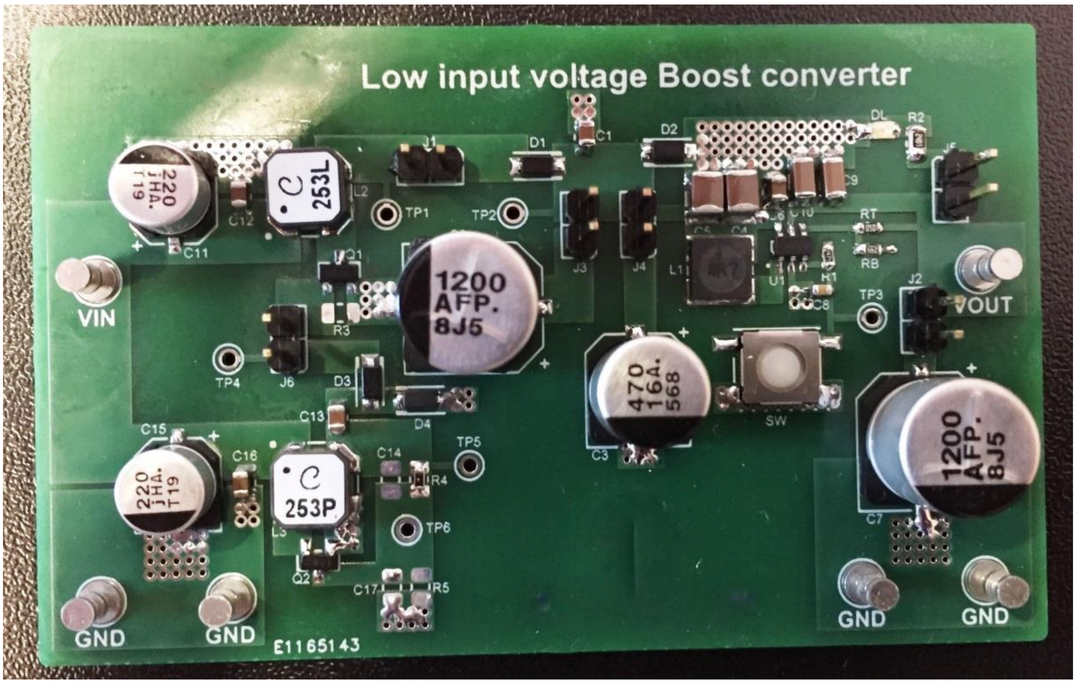



***Figure 9.7*** *Overview of the experimental setup used to obtain a stabilized 5V voltage from a 400 mV source.*

Unlike conventional Start-Stop systems, which use AGM lead-acid batteries capable of restarting the engine only a few times before reaching the predetermined discharge threshold, the auxiliary energy storage system (AESD) proposed in this chapter is designed to allow up to 100 restarts of the internal combustion engine within one hour, without overstressing the 12V battery.

On the other hand, compared to the existing systems that use the energy harvested by the panoramic sunroof equipped with photovoltaic cells only for the ventilation of the cabin during the summer, the system proposed in this thesis stores that amount of energy to supply the Start-Stop system.

Another important resource that can be exploited is the kinetic energy available when the vehicle brakes, which is why the implementation of such a system leads to maximizing the life of the brake pads and discs in an efficient way.

In addition to the benefits of reducing pollutant emissions and fuel consumption for conventional or hybrid electric vehicles, this system can bring other benefits, which improve both the reliability of the heat engine and the comfort of the driver and passengers.

# Chapter 10

# Conclusions

The issue of pollution, along with rising energy consumption, has become a global concern in recent decades and the car industry is increasingly forced to take actions in order to limit the harmful effects caused by these problems.

For this reason, the present paper aims to offer a series of design methods meant to facilitate the transition to less polluting vehicles with the aid of circuits, algorithms and technical solutions that can be implemented mainly in hybrid powertrains.

The motivation behind the decision to focus on the development of hybrid powertrains is influenced by several factors, including the age of the car fleet in our country, the energy deficit in the national system, the lack of battery charging infrastructure for electric cars, low purchasing power of Romanian drivers, as well as the difficulty of recycling the materials which are used to fabricate high voltage rechargeable batteries.

Studies have shown that, by 2021, Romania's national energy system did not have the capacity to sustain a consistent renewal of its fleet with fully electric vehicles and the transition could take several decades, even if the current potential of renewable energy resources would be properly exploited. On the other hand, a feasibility study has been carried out and it allows potential buyers to focus on a certain type of powertrain, depending on their budget, as well as on the duration and the mode of exploitation for the vehicle.

Moreover, this paper proposes an original method utilized for sizing the main components of hybrid powertrains, both series and parallel, as well as the development of algorithms capable of managing the energy transfer between different subassemblies, the main purpose being to reduce the energy consumption, together with the polluting emissions, without compromising the overall performance of the car.

A series of recommendations have also been proposed on the use of certain modern design techniques, as well as state-of-the-art composite materials, which further reduce energy consumption and pollutant emissions from the atmosphere.

In addition to the aforementioned methods, a number of constructive types, configurations and architectures of subassemblies which are unused or rarely used in the automotive industry have been proposed, along with electronic power systems and circuits, designed to improve the energy efficiency of all types of propulsion systems, but focusing on hybrid systems. This has been achieved both by designing a standalone analog circuit whose main purpose is to balance the charge of lithium cells connected in series and by developing an auxiliary system for storing energy harvested from various sources, which can be used in conjunction with a Start-Stop system.

## 10.1 Obtained results

Chapter 1 presented the field of the doctoral thesis, the purpose of the doctoral thesis and a summary of its content.

Chapter 2 presents a series of information regarding the air pollution, focusing on vehicle emissions. On the other hand, the issues related to energy generation and conversion were highlighted, as well as the main energy sources, especially renewable ones, which have a high potential for exploitation and ensuring the quantity needed to satisfy the consumption during the next period. This chapter is of particular importance for the development of less polluting vehicles, as it is very necessary to know the primary sources from which the energy used to power them is derived. Thus, under certain conditions, biofuels that power conventional heat engines can have a less harmful effect on both human health and the environment compared to the electricity (used to power all-electric vehicles) produced by burning coal or hydrocarbons. On the other hand, if properly exploited, renewable energy sources can indeed represent a less polluting alternative to those currently used.

In Chapter 3 it was conducted a study on the implications of the transition to less polluting vehicles (which is applicable at least for our country) and on the other hand, a series of information and calculations were provided, to determine the optimal choice regarding the most suitable type of powertrain for vehicles, depending on certain criteria, which any buyer can apply to meet their own needs. Thus, from the sustainability standpoint, the current energy situation does not allow the transition to fully electric vehicles in the near future. On the other hand, in terms of cost-effectiveness, hybrid electric models equipped with diesel engines have an advantage over both conventional and fully electric ones.

Chapter 4 deals mainly with hybrid powertrains for motor vehicles, as well as the control strategies that can be applied to them, thus classifying the types of hybrid powertrains proposed in the literature.

Next are presented the limitations that did not allow until recently the development and implicitly the penetration on the market of some hybrid electric vehicles that are really competitive in many aspects, compared to the conventional ones, which are equipped only with thermal engines. Then, there are highlighted some methods proposed by the author in order to improve the efficiency of heat engines, and thus reduce pollutant emissions, then to optimize energy consumption for the traction electric motor, to optimize the efficiency of the electric generator, together with its associated power converters, followed by methods of improving the transmissions and energy storage devices.

The chapter concludes with a summary of two types of currently available hybrid powertrains, as well as a list of fully-electric and hybrid vehicles, which highlights the architecture used, some technical features and the minimum purchase price, the main purpose being to facilitate the selection process for potential buyers, if they choose to apply the methodology presented in Chapter 3 before purchasing a car.

Chapter 5 deals with the design of hybrid powertrains and proposes a method of real-time measurement of heat engine parameters, by using a computerized interface dedicated to fault diagnosis. Furthermore, this method is validated by mathematical calculations and computer-assisted simulations, in order to confirm the obtained results.

Next, Chapter 6 proposes the development of a plug-in series-hybrid powertrain, based on the methodology presented above, as well as the implementation of an algorithm that aims to manage its energy consumption. Thus, by measuring some parameters of the internal combustion engine that equips a conventional car, during its travel on public roads, it was possible to determine the basic characteristics of the proposed hybrid powertrain and to properly size the main components, in order to maintain the performance of the original classic engine from which the measurements were taken.

In Chapter 7, two types of parallel-hybrid powertrains were proposed, the development and sizing of which were also based on the methodology proposed in Chapter 5. Therefore, the first proposed powertrain is capable of matching the performance of an internal combustion engine of a larger displacement, while the second one also allows the vehicle to travel in full electric mode, in order to reduce both fuel consumption and pollutant emissions.

In Chapter 8, the focus was moved on the development of a standalone analog active cell-balancing circuit for lithium-based batteries connected in series, which are part of the hybrid and fully electric vehicles.

Chapter 9 focused on the design and implementation of an auxiliary system for storing energy from different sources, which can be used, in particular, to reduce both fuel consumption and pollutant emissions by the means of Start-Stop systems.

Chapter 10 summarizes the conclusions of this thesis, starting with the results obtained, continuing with the presentation of the original contributions, as well as the list of original publications, while at the end are presented the perspectives for further development.

## 10.2 Original contributions

1. It has been carried out an analysis on the pollutant emissions which are produced, in particular, by motor vehicles, as well as on the energy sources available on Earth. Moreover, the main forms of renewable energy were presented, along with their potential to meet current consumption, together with the methods of conversion and the associated conversion facilities [Chapter 2].
2. It was made an analysis on the evolution of the price for crude oil on the international market, as well as the price of fossil fuels in Romania, in recent years. In addition, statistics have been presented on the production and consumption of electricity in our country in recent times. In the context of the transition to less polluting vehicles, calculations were made to establish the necessary amount of electricity, in order to renew a fraction of the current car fleet in Romania. Moreover, the distribution by age categories and pollution norms of the vehicles currently registered in our country was analyzed, in order to be able to estimate the time required for the transition to fully electric vehicles to take place [Subchapter 3.1].
3. A feasibility study was carried out in order to determine the optimal type of powertrain according to certain criteria, such as the duration of operation for the vehicle and the available budget, respectively. To this end, calculations were made to determine the total expenses related to car acquisition, repairs, payment of taxes, maintenance, etc., for different scenarios of operation for the vehicle, taking into account the type of fuel used. Moreover, a comparison was made both in terms of weight and acquisition cost for a potential hybrid car equipped with a powertrain that was proposed in this thesis [Subchapter 3.2].
4. It was made a presentation of the main types of hybrid powertrains found in the literature, together with their control strategies [Subchapter 4.1].
5. A number of improvements have been proposed for the energy consumption of motor vehicles, which can be achieved by redesigning the major components of hybrid powertrains and which can also lead to a reduction in pollutant emissions that are mainly caused by the internal combustion engines [Subchapter 4.2].
6. It was created a brief presentation of two parallel-hybrid powertrains that equip newly produced car models, as well as a list of various hybrid and electric models marketed in Europe, in 2021, in order to highlight the diversity of architectures available on the car market [Subchapter 4.3].
7. A method of real-time measurement and specification of many important parameters for heat engines has been presented, in order to facilitate the development of powertrains. This method has been validated both by mathematical calculations and by computer-assisted simulations. Several

general design methods have also been proposed, to improve the energy consumption of motor vehicles [C3], [J3], [R5], [Chapter 5].

8. It has been proposed a plug-in series-hybrid powertrain, which was designed based on information collected from a conventional car when traveling on public roads, during different seasons, using the methodology presented before. In addition to sizing the main components of the series-hybrid powertrain, it has been developed an algorithm capable of managing (mainly) the power delivered by the internal combustion engine to the electric generator, in order to store the necessary energy inside the high voltage battery [C4], [J3], [R5], [Chapter 6].
9. A series of real-time measurements were performed, which contributed to the sizing of the main components of a plug-in parallel-hybrid powertrain, which is capable of matching the performance of a larger displacement internal combustion engine. It has also been developed an algorithm on the basis of which the energy stored within the high voltage battery can be delivered to the electric traction motor, in order to ensure the necessary power while driving the vehicle on public roads [C1], [R1], [Subchapter 7.1 ].
10. On the other hand, based on the methodology of measuring parameters in real time using a diagnostic interface, it was proposed a plug-in parallel-hybrid powertrain which is capable of matching the performance of a conventional engine featuring a larger displacement, but at the same time, it allows the vehicle to move in fully electric mode. In addition to this, it was developed an algorithm dedicated to the management of electricity stored within the high voltage battery pack, based on which the main subassemblies of the proposed hybrid powertrain were dimensioned [C2], [R2], [Subchapter 7.2].
11. An active, standalone analog cell-balancing circuit has been developed to equilibrate the charge of lithium cells connected in series, which are part of the battery packs that are used in both hybrid and electric vehicles. In addition to mathematical calculations and computer-assisted simulations, an experimental set-up was performed, with the help of which the concept proposed in this thesis was validated [J1], [R3], [Chapter 8].
12. An auxiliary system for storing energy from various sources has been proposed, developed and partially implemented, on the basis of which both fuel consumption and the amount of exhaust emissions can be reduced through the usage of intelligent Start-Stop systems. Energy harvesting can be achieved by the means of devices placed in different predefined areas of the vehicle [J2], [R4], [Chapter 9].

## 10.3 List of original publications

### 10.3.1 Articles presented at international conferences

[C1] **B. Anton**, A. Florescu, *Matching the Performances of a Diesel Engine with a Mild-Hybrid Driving System, based on Telemetry Data*, în Proceedings of the 10th International Symposium on Advanced Topics în Electrical Engineering (ATEE 2017), March 23-25, 2017, Bucharest, România, pp. 159-U941, ISBN: 978-1-5090-5160-1, ISSN: 1843-8571, Web of Science Categories: Engineering, Electrical & Electronic, Accession Number: WOS: 000403399400032 [ISI Web of Knowledge].

[C2] **B. Anton**, A. Florescu, *Simple power management control for a plug-in mild-hybrid Diesel powertrain*, Electronics, Computers and Artificial Intelligence (ECAI) 2017 – International Conference – 9th Edition, 29 June - 01 July, 2017, Targoviste, România, ISBN: 978-1-5090-6457-1, DOI: 10.1109/ECAI.2017.8166408, WOS: 000425865900024 [ISI Web of Knowledge].

[C3] **B. Anton**, A. Florescu, *Measuring vehicle's powertrain parameters using diagnostics interface*, 2020 12th International Conference on ECAI, Bucharest, România, 2020, ISBN: 978-1-7281-6843-2, ISSN: 2378-7147, Web of Science Categories: Engineering, Electrical & Electronic, Accession Number: WOS: 000627393500132 [ISI Web of Knowledge].

[C4] **B. Anton**, A. Florescu, *Design guidelines for series-hybrid powertrains*, 2020 12th International Conference on ECAI, Bucharest, România, 2020, ISBN: 978-1-7281-6843-2, ISSN: 2378-7147, Web of Science Categories: Engineering, Electrical & Electronic, Accession Number: WOS: 000627393500088 [ISI Web of Knowledge].

### 10.3.2 Articles published in international scientific journals

[J1] **B. Anton**, A. Florescu, S. G. Roșu, *Standalone analog active cell-balancing circuit for automotive Battery Management Systems*, Revue Roumaine des Sciences Techniques – Serie Electrotechnique et Energetique, vol. 63, 3, pp. 306–313, 2018, Bucharest, Iul-Sept. 2018, ISSN: 0035-4066, Web of Science Categories:Engineering, Electrical & Electronic, Accession Number: WOS: 000454752800012 [ISI Web of Knowledge].

[J2] **B. Anton**, A. Florescu, L. A. Perișoară, A. Vasile, R. C. Constantinescu, S. G. Roșu, *Methods of maximizing power efficiency for hybrid vehicles*, Revue Roumaine des Sciences Techniques – Serie Electrotechnique et Energetique, vol. 64, no. 1, pp. 57– 62, 2019, Published: Jan-Mar 2019, WOS: 000464302300010 [ISI Web of Knowledge].

[J3] **B. Anton**, A. Florescu, *Design and development of series-hybrid automotive powertrains*, IEEE Access, Volume: 8, Pages: 226026-226041, Published: 2020, Web of Science Categories: Computer Science, Information Systems; Engineering, Electrical & Electronic; Telecommunications, ISSN: 2169-3536, DOI: 10.1109/ACCESS.2020.3044500, WOS: 000603731500001 [ISI Web of Knowledge] **(Q1 article, awarded by UEFISCDI in 2021)**.

### 10.3.3 Scientific research reports

[R1] **B. Anton**, *Echivalarea performanțelor unui motor Diesel cu un sistem de propulsie microhibrid, bazată pe date de telemetrie*, June 2017.

[R2] **B. Anton**, *O strategie simplă de control al puterii pentru un propulsor Diesel hibrid care permite încărcarea acumulatorilor de la rețeaua electrică*, December 2017.

[R3] **B. Anton**, *Circuit analogic autonom pentru echilibrarea celulelor din sistemele de încărcare a bateriilor de acumulatori utilizate în industria auto*, June 2018.

[R4] **B. Anton**, *Metode de optimizare a consumului de energie pentru automobile*, December 2018.

[R5] **B. Anton**, *Considerente de proiectare pentru un sistem de propulsie de tip hibrid-serie*, June 2019.

### 10.3.4 Projects and contracts

[P1] *Excellence Research Grants* Programme, UPB – GEX 2017. Identifier: UPB – GEX2017, Contract number: 33/25.09.2017.

[P2] *Dezvoltarea competenţelor de antreprenoriat ale doctoranzilor şi postdoctoranzilor – cheie a succesului în carieră (A-Succes)* Programme, Contract number: 51675/09.07.2019 POCU/380/6/13 – Cod SMIS: 125125.

## 10.4 Perspectives for further developments

Given that hybrid powertrains are the best choice for the transition to less polluting vehicles and this will take place over the next few decades, their development is very important.

Therefore, regarding the systems proposed and discussed in this thesis, the following directions of further development can be identified:

1. The feasibility studies carried out in Chapter 3 can be improved by constantly updating the statistical data on the production and consumption of electricity in our country, as well as the share of each type of fuel used to generate it. On the other hand, updates of fossil fuel prices, as well as electricity prices (by distributors), depending on annual consumption or power delivered, should be included in these statistics. Moreover, the evolution of the Romanian vehicle fleet can be continuously monitored, in order to obtain conclusive data, in terms of choosing the optimal type of powertrain for the vehicle to be purchased. For this purpose, the study on the costs related to the purchase, operation and sale of a vehicle could be expanded, by including an extended

number of brands and models, but also by adding or detailing operations specific to each category of expenses.

2. The measurement method proposed in Chapter 5 may be applied to various models of cars or other types of vehicles developed by different manufacturers and may be used to collect other parameters from various control modules installed in the vehicle, which may contribute to the improvement of energy management.
3. Any of the hybrid powertrains proposed and presented in Chapters 6 and 7 could be practically implemented on a motor vehicle, and after validation in real driving conditions, both the sizing of the basic components of the systems, as well as the algorithms that manage the energy flow may be adjusted, in order to obtain improved results compared to the original models.
4. The active standalone analog cell-balancing system presented in Chapter 8 may be extended to several series-connected lithium-based cells and validated or enhanced by using a high-voltage battery pack that can be found in a hybrid or all-electric vehicle.
5. The auxiliary energy storage system, which was presented in Chapter 9, could be developed as a prototype, validated and improved. After that, it can be implemented on a conventional, hybrid or even fully electric vehicle (with the appropriate modifications).

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