Universitatea Națională de Știință și Tehnologie Politehnica București
FACULTATEA DE INGINERIE ELECTRICA

TEZĂ DE DOCTORAT

- BRIEFING -

CONTRIBUȚII PRIVIND SISTEMUL DE MANAGEMENT AL BATERIILOR UTILIZATE ÎN TRANSFERUL WIRELESS AL ENERGIEI ELECTROMAGNETICE LA AUTOVEHICULELE ELECTRICE

CONTRIBUTIONS ON BATTERY MANAGEMENT SYSTEM USED IN THE WIRELESS TRANSFER OF ELECTROMAGNETIC POWER IN ELECTRIC VEHICLES

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List of abbreviations

WPT – Wireless Power Transfer
VE / EV – Vehicul Electric / Electrical Vehicle
BMS / BMS – Sistem de Management al Bateriei / Battery Management System
VH / HV – Vehicul Hibrid / Hybrid Vehicle
IEEE - Institutul de Inginerie Electrică şi Electronică
WiTricity – Wireless Electricity
IPT – Inductive Power Transfer
IRPT – Inductive Resonant Power Transfer
CWPT – Capacitor Wireless Power Transfer
IGU / GUI – Interfață Grafică cu Utilizatorul / Graphical User Interface
CC / DC – Curent Continuu / Direct Current
CI / IC– Combustie Internă / Internal Combustion
CA / AC – Curent Alternativ / Alternative Current
AMDE – Analiza Modurilor de Defectare si a Efectelor
FMEA – Failure Mode and Effects Analysis
PAC / CAD – Proiectare Asistată de Calculator / Computer Aided Design
$L_{p,s}$ – autoinductanță primar / secundar
$C_{p,s}$ – autocapacitate primar / secundar
k – Coeficient de cuplare
Q – Factor de calitate
NiCd – Nichel Cadmiu
NiMH – Nichel Metal Hydrid
Li-Ion – Litiu Ioni
LiS – Litiu Sulf
RSA / SAR – Raport Specific de Absorbție / Specific Absorbtions Rate
SWn – Switch / Comutator n
ICR - Lithium Cobalt Oxide cylindrical cell
AIAG - Automotive Industry Action Group
VDA - Verband der Automobilindustrie
ISO - International Organization for Standardization
IEC - International Electrotechnical Commission
ANIS - Automotive Nivel de Integritate a Siguranței
ASIL - Automotive Safety Integrity Level
OS / SG – Obiectiv de Siguranță / Safety Goal
QM – Quality Management
FTA – Fault Tree Analysis
IPR / RPN – Indice de Prioritate al Riscului / Risk Priority Number
APE / EDA – Automatizarea Proiectării Electronice / Electronic Design Automation
PEAC / CAD – Proiectare Electonică Asistată de Calculator / Electronic Computer Aided Design
FPGA – Field Programmable Gate Arrays
FAC / CAM – Fabricare Asistată de Calculator / Computer Aided Manufacturing
APIS IQ-RM - Automation Process Innovation Software Integrated Quality Risk Management
CC / CC – Caracteristică Critică / Critical Characteristic
IDE – Integrated Development Environment

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CHAPTER 1
INTRODUCTION

The purpose of this paper is to examine and analyze wireless power transfer in the context of electric vehicles. The paper focuses on identifying the main advantages and challenges associated with this technology, evaluating the efficiency of wireless transfer systems, as well as their impact on the infrastructure and users of electric vehicles and especially on the Battery Management System (BMS/BMS) which has become essential to optimize the performance, reliability and durability of batteries in electric vehicles.

The course will explore the main components of wireless transfer systems such as induction coils, control electronics and power management systems. Existing wireless charging methods such as magnetic resonance charging and electromagnetic induction charging will also be reviewed, evaluating them in terms of efficiency, compatibility and technical feasibility. The thesis focuses on the analysis and development of an electric battery management system for electric vehicles, the main purpose of this system is to monitor and control key battery parameters such as voltage, current, temperature and state of charge to maximize efficiency and their lifespan.

I hope this paper will be of interest and make significant contributions to the field of battery management systems for electric vehicles. By investigating and analyzing these systems in detail, I propose to stimulate and develop innovative and efficient solutions for battery management in electric vehicles, thus contributing to the development of a more sustainable and greener mobility.

1.1. CURRENT STATE OF THE GLOBAL AUTO INDUSTRY

The automotive industry is a key driver of the world economy and represents a major sector of production, employment and innovation. Sustainability and environmental impact by reducing carbon emissions remain key priorities. The automotive industry is committed to the development of alternative technologies, such as hydrogen vehicles and renewable fuels, as well as the implementation of sustainable practices in production processes [1].

The current development trends of the industry are:

- The transition to electric mobility;
- Autonomy and autonomous driving technology;
- Digitization and personalization.

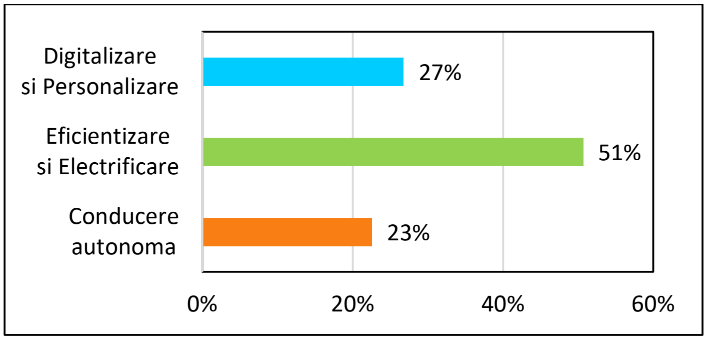


Fig. 1.1. Distribution of initiatives in relation to automotive market trends [1]

In terms of electric batteries, current research is moving towards increasing energy densities (160 Wh/kg) as well as investigating various Li-based chemistries to support market demands for electric battery capacity. The LiSi or Li-air (oxygen) combination have some of the highest energy densities, with a multiplication factor of about 10 times higher than the Li battery with graphite anode, the cost advantage being clearly in favor of silicon.

In conclusion, the automotive industry is in a period of significant transformation. Current and future challenges and opportunities are driving rapid change and adaptation in the field. Automakers are turning their attention to electric vehicles, advanced technologies, and innovative mobility services while facing infrastructure, regulatory, and security challenges. By addressing these challenges and looking to the future, the automotive industry has the potential to create sustainable, efficient and safe solutions for public and personal transport. Through collaboration, innovation and adaptability, the automotive industry can help develop greener mobility and improve the quality of life for people around the world.

1.2. MOTIVATION FOR CHOOSING THE RESEARCH TOPIC

The choice of the topic of wireless energy transfer to cars based on electric propulsion and electric battery management is determined by the increased importance of sustainable mobility and the development of electric vehicles in recent decades. This theme addresses two crucial aspects of the evolution of the automotive industry: the efficient and convenient charging of electric vehicles and the optimization of battery performance and lifetime. In this chapter, we will explore the motivations behind the choice of this theme and their importance in the current context:

- Sustainable mobility and the reduction of carbon emissions;
- Improved autonomy of electric vehicles;
- Efficiency and convenience of loading;
- Optimizing performance and battery life;
- Innovation and research in wireless transfer and battery management.

In conclusion, the choice of the topic of wireless energy transfer to cars and electric battery management is motivated by the need to develop sustainable and efficient solutions for the mobility of the future. In a world where sustainability and energy efficiency are becoming higher priorities, wireless transfer and battery management are key directions to meet these challenges. Through research, innovation and collaboration, we can contribute to the development of efficient wireless charging infrastructure and advanced management systems, thereby strengthening the evolution of electric vehicles and facilitating the transition to sustainable mobility..

1.3. RESEARCH OBJECTIVES

Car battery management is an essential aspect in the development of electric vehicles and in ensuring their performance, reliability and durability. Research in this area aims to improve battery performance, extend battery life, optimize energy use and ensure a safe and efficient experience for electric vehicle users.

The development of software to control the management of electric batteries in cars is an essential objective in the evolution of electric vehicles. This research area focuses on the development of algorithms and control systems that optimize the performance, durability and efficiency of batteries, thus ensuring an optimal and safe experience for electric vehicle users. In this thesis, we will explore the key research objective in the development of electric battery management control software and its importance in the context of electric vehicle development. By means of advanced algorithms and sophisticated control systems, the research aims to improve the efficiency and energy storage capacity of batteries, thus enabling the increase of the autonomy of electric vehicles. By optimizing energy management and charging and discharging characteristics, battery performance can be maximized and a superior user experience for electric car drivers can be ensured.

The specific objectives of this thesis, which support the general objectives listed above, are the following:

- analysis, modeling and simulation in the SimulIDE simulation application of the battery management system using the Arduino Uno controller;
- designing and developing the prototype of the battery management system around the Arduino Uno controller;
- development of the control program in the C language of the battery management system
- integration and testing of the battery management system prototype;

In conclusion, the development of electric battery management control software is a crucial goal in the evolution of electric vehicles. By optimizing battery performance and autonomy, extending battery life, ensuring safety and proper integration into the vehicle system, research in this area contributes to the development of a superior experience for electric car users.

1.4. THESIS STRUCTURE AND CONTENT

The work is structured in 4 chapters as follows:

In **Chapter 1 - Introduction**, general aspects related to the formulation of the problem in this research are presented. In the second part, the objectives of this doctoral thesis are presented.

Chapter 2 entitled **The technology of wireless transfer of electromagnetic energy to electric cars** is dedicated to the description of the most known and used wireless transfer systems of electromagnetic energy and electric battery management systems, a market study on the presence of these technologies at the level is also presented world.

In **Chapter 3** entitled **Contributions regarding the realization of the BMS prototype**, a detailed analysis of an electric battery management system is presented from the functional point of view, risk, simulation and implementation of a prototype based on Li-Ion electric cells.

In **Chapter 4** - **Conclusions**, the conclusions of the scientific activity carried out during the development of the doctoral thesis, as well as a series of future research directions, are presented.

1.5. DISSEMINATION OF RESULTS

The dissemination of the results was achieved by publishing a number of 9 scientific articles, of which 1 as first author and 8 as co-author, as follows:

1. **Horatiu Samir Popescu**, Marius Florin Stăniloiu, Mihai Iordache, *"A method for extracting the main parameters of an NPN bipolar transistor from datasheet for use in the SPICE model",* MPS 2023, DOI 10.1109/MPS58874.2023.10187554, Publisher: IEEE.
2. Marius Florin Stăniloiu, **Horatiu Samir Popescu**, Mihai Iordache, *„SPICE model of a "n" channel MOSFET transistor",* MPS 2023, DOI 10.1109/MPS58874.2023.10187532, Publisher: IEEE.
3. Mihaela Grib, Mihai Iiordache, Alexandru Radu Grib, **Horatiu Popescu**, Ovidiu Laudatu, Marius Stăniloiu, *„The Use of Thévenin, Norton and Hybrid Equivalent Circuits in The Analysis and Polarization of Nonlinear Analog Circuits",* 2022 International

Conference and Exposition on Electrical And Power Engineering (EPE), DOI 10.1109/EPE56121.2022.9959871, Number: **WOS:000709089900001,** Publisher: IEEE.

4. Marius-Florin Stăniloiu, **Horatiu-Samir Popescu,** Georgiana Rezmeriță, Ionela Vlad, Mihai Iordache, *„SPICE model of a real Zener diode tested at room temperature”,* 2022 International Conference and Exposition on Electrical And Power Engineering (EPE), DOI 10.1109/EPE56121.2022.9959813, Publisher: IEEE.
5. Mihai Iordache, **Horatiu Samir Popescu**, Ionela Vlad, Marius Florin Staniloiu*, „ACAP - Analog Circuit Analysis Program”,* 2021 12th International Symposium on Advanced Topics in Electrical Engineering (ATEE), DOI 10.1109/ATEE52255.2021.9425307, Accession Number: **WOS:000676164800143**, Publisher: IEEE.
6. Victor Bucata, Mihai Iordache, Ionela Vlad, Alina Orosanu, **Horatiu Samir Popescu**, Marius Florin Staniloiu*, „Thévenin Equivalent Circuits for Magnetisc Coupling Resonators (Series–Series, Series– Parallel) in Wireless Power Transfer Systems”,* 2021 International Conference on Applied and Theoretical Electricity (ICATE), DOI 10.1109/ICATE49685.2021.9464933, Number: **WOS:000709089900001,** Publisher: IEEE.
7. Victor Bucata, Mihai Iordache, Ionela Vlad, Alina Orosanu, **Horatiu Samir Popescu,** Marius Florin Staniloiu*, „Wireless Power Transfer Systems: Thévenin Equivalent Circuits for Parallel-Series and Parallel-Parallel Magnetic Resonator Configurations”,* 2021 International Conference on Applied and Theoretical Electricity (ICATE), DOI 10.1109/ICATE49685.2021.9464974, Accession Number: **WOS:000709089900011,** Publisher: IEEE.
8. Marius Florin Staniloiu, **Horatiu Samir Popescu**, Bogdan Ionut Glod, Mihai Iordache*, „SPICE model of a real capacitor : Capacitive feature analysis with voltage variation”,* 2020 International Conference and Exposition on Electrical And Power Engineering (EPE), DOI 10.1109/EPE50722.2020.9305554, Publisher: IEEE.
9. Marius Florin Staniloiu, **Horatiu Samir Popescu**, Bogdan Ionut Glod, Mihai Iordache, *„SPICE Model of a Real Coil Inductance feature analysis with current variation”,* 2020 International Conference and Exposition on Electrical And Power Engineering (EPE), DOI 10.1109/EPE50722.2020.9305677, Publisher: IEEE.

CHAPTER 2

THE TECHNOLOGY OF WIRELESS TRANSFER OF ELECTROMAGNETIC ENERGY IN ELECTRIC CARS

The technology of wireless transfer of electromagnetic energy in electric cars represents a significant innovation in the field of electric mobility. This technology provides a convenient and efficient way to charge electric vehicles, eliminating the need for physical connection through cables and sockets.

Wireless energy transfer is based on the law of electromagnetic induction. A transfer system consists of two main components: a charging station or transmitter and a receiver mounted on the electric vehicle. The transmitter generates a high-frequency oscillating electromagnetic field, and the receiver, located under the vehicle, captures the electromagnetic energy and converts it into electrical energy to charge the battery.

In conclusion, the technology of wireless transfer of electromagnetic energy represents a promising direction in the field of electric mobility. This provides convenience, reliability and flexibility in charging electric vehicles, eliminating the need for physical connection. With continued research and technological development, this technology can become a common and affordable solution for electric vehicle charging in the future of sustainable mobility.

2.1. BRIEF HISTORY OF WIRELESS TRANSFER OF ELECTROMAGNETIC ENERGY

The technology of wireless transfer of electromagnetic energy in electric cars is the result of an evolutionary process that began a long time ago. The history of this technology spans several decades and has gone through several key stages in its development. Figure 2.1 shows the development timeline of wireless electromagnetic energy transfer systems.

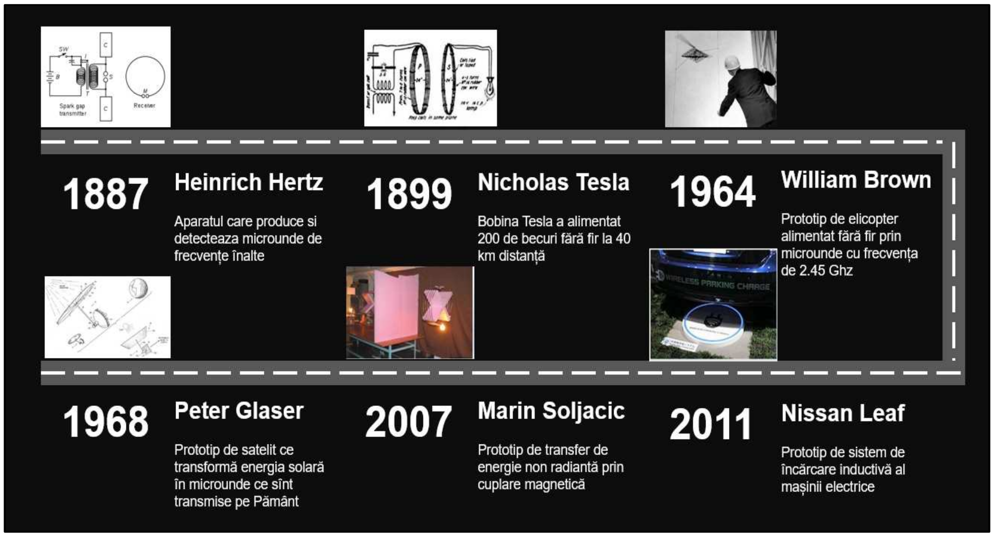


Fig. 2.1. Chronology of the development of wireless energy transfer systems [3]

2.2. CURRENT STATE OF KNOWLEDGE IN THE FIELD

Wireless transfer of electromagnetic energy, also called contactless power transfer, is a type of energy transfer without direct contact (conductive wires) through various transfer technologies. There are several methods of wireless transfer of electromagnetic energy, some of the most commonly used are listed below [3]:

- Electromagnetic induction;
- Electromagnetic resonance;
- Microwaves;
- Laser.

Figure 2.2 shows a classification of the various types of wireless power transfer:

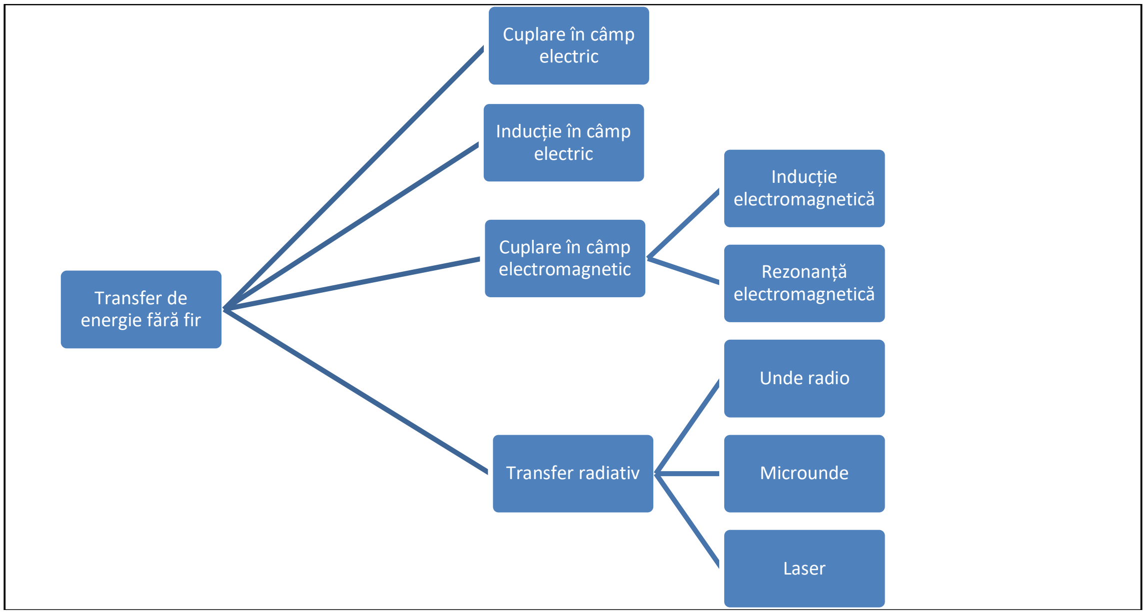


Fig. 2.2. Wireless electromagnetic energy transfer methods [4]

2.3. WIRELESS ELECTROMAGNETIC ENERGY TRANSFER METHODS

The basic block diagram of a wireless power transfer system for static electric or hybrid vehicle charging application is illustrated in figure 2.2. For the transfer of energy from the transmitting coil to the receiving coil, alternating energy from the electrical network is converted into high-frequency alternating energy by converter devices. To improve system efficiency, series/parallel compensation topologies are present on both the receiver and transmitter sides. Also included is the Power Management, Communications and Battery Management (BMS) system to avoid any health and safety issues and ensure stable operation. Magnetic ferrite plates are used on both the transmitter and receiver sides to reduce any harmful magnetic leakage fluxes and improve magnetic flux distribution.

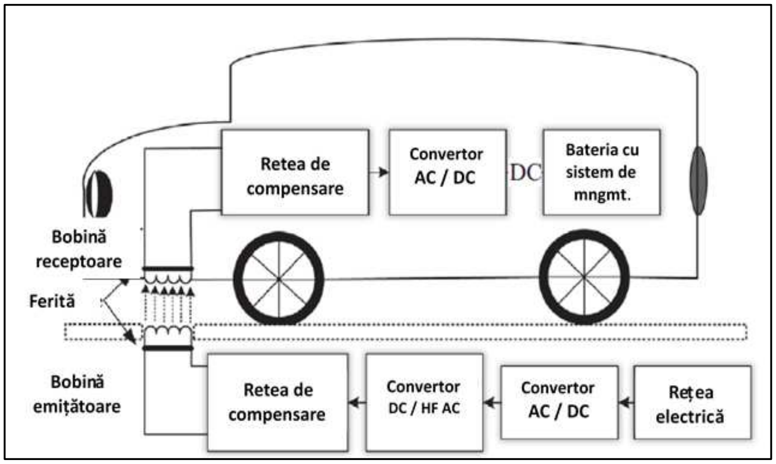


Fig. 2.2. Electric Vehicle Wireless Power Transfer System Architecture [5]

The receiver coil mounted under the car together with the power electronics, converts the oscillating magnetic field into high-frequency alternating current which in turn is converted into direct electric current, which through the battery management system is stored in electric cells based mainly on Li chemistry Ion (iron sulfate or manganese oxide due to stability and safety in operation).

2.3.1. Capacitive wireless transfer of electrical power (CWPT)

Capacitive wireless power transfer is an innovative method of transmitting electromagnetic energy between two or more devices without the need for a physical connection through cables. This technology is based on the principle of electrical capacitance, where two objects with opposite electrical charges can transfer electrical energy to each other by means of an electric field created between them. The low cost and simplicity of CWPT technology, using advanced geometric and mechanical structures of coupling capacitors, is very useful for low-power applications such as portable electronic devices, cell phone chargers, and rotating machinery.

To date, the application of CWPT for electric vehicles has been limited due to large air gaps and high-power level requirements. A stationary laboratory prototype with power >1 kW has been demonstrated with an efficiency of about 83% from the DC source to the battery bank at the operating frequency of 540 kHz.

Capacitive wireless power transfer is an exciting direction in the field of wireless charging and power transfer. With the continued development of technologies and research in this field, current limitations can be overcome and significant advantages for charging and using devices can be achieved.

2.3.2. Wireless inductive transfer of electrical power (IPT)

Wireless inductive power transfer is an advanced and increasingly widespread method of transmitting electromagnetic energy between devices without the need for a physical connection through cables. This technology is based on the principle of electromagnetic induction, where a variable magnetic field is used to transfer electrical energy from a source to a receiver.

Traditional IPT was developed by Nikola Tesla in 1914 to wirelessly transfer electromagnetic energy to power consumers. The basic block diagram of the traditional IPT is shown in figure 2.5 It is based on several electric vehicle charging structures. IPT has been tested and used in a wide variety of fields from milliwatts to kilowatts to transfer contactless power from source to receiver. In 1996, the General Motors (GM) Chevrolet S10 EV was launched, which used a system that provided Level 2 power (6.6 kW) for slow charging and Level 3 (50 kW) for fast charging. A 6.6 kW Level 2 EV charger was demonstrated by the University of Georgia, which could charge battery voltages from 200 V to 400 V at an operating frequency of 77 kHz [5].

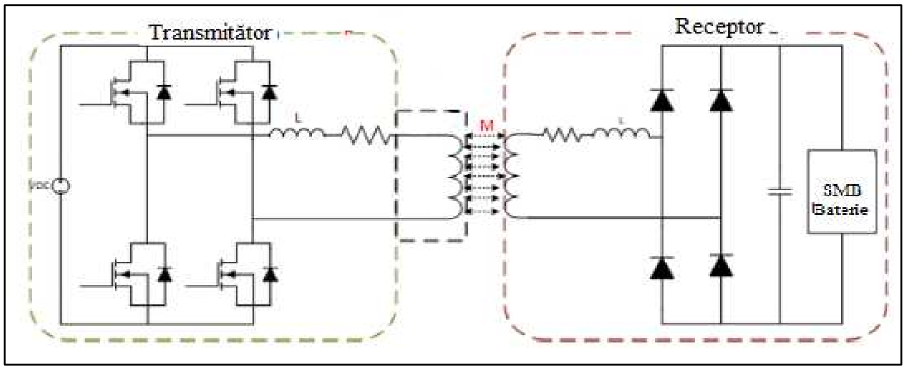


Fig. 2.5. Diagram of wireless inductive transfer [5]

Wireless inductive transfer of electrical energy is an evolving technology and ongoing research. With the continuous development of coil technologies and control circuits, as well as improvements in the efficiency and performance of inductive transfer, this method is becoming increasingly promising for wireless charging of electric devices and vehicles.

2.3.3. Wireless resonant inductive transfer of electrical power (IRPT)

Magnetic resonant wireless transfer of electrical energy is an advanced and promising method of transmitting electromagnetic energy between devices without the need for a physical connection through cables. This technology is based on the principle of magnetic resonance, where two resonant coils are tuned to the same frequency, creating a strong magnetic field that allows efficient energy transfer.

There are several important aspects to consider regarding wireless magnetic resonance transfer of electrical energy:

- Resonant coils: Magnetic resonant transfer involves the use of two or more resonant coils that are placed in the power source and receiver, figure 2.6. These coils are designed to be resonant at the same frequency so that they create a strong magnetic field between them;
- Magnetic Resonance: When the resonant coils are tuned to the same resonant frequency, the energy transfer becomes maximum. Thus, the energy is efficiently transferred between the source and the receiver by means of the magnetic field resulting from the resonance;
- Control Circuit: In order to regulate and control the power transfer, a suitable control circuit is required in both devices. It monitors and adjusts the strength and frequency of the generated magnetic field, ensuring safe and efficient energy transfer;

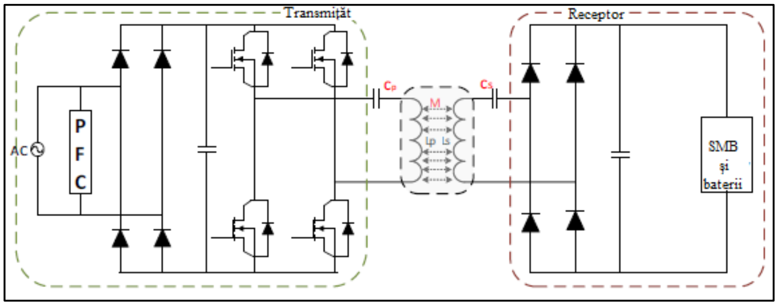


Fig. 2.6. Wireless inductive resonant transfer diagram [5]

The mathematical formula is described in relation 2.1, where $f_{r(p,s)}$ is the resonant frequency of the primary and secondary coils, and L and C are the self-inductance and resonant capacitor values of the transmitter and receiver coils, respectively. When the resonant frequencies of the primary and secondary coils are matched together, efficient power transfer is possible. The operating frequency ranges from tens of kilohertz to several hundreds of kilohertz. The magnetic flux generated in this frequency range, without a magnetic core, has a significant negative effect on the mutual inductance and therefore the reduction of the coupling coefficient (k). The resonant frequency of the inductive resonant wireless transfer (IRPT) has the expression:

$$\boldsymbol{f_{r(p,s)} = \frac{1}{2\pi\sqrt{L_{p,s}L_{p,s}}}} \qquad \textbf{(2.1)}$$

The value of the coupling coefficient k varies from 0.2 to 0.3 due to the minimum clearance requirement of electric vehicles, which is 150–300 mm. Equation 2.2 can be applied to calculate the coupling coefficient, L_p and L_s are the self-inductances of the transmitter and receiver coils respectively, L_m is the mutual inductance between the two coils. If the primary and secondary coils are strongly coupled, the mutual inductance value would be higher and vice versa according to equation (2.2). The coupling coefficient of the wireless inductive resonant transfer IRPT has the expression:

$$k = \frac{L_m}{\sqrt{L_p L_s}} \qquad \textbf{(2.2)}$$

Ferrite magnetic cores in a variety of structures are used to improve the coupling coefficient in the design of the wireless transformer, at high frequency, the proximity effect can affect the power transfer efficiency. To avoid such problems, thin twisted wire based on individually insulated wire is commonly considered in the design. This can also reduce parasitic resistance and improve the quality factor Q of the coil. The quality factor Q can be calculated by the equation determined by the frequency f, the self-inductance L of the primary or secondary coil and the resistance R of the coils, according to formula (2.3). The quality factor of IRPT wireless inductive resonant transfer has the expression:

$$Q = \frac{\omega L_{p,s}}{R_{p,s}} = \frac{2\pi f L_{p,s}}{R_{p,s}} \tag{2.3}$$

Magnetic resonance wireless transfer of electrical energy is an evolving technology and ongoing research. With the continuous development of resonant coil technologies and control circuits, as well as improvements in the efficiency and performance of magnetic resonance transfer, this method is becoming increasingly promising for wireless charging of electric devices and vehicles.

2.3.4. Compensation networks

As shown in figure 2.7, compensation capacitors are added in series and parallel combinations on both sides of the transmitter and receiver in static wireless charging systems for electric vehicles to create inductance at resonance. Four types of compensation network topologies exist, namely series-series (SS), series-parallel (SP), parallel-series (PS) and parallel-parallel (PP), being shown in figure 2.7 [5].

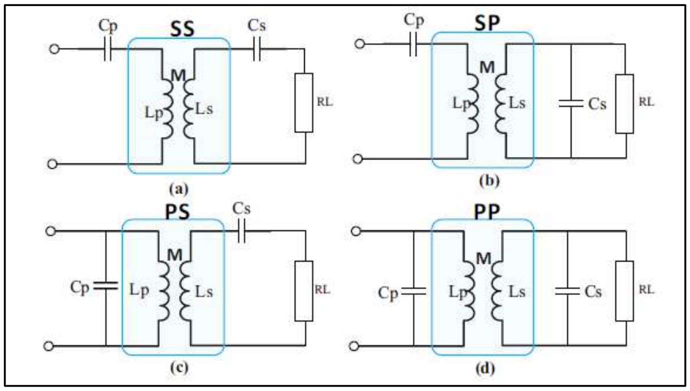


Fig. 2.7. Compensation topologies: (a) Series-Series; (b) Series-Parallel; (c) Parallel-Series; (d) Parallel-Parallel [5]

Source compensation is required to eliminate the phase difference between current and voltage and to minimize reactive power in the source. Installing a secondary compensation network maximizes load power transfer and efficiency. The Series-Series compensated topology is best suited for electric vehicle applications because it offers two significant advantages. The first advantage is that the capacitor value on the source and receiver side is independent of load and mutual inductance conditions. The second advantage is that such systems maintain unity power factor by drawing active power at the resonant frequency, since the reflected impedance from the receiver coil does not add an imaginary part in the transmitter coil. This Series-Series topology based system can provide a better battery charging option as it can provide a constant voltage and current for the battery.

2.3.5. Transformer topologies in wireless power transfer

In wireless charging systems, the transmitter and receiver elements are made of multiple layers of components to achieve maximum power transfer efficiency and reduce electromagnetic interference cost-effectively. There are three main components of wireless transformers: coil, shielding material (ferrite and aluminium plate), and protective and support layers.

In electric vehicle wireless charging systems, an air-core transformer concept is used to transfer a few watts to kilowatts of power from the source to the receiver. There are a variety of planar coil shapes such as circular, rectangular, and hybrid arrangements have been used in the design of wireless transformers to improve performance and solve misalignment problems between the emitter and receiver pads [5].

2.3.6. Static vehicle charging systems by wireless power transfer

Wireless charging systems provide a user-friendly environment for consumers and avoid safety issues with traditional wired chargers. The static charging system can easily replace the plug-in charger with minimal driver involvement and solves associated safety issues such as electric shock hazards. The primary coil is installed below, in the road or in the ground, with converters and additional power circuits. The receiver coil, or secondary coil, is normally installed under electric vehicles in the front, rear or centre.

The received energy is converted from alternating to direct form using the power converter and transferred to the battery bank. The charging time depends on the power level of the source, the dimensions of the charging stand and the distance between the two windings. The average distance between the ground and platform of light commercial vehicles is about 150 mm – 300 mm. The system can be installed in parking areas, houses, commercial buildings, shopping centres.

Their prices range from about 2000 – 10,000 USD for the charging power levels 3.3 kW – 7.2 kW. Their power levels meet international SAE standards (J2954), the power class falling into one of levels 1 (3.3 kW) and 2 (7.7 kW), with the frequency range 81.9 kHz – 90 kHz. Currently, the SAE organization is working on standards, which are related to the permissible misalignment and installation location of the receiving coil in the car [5].

2.3.7. Dynamic vehicle charging systems through wireless power transfer

Electric vehicles suffer from two major obstacles - cost and range. To increase the range, electric vehicles must either charge quite frequently or install a larger battery, which leads to additional problems such as cost and weight. In addition, it is not economical to charge an electric vehicle frequently.

The dynamic wireless charging system for electric vehicles is a promising technology that can reduce the problems associated with the range and cost of electric vehicles. It is an efficient solution for the future automation of electric vehicles, a direct charging on the move. The primary coils are embedded in the concrete of the road at a certain distance, with high voltage, high frequency alternating current source and compensation circuits to the public power grid. As with the static application, the secondary coil is mounted under the vehicles and when the vehicle passes over the transmitter, it receives a variable magnetic field through a receiver coil and converts it to direct current to charge the battery using the power converter and management system of the battery.

The frequent on-the-go charging facilities of electric vehicles reduce the total battery capacity requirement by about 20% compared to current electric vehicles. For dynamic systems, the transmitter elements and power system must be installed in specific locations and predefined routes.

2.3.8. Interconnection of electric vehicles to the public power grid

The express demand for electric vehicles has led to the need for fast charging and efficient energy transfer methods. With the increase in the number of electric vehicles, the energy demands on the distribution networks have increased rapidly and created a negative impact on it. To offset the additional energy demands, renewable energy sources have been introduced into the electricity grid but have limited support facilities.

The grid-connected vehicle concept can provide a solution alongside advanced planning for charging and discharging in the distribution network, allowing electric vehicles to become an active part of the electric grid and participate in the energy exchange between vehicles and the electric system. Thus, we will have bidirectional charging, the technology allows electric vehicles to charge their battery from the electrical grid, but at the same time, allows them to return the energy stored in the battery back to the electrical grid when needed.

Electric vehicle batteries can be considered as energy storage systems that can be used to balance the demand and supply of energy on the grid. Thus, electric vehicles connected to the grid can help manage consumption fluctuations or provide energy during peak consumption periods. Flexibility is provided to grid operators, allowing them to address the challenges of managing variable renewable energy, such as solar and wind, that depend on weather conditions.

2.4. INTERNATIONAL HEALTH, SAFETY AND ENVIRONMENTAL IMPACT STANDARDS

Wireless transfer systems offer significant advantages over wired charging, but they also come with three major potential health and safety issues – electrical, magnetic and fire hazards. These systems operate at high current and voltage levels, which can create the risk of electric shock due to accidental device failure or damage resulting from environmental conditions (hot or cold) and physical damage. In addition, Level 1 (3.7 kW) and Level 2 (7.7 kW) transfer systems are mostly installed in homes, dormitories, and public parking areas, where the transmitter load plates are installed in soil or concrete. Magnetic fluxes generated at high power levels can exceed minimum standards and regulations set by standards agencies and can be harmful to the general community. To protect the surrounding flora and fauna, Electromagnetic Compatibility (EMC) and Electromagnetic Interference (EMI) must be checked so as not to pose safety issues of the technology.

2.5. BATTERY MANAGEMENT SYSTEM

In recent decades, electric cars have gained popularity and become an increasingly viable alternative to vehicles with traditional internal combustion engines. This transition to electric mobility is based on the development and implementation of an essential element: the battery. An efficient, safe and durable battery is vital to the performance and success of electric cars. This goal is achieved and maintained through the Battery Management System (BMS). It is a critical and complex component of an electric vehicle and has the role of monitoring, controlling and protecting the vehicle's battery. This advanced technology system brings numerous benefits and solutions to successfully manage the vehicle battery by learning from operating parameters, driving habits and environmental conditions to ensure the best performance and safety.

One of the main roles of BMS is to monitor individual battery cells. Typically, a battery for an electric vehicle is made up of a series of cells, and each of them can have different characteristics. The BMS analyzes voltage, temperature and other critical parameters in real time for each cell, ensuring that it is operating at optimal parameters. Another important aspect of BMS is maintaining a proper cell balance. During use and following charge and discharge cycles, the cells may behave differently, leading to imbalances. The BMS precisely manages the charging and discharging of individual cells, thus avoiding situations where some of them are overcharged or undercharged, which could affect battery performance and durability over time.

In conclusion, the battery management system (BMS) in electric cars is an essential component that ensures the performance, safety and durability of batteries and, by implication, electric vehicles. This advanced system monitors and controls the battery cells individually, maintains a proper balance between them, protects against critical situations and optimizes the efficiency and performance of the electric vehicle. Effective implementation and continued development of BMS will play a crucial role in accelerating the transition to electric mobility, helping to reduce carbon emissions and create a more sustainable future for road transport..

2.5.1. Functions and specifications of a Battery Management System

A battery is an electrochemical device that converts chemical energy into electrical energy. In rechargeable systems in the automotive industry, the battery is recharged in a reverse process to power generation. The basic unit of a battery is the electric cell, a battery being composed of several electric cells connected in series/parallel to obtain the desired voltage or capacity [49].

The major components of an electric cell are:

1. The negative anode or electrode, the electron generator in the external circuit of the battery that is oxidized during the electrochemical reaction;

2. The cathode or positive electrode that accepts electrons from the external circuit and is reduced during the electrochemical reaction;

3. The electrolyte or ionic conductor that allows charge transfer as ions inside the cell between the anode and the cathode, can be of a liquid nature with various solvents or of a solid nature.

In an electric car there are two electrical battery systems, each with different functions: the 12 V battery generally built on Pb/Acid chemistry to provide high currents for short periods of time needed to start the engine and the 12 V consumers and 48 V – 800 V batteries that must provide the energy needed for the vehicle's traction. To meet the requirements of lifetime, capacity and high number of charge/discharge cycles, batteries must be assisted by charge/discharge management systems (BMS) to guarantee operation in the safe operating zone and thus extend the life of batteries. BMS costs are a fraction of electric battery costs with a major impact on electrical system efficiency. The BMS architecture can be divided into two major components: the hardware (physical) equipment and the software monitoring applications that actively control the battery parameters.

Most commercial BMS systems use the technique of measuring electrical charges (coulombs) and measuring voltage variations as a method of measuring battery parameters. The key functions of a battery management system in electric cars can be classified as follows:

1. Individual monitoring of battery cells;
2. Loading and unloading balance;
3. Protection against overload and over discharge;
4. Thermal protection;
5. Effective performance management;

6. Diagnostics and troubleshooting;
7. Communication and Connectivity.

2.5.2. System Architecture Models of Battery Management Systems (BMS)

There are several battery management system (BMS) architectures in electric cars, each with its own characteristics and benefits. Here are some of the most common models: Centralized Architecture, Distributed Architecture, Hybrid Architecture. Each architectural model has its own advantages and disadvantages and can be chosen according to the specific requirements of the electric vehicle as well as the manufacturer's priorities. Regardless of the chosen architecture, the battery management system plays a crucial role in ensuring optimal battery performance, safety and durability, thus contributing to the success of electric cars and promoting sustainable mobility [51].

2.5.3. Battery Management Systems (BMS) Hardware Architecture Models

The hardware architecture models for Battery Management Systems (BMS) used in electric vehicles (EVs) are designed to efficiently manage and monitor the vehicle's battery, ensuring optimal performance, safety and durability. Here are some of the most common hardware architecture models for BMS: Integrated Architecture, Separate Architecture, Locally Distributed Architecture.

2.5.4. Master / Slave architecture of the system topology

Due to the large number of batteries in hybrid or electric vehicle propulsion applications with high voltages (48 V – 600 V), centralized system solutions are generally replaced by Master-Slave distributed system solutions. The slave subsystems directly monitor the parameters of the battery cells that they transmit to the master module for their processing and control of the system functions through the implemented algorithms. Thus, through the modular architecture, the battery management system provides increased flexibility in terms of controlling several types of battery packs with variable sizes. Scalability being a quality feature required for such applications, distributed design is the best solution while also ensuring increased system efficiency.

2.5.5. Battery Management System (BMS) software architecture models

There are several software architecture models for battery management system (BMS) used in electric vehicles (EV), we list the most common software organization concepts for BMS: Monolithic Architecture, Modular Architecture, Locally Distributed Architecture, Internet Distributed Architecture (cloud), Open Source architecture.

2.5.6. The process of balancing the electric cells of the battery

The battery is made up of a group of individual electric cells, and its quality and performance largely depend on the condition of each cell. In this context, the battery management system (BMS) has a crucial role in monitoring and controlling the cells, ensuring safe and efficient operation of the battery. One of the key aspects of BMS is the cell balancing process which is the process of adjusting the charging or discharging of each individual cell in a battery so that they have approximately the same level of stored energy [52].

Over time, cells may behave differently due to manufacturing variations, uneven wear, or the influence of the operating environment. Therefore, some cells can become overcharged while others can be undercharged, which can lead to imbalances and lower overall battery performance. Individual cell monitoring involves constant checking of voltage, temperature and current parameters. This individual monitoring allows the identification of cells that show significant differences compared to the rest, indicating an imbalance. Once these differences are detected, the BMS can initiate the balancing process to bring the cells to close charge and discharge levels. BMSs use different methods to balance power cells, and the most common methods include: passive balancing, active balancing, hybrid balancing. Balancing electric cells brings many benefits to battery and electric vehicle operation: extending battery life, improving performance, increasing safety, maximizing range.

In conclusion, the process of balancing electric cells in the battery management system (BMS) of electric vehicles is a key element in ensuring optimal battery performance and durability. By monitoring individual cells and using appropriate balancing methods, the BMS helps to maximize vehicle performance and safety, thus promoting the adoption and development of electric mobility for a more sustainable future.

2.6. ELECTRIC VEHICLE BATTERY CAPACITY CALCULATION

Battery capacity is the amount of electrical energy a battery can store and provide to power the vehicle's electric motor. The calculation of the battery capacity and its composition of electric cells are critical aspects for ensuring the autonomy, performance and durability of electric cars. In this chapter, we will explore the process of calculating battery capacity and the structure of the electrical cells that compose it [53].

Battery capacity, often expressed in kilowatt-hours (kWh) or amp-hours (Ah), is a measure of the amount of electrical energy a battery can store and release. This determines the range of the electric vehicle, i.e. the distance the vehicle can travel on a single charge. The electric vehicle battery is made up of several electric cells that work together to store and supply the electrical energy needed by the vehicle. Electric cells are individual units that can be combined to form modules and later the battery pack. For a larger capacity battery, we can combine the cells in series and parallel to achieve the desired total capacity. Generally, this involves creating modules of cells connected in series and then connecting these modules in parallel to form the battery pack. To make this calculation, we need the following information:

- The capacity of an individual cell (expressed in Ah);
- Voltage of an individual cell (expressed in V);
- Desired total battery capacity (expressed in Ah).

To calculate the number of cells needed in series, divide the desired total voltage by the voltage of an individual cell. To calculate the number of modules needed in parallel, the total desired capacity is divided by the capacity of a cell module, which in turn is calculated from the number of cells in series multiplied by the capacity of a cell.

2.7. TECHNICAL RISK ANALYSIS IN THE AUTO INDUSTRY

The automotive industry is one of the most dynamic and complex industries in the world, and the development of modern vehicles involves the integration of advanced technologies, sophisticated systems and complex production processes. In such an industry, vehicle safety, reliability and performance are of crucial importance to meet consumer demands and expectations, as well as to comply with strict industry regulations. To ensure these high standards, the automotive industry frequently uses a technical risk analysis method known as Failure Modes and Effects Analysis (FMEA). This chapter will explore the need for FMEA analysis in the automotive industry and the benefits this approach brings to the vehicle development and production process [54]. FMEA is a proactive analysis method, used to identify and assess potential failure modes, as well as to develop preventive and corrective measures before these defects and their effects occur in practice. In the automotive industry, where thousands of complex components are produced and assembled into a vehicle, there are many opportunities for problems or defects to occur. By applying FMEA analysis, these potential deviations are identified and managed, which helps to avoid accidents, improve product quality and protect the reputation of car manufacturers.

2.7.1. The motivation for analyzing the effects of failure modes

One of the main reasons why the automotive industry applies FMEA analysis is to ensure the safety of vehicles and their users. Road safety is a priority for all car manufacturers, and through FMEA analysis, potential vulnerabilities or failures that can lead to serious accidents can be identified and corrected. FMEA helps improve the design and manufacturing of critical vehicle components such as the braking system, airbags, driver assistance systems and more.

In addition, FMEA analysis is also useful for optimizing vehicle reliability. In a competitive industry, consumer confidence in vehicle quality and durability is critical to an automaker's success. By identifying and eliminating potential defects, FMEA enables the development of more reliable vehicles with lower maintenance costs, leading to increased customer satisfaction and strengthening the manufacturer's brand.

FMEA allows the identification of potential quality problems and factors that can affect the quality of automotive components. By applying preventive and corrective measures, the quality of vehicle components and systems can be improved, ensuring that automotive products are delivered to customers with high levels of reliability and performance. The quality, safety and reliability of vehicles play a crucial role in building a car manufacturer's reputation. FMEA contributes to the development of more reliable and safer vehicles, which can lead to increased customer confidence and strengthening of the manufacturer's brand.

In conclusion, FMEA technical risk analysis is an essential method in the automotive industry to ensure the safety, reliability and performance of vehicles. By identifying and managing potential defects, FMEA analysis contributes to increasing the quality of automotive products, improving the reputation of manufacturers and customer satisfaction. In a dynamic and competitive industry, FMEA is an essential tool for ensuring a safer and more sustainable future for the automotive industry [45].

2.7.2. Evaluation of failure modes and effects in wireless power transfer

The use of Failure Modes and Effects Analysis (AMDE / FMEA) in the wireless transmission of electricity to electric vehicles (EVs) is an essential approach to ensure the safety, reliability and performance of this innovative charging system. Wireless transmission of electricity to EVs, also known as "wireless charging" or "induction charging," is an emerging technology that eliminates the need for physical connections between the car and the power source. This involves the use of an electromagnetic field to transfer energy to the vehicle's battery, thus providing a more convenient and efficient way of charging.

By applying AMDE / FMEA analysis the car manufacturer can develop a safer, more efficient and more reliable wireless transfer and battery management system for electric vehicles, thus helping to maximize battery performance, extend battery life and improve satisfaction customer.

2.7.3. FMEA Analysis and Functional Safety (FS)

Functional safety (FS) is an essential component in modern industry, where complex systems are used to ensure the safe and correct operation of equipment, vehicles, infrastructure and more. In the context where advanced techniques and technologies are used in various fields, such as the automotive, aeronautical, railway, energy, medical industries, ensuring safe operation becomes a critical priority. In this context, Failure Modes and Effects Analysis (FMEA) plays a significant role in improving the functional safety of systems and reducing associated risks. Functional safety is that part of the overall safety of a system or piece of equipment that depends on the correct operation of automatic protection in response to its inputs or failure in a predictable manner. The automatic protection system should be designed to adequately handle likely human errors, systematic errors, hardware failures, and operational or environmental stress.

ISO 26262, entitled "Road vehicles - Functional safety", is an international standard for the functional safety of electrical and/or electronic systems that are installed in series production road vehicles (except mopeds), defined by the International Organization for Standardization (ISO) in 2011 and revised in 2018. The standard aims to address possible hazards caused by the faulty behavior of electronic and electrical systems in vehicles. Although entitled "Road vehicles - Functional safety", the standard covers the functional safety of electrical and electronic systems, as well as that of the systems as a whole or their mechanical subsystems.

2.7.4. ANALYSIS OF FAILURE MODES AND THEIR EFFECTS IN THE CONTEXT OF FS

As a general definition, Safety Goals (SG) are high-level objectives that the BMS must meet to keep lithium-based battery safety under control. These are derived from a hazard analysis and risk assessment of the specific automotive application under study and must be consistent to control the risk to an acceptable level. The automotive safety integrity level (ASIL) is the risk classification defined by the ISO 26262 standard, an adaptation of the safety integrity level (SIL) used in the IEC 61508 standard. This classification helps define the necessary risk reduction mentioned above, the ASIL is established by analysing the probability and consequences of a hazard. The standard classifies the necessary risk reduction as: ASIL A, ASIL B, ASIL C, ASIL D and QM (Quality Management). ANIS / ASIL D imposes the highest safety requirements on the integration of functions, achieving the highest risk reduction, and ANIS / ASIL A the lowest. Risks classified as MC / QM must be subject to a regular quality management design process. Risk assessment consists of listing the identified hazards and their causes, planning the measures that can be applied to prevent or mitigate the hazards, and assessing the risk to identify the necessary reduction.

The FMEA methodology uses three key parameters to assess the risks and effects of defects: Severity (S), Frequency of Occurrence (A/O) and Probability of Detection (D), these parameters being used to calculate the Risk Priority Index (RPN). The severity rating is rated on a scale of 1 to 10, where 1 represents a very low impact with no major effects on the system or users and 10 represents a very high impact with serious consequences on system security, performance, or reliability. To determine the probability of occurrence of the failure mode, it is necessary to have data on failure rates (from databases) and data on operational failures. It is scored on a scale from 1 to 10, where 1 represents a very low probability of occurrence, with a minimal chance of the failure mode occurring, and 10 represents a very high probability of occurrence, with a high risk of the failure mode occurring. For each failure mode, the detection probability parameter D/D has been defined, it is rated on a scale from 1 to 10, where 1 represents a very high detection capability, with advanced mechanisms for monitoring and early detection of defects, and 10 represents a very low detection capability, with a high probability of the failure mode going unnoticed.

Based on the 3 parameters S, O, D to calculate a Risk Priority Index RPN (in English: Risk Priority Number (RPN)) is calculated as follows: IPR = Severity of the effect (S) × Probability of Defect Occurrence (O) × Probability of Defect Detection (D). The risk criticality matrix allows the assessment of risks from a qualitative aspect and provides a means of identifying and comparing each failure mode with all other modes, in relation to the severity (severity) estimated by the severity categories (I to IV), represented in the matrix on its horizontal axis. The levels of probability of occurrence are plotted on the vertical axis of the matrix, in ascending order. The resulting matrix highlights the criticality distribution of part/equipment failure modes and provides a tool for prioritizing corrective actions.

2.8. COMPUTER-AID DESIGN (CAD) IN THE SIMULATION OF A BATTERY MANAGEMENT SYSTEM (BMS)

In recent decades, computer-aided design (CAD) has revolutionized the automotive industry and the field of electrical and electronic circuit design and development, bringing with it innovations, increased efficiency and accelerated development of modern vehicles. CAD is a design and modeling system that uses information technology to create and analyze 2D or 3D digital models of automotive components, assemblies and vehicles. With the help of CAD, engineers can explore and optimize the design before building the physical prototypes, saving time and resources and ensuring high quality end products having a significant impact on the electronics industry as well, giving engineers a more efficient, accurate and innovative for the development and testing of complex electronic circuits.

PAC / CAD for electrical and electronic circuits is based on the use of specialized software programs that allow the design, simulation, analysis and optimization of circuits in a digital environment. This allows engineers to test multiple design variants and identify possible errors before moving to physical production of the circuits. A crucial aspect of PAC/CAD in the automotive industry is that it covers a wide range of areas, including exterior and interior design, mechanical engineering, simulations and performance analysis.

2.8.1. Introduction to Computer Aided Design (CAD)

Computer-aided design (CAD) is the use of computers or workstations to assist in the creation, modification, analysis or optimization of a design. This computer application is used to increase designer productivity, improve design quality, improve communications through documentation, and create a manufacturing database. The output of CAD software is often in the form of an electronic file for printing, machining or other manufacturing operations. In mechanical design the method is also known as mechanical design automation (MDA), which includes the process of creating a technical drawing with the use of computer software and the use of CAD in the design of electronic systems is known as Automation of Electronic Design (EDA).

CAD software for mechanical design either uses vector graphics to represent the objects of traditional drawings or can also produce raster graphics that show the general appearance of the designed objects. As in manual drafting of technical and engineering drawings, the CAD output must convey information such as materials, processes, dimensions and tolerances according to application-specific conventions. CAD is an important industrial art widely used in many applications, including automotive, shipbuilding and aerospace, industrial and architectural design, prosthetics and many others. CAD is also widely used to produce computer animation for special effects in films, commercials, and technical manuals, often called digital content creation. Because of its enormous economic importance, CAD has been a major driving force for research in computational geometry, computer graphics (both hardware and software), and discrete differential geometry.

2.8.2. Brief History in Computer Aided Design (CAD)

Beginning in the mid-1960s, with the IBM Drafting System, computer-aided design systems began to offer more capabilities than that of reproducing manual drawing with electronic drawing, making the cost-benefit ratio for companies to switch to CAD clear. The advantages of CAD systems over manual drawing are the capabilities we often take for granted from today's computer systems: automatic BOM generation, automatic IC layout, interference checking and more.

Modern CAD packages can also frequently allow rotations in three dimensions, allowing a designed object to be viewed from any desired angle, even from inside and outside. CAD technology is used in the design of tools and machinery as well as in the design of all types of buildings, from small residential types (houses) to the largest commercial and industrial structures (hospitals and factories). CAD is mainly used for detailed engineering of 3D models or 2D drawings of physical components, but it is also used throughout the engineering process, from conceptual design and product layout, through analysis of strength and dynamic properties of assemblies to the definition of component manufacturing methods. In addition, many CAD applications now offer advanced rendering and animation capabilities so that engineers can better visualize their product designs.

CAD has become a particularly important technology in the field of computer-aided design, with benefits such as lower product development costs and a much shortened design cycle. CAD allows designers to plan and develop work on screen, print it and save it for later editing, saving time on their drawings [10].

2.8.3. Types of CAD software applications

In the early 2000s, some CAD system software vendors shipped their distributions with dedicated license management software that could control how often or how many users could use the CAD system. Applications can run either on a local machine by loading from a local storage device or on a local network file server at a specific IP address. CAD software allows engineers and architects to design, inspect and manage engineering projects in an integrated graphical user interface (GUI) on a personal computer system.

A geometric modeling kernel is a software component that provides solid modeling and surface modeling features of CAD applications such as Autodesk's ShapeManager or Siemens' Parasolid. Based on market statistics, commercial software from Autodesk, Dassault Systems, Siemens PLM Software and PTC dominate the CAD industry. The following is a list of the major CAD applications, grouped by usage statistics:

- Commercial software applications: Autocad and Fusion 360 from Autodesk, CATIA from Dassault Systèmes, ArchiCAD from Graphisoft;
- Public source software applications that allow users free access to the development process: FreeCAD, LibreCAD, OpenSCAD;
- Free software applications: Tinkercad.

2.8.4. Introduction to the field of Computer Aided Design in Electronics in CAD

Electronic Design Automation (EDA), also called Computer Aided Electronic Design (ECAD), is a CAD category consisting of software tools for designing electronic systems, such as integrated circuits (IC) and circuit boards printed circuits (PCB). The tools work together in a design flow that chip designers use to design and analyze entire semiconductor chips. Since a modern semiconductor chip can have billions of components, EDA tools are essential for their design. Before the development of EDA, integrated circuits were designed and placed on the circuit board by hand.

2.8.5. Development of Computer Aided Design in Electronics in CAD

The year 1981 marked the beginning of EDA as an industry. For many years, large electronics companies such as Hewlett Packard, Tektronix, and Intel pursued EDA internally, with managers and developers beginning to break away from these companies to focus on the EDA field as a business. Daisy Systems, Mentor Graphics and Valid Logic Systems were all founded around this time, at the same time the US Department of Defense began funding VHDL as a hardware description language, within a few years many EDA companies were established, each with a slightly different emphasis [10].

The field of EDA for electronics has rapidly grown in importance with the continued scaling of semiconductor technology. Manufacturers use technology design service companies that use EDA software to evaluate an incoming design for production preparation. EDA tools are also used to program design functionality into customizable integrated circuits called Field Programmable Gate Arrays (FPGA) [10]. Computer Aided Electronic Design or ECAD is a technology that has been widely used in the engineering and product design industries for years. However, as with any technology, there are some specialists who have resisted the assistive tools, preferring instead the manual drafting process.

2.8.6. Electronic Computer Aided Design (ECAD) capabilities

Computer Aided Electronic Design (ECAD) software is used to create and modify both 2D and 3D diagrams and layouts to design, evaluate and document electrical printed circuit boards (PCB). In the development process, ECAD software can be used to explore different iterations of a printed circuit board (PCB), either abstractly as a diagram or in detail as a 3D layout or assembly. Designers can build different alternatives and options, comparing them with each other, generating the production documentation, which is released to the production as part of the specifications used to procure, manufacture and produce the PCBs. ECAD applications offer a combination of the following capabilities: Diagramming capabilities Routing capabilities 3D assembly capabilities Collaboration capabilities Multi-plate design capabilities Rule checking capabilities Export capabilities.

2.8.7. Tinkercad – the online platform for modeling and simulating electronic circuits

Tinkercad is an online collection of software tools from Autodesk that allow designers to create 3D models as well as electrical/electronic circuits. As a result, this 3D modelling software is easy to use and is currently in both academic and designer environments, allowing users to create 3D printing compatible models, a great option for newbies in the technology. In addition, the app allows you to add electronic circuits to 3D models to create objects with light and movement. The result can even be simulated on the online platform to check how the components will respond in real life. Additionally, Autodesk has made many resources available to its community. The software works on any computer with an Internet connection, requiring the creation of an online account, and provides backup copies of 3D models to the cloud [44].

CHAPTER 3

CONTRIBUTIONS REGARDING BMS PROTOTYPE REALIZATION

3.1 USING THE V-MODEL OF HARDWARE AND SOFTWARE DEVELOPMENT

The development model in V (V-Model) [11], presented in figure 3.1. is a framework used in hardware / software development and project management to ensure a structured and coordinated approach to the entire development cycle. This model is an extension of the classic waterfall model and is called the "V-Model" because of its graphic shape resembling the letter V.

The main feature of V-Model consists of close associations between each development phase and the corresponding testing phase, starting with initial specifications and continuing with unit testing, integration, system testing and validation/acceptance testing. In other words, each development stage has an associated testing stage in the V-Model. Figure 3.1 shows the pairing of the corresponding development and testing levels.

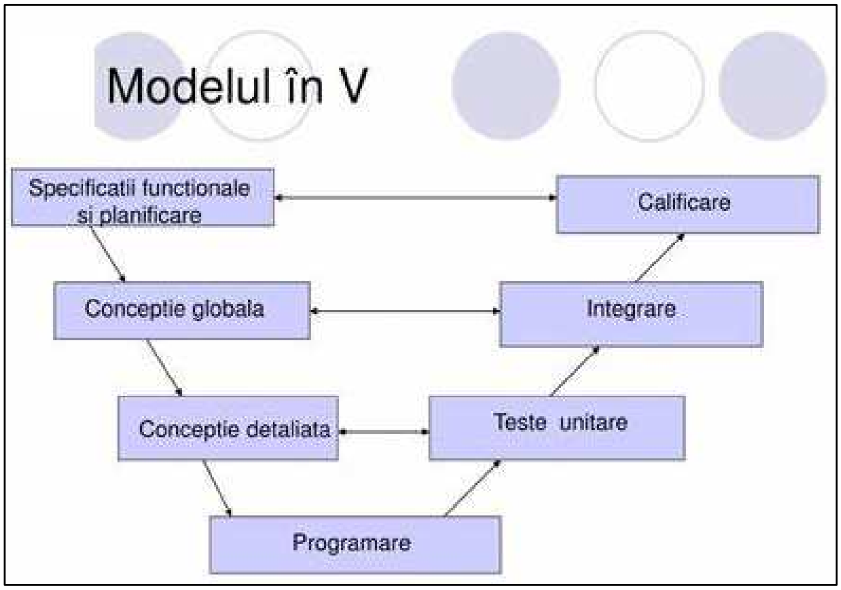


Fig. 3.1. The V-development model of products containing hardware and software [11]

The V-pattern for a battery management system helps to closely coordinate development and testing, ensuring that every functionality and feature is properly verified and validated. This process can contribute to the development of a safe, efficient and reliable battery management system for electric vehicles, which has a positive impact on battery performance and durability and provides a more enjoyable driving experience for users.

3.2 ANALYSIS OF BMS SPECIFICATIONS

3.2.1 BMS system specification analysis

The functions implemented in this BMS prototype are essential to ensure safe, efficient and reliable battery operation. This chapter will explore in detail the key functions of the VH/VE battery management system to be implemented:

- Individual cell monitoring;
- Cell balancing;
- Protection against overload and excessive discharge;
- Battery temperature control;
- Diagnosis and detection of defects;
- Battery health monitoring and reporting

3.2.2 BMS hardware specification analysis

The hardware specifications of the battery management system implementing the system functions listed in chapter 3.1.1 include the following main hardware components: Microcontroller, Sensors, Measurement circuits, Switches and protections, Connectors and communication interfaces, Display or user interface, Memory, Balancing module, Overvoltage and overcurrent protection modules.

3.2.3 BMS software specification analysis

The software specifications of the battery management system implementing the system functions listed in chapter 3.1.1 include the following main components:

- Real-time operating system (SOTR / RTOS;
- CAN, LIN, UART, SPI, Bluetooth communication protocols;
- Load / download control algorithm;
- Balancing algorithm;
- Protection algorithm and warnings;
- Data display algorithm;

3.3 TECHNICAL RISK ANALYSIS OF BMS FUNCTIONS

This chapter will implement technical AMDE risk analysis of BMS, which is a method of analyzing possible failure modes and their effects on BMS functions, used to identify and evaluate potential problems and risks in BMS design. To implement the analysis, a software tool to assist the AMDE quality methodology called APIS IQRM was used. APIS IQRM (Automation Process Innovation Software - IQ-RM) is a software developed by the company APIS Informationstechnologien GmbH, specialized in the development of software solutions for the automotive and aeronautical industries. All the root cause defects on the last level will be linked to the intermediate level containing the failure modes which in turn will be linked to the effects on the first level, the application thus generating a functional network and a network of defects based on the cause-effect principle.

3.3.1 Structural analysis of BMS

By applying structural analysis in FMEA, an electric battery management system can be developed and implemented in a safer, more reliable and better performing way to ensure optimal operation and extend battery life. The first step is to identify and list all the main components of the BMS to be analyzed. APIS IQ-RM presents the structure in a tree form, the top of the tree being represented by the BMS, then the following nodes in the tree being the 3 big components of the system, the mechanical (case), the hardware (electronics) and the software (control application). The mechanical component is no longer refined into other subcomponents, thus, at the third level in the tree on the mechanical side we find the dimensional characteristics of the case. The hardware component being more complex than the mechanical one is refined in the sub-components that represent the battery cell monitoring board, the control board, the electric cells and the current sensor, on the next level finding the characteristics of each of these sub-components. The software component will have refined third-level control application modules, namely the microcontroller initialization module, the power cell initialization module, the current reading module, the analog-to-digital conversion module, and the power cell balancing module. Figure 3.4 shows all the identified components, displayed in a horizontal hierarchical tree structure, which reflects the architecture of the BMS, the technical solution for implementing the system requirements.

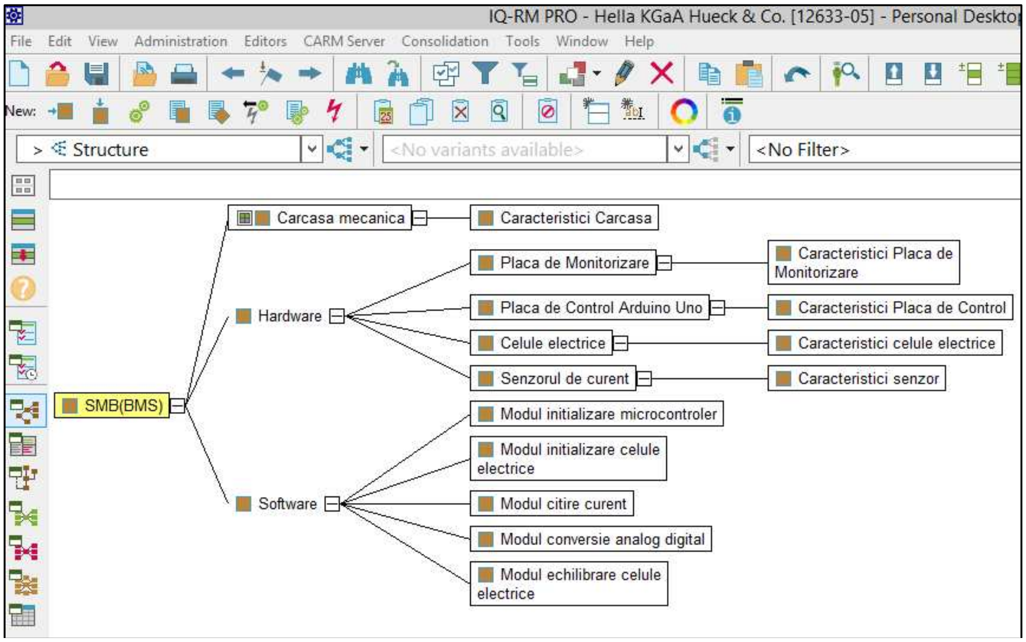
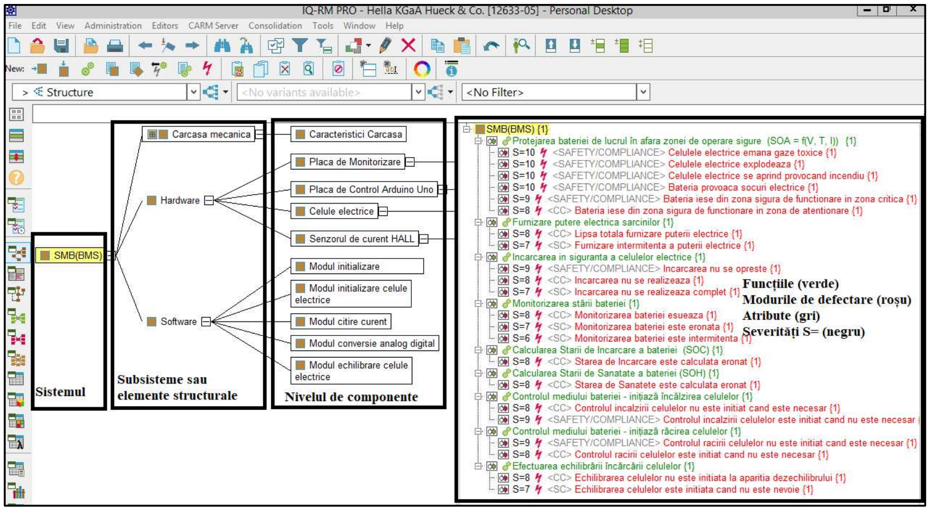


Fig. 3.4. Main components of BMS

3.3.2 Functional analysis of BMS

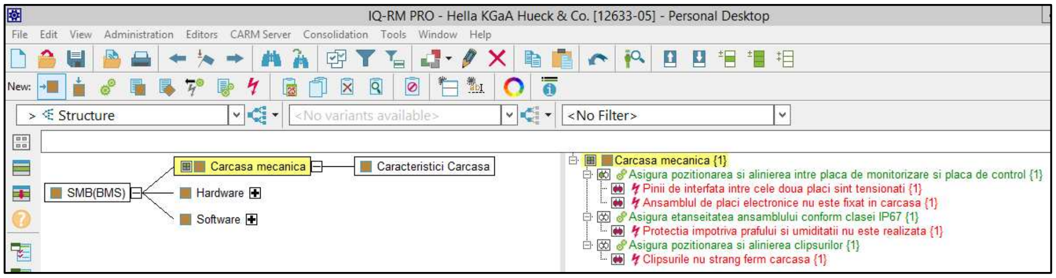
The purpose of the functional analysis is to identify the functions of the BMS to be analyzed under AMDE and to determine the potential failure modes associated with these functions. For each function identified, it describes in detail what it entails and what results should be obtained from the performance of that function. A number of 9 functions of BMS and a number of 22 effects of failures of these functions were identified according to figure 3.5. The functions documented at the first level of analysis will be refined into sub-functions at the next level, which will branch the analysis in 3 directions. The first direction will be the mechanical one and will analyze the BMS case, the second direction will be the electronic one that will analyze the hardware part and the third direction will be that of the control application or software.



- SMB(BMS) {1}
  - Protejarea bateriei de lucrul în afara zonei de operare sigure (SOA = f(V, T, I)) {1}
    - S=10 <SAFETY/COMPLIANCE> Celulele electrice emana gaze toxice {1}
    - S=10 <SAFETY/COMPLIANCE> Celulele electrice explodeaza {1}
    - S=10 <SAFETY/COMPLIANCE> Celulele electrice se aprind provocand incendiu {1}
    - S=10 <SAFETY/COMPLIANCE> Bateria provoaca socuri electrice {1}
    - S=9 <SAFETY/COMPLIANCE> Bateria iese din zona sigura de functionare in zona critica {1}
    - S=8 <CC> Bateria iese din zona sigura de functionare in zona de atentionare {1}
  - Furnizare putere electrica sarcinilor {1}
    - S=8 <CC> Lipsa totala furnizare puterii electrice {1}
    - S=7 <SC> Furnizare intermitenta a puterii electrice {1}
  - Incarcarea in siguranta a celulelor electrice {1}
    - S=9 <SAFETY/COMPLIANCE> Incarcarea nu se opreste {1}
    - S=8 <CC> Incarcarea nu se realizeaza {1}
    - S=7 <SC> Incarcarea nu se realizeaza complet {1}
  - Monitorizarea stării bateriei {1}
    - S=8 <CC> Monitorizarea bateriei esueaza {1}
    - S=7 <SC> Monitorizarea bateriei este eronata {1}
    - S=6 <SC> Monitorizarea bateriei este intermitenta {1}
  - Calcularea Starii de Incarcare a bateriei (SOC) {1}
    - S=8 <CC> Starea de Incarcare este calculata eronat {1}
  - Calcularea Starii de Sanatate a bateriei (SOH) {1}
    - S=8 <CC> Starea de Sanatete este calculata eronat {1}
  - Controlul mediului bateriei - inițiază încălzirea celulelor {1}
    - S=8 <CC> Controlul incalzirii celulelor nu este initiat cand este necesar {1}
    - S=9 <SAFETY/COMPLIANCE> Controlul incalzirii celulelor este initiat cand nu este necesar
  - Controlul mediului bateriei - inițiază răcirea celulelor {1}
    - S=9 <SAFETY/COMPLIANCE> Controlul racirii celulelor nu este initiat cand este necesar {1}
    - S=8 <CC> Controlul racirii celulelor este initiat cand nu este necesar {1}
  - Efectuarea echilibrării încărcării celulelor {1}
    - S=8 <CC> Echilibrarea celulelor nu este initiata la aparitia dezechilibrului {1}
    - S=7 <SC> Echilibrarea celulelor este initiata cand nu este nevoie {1}

Fig. 3.5. BMS functions and defects analyzed

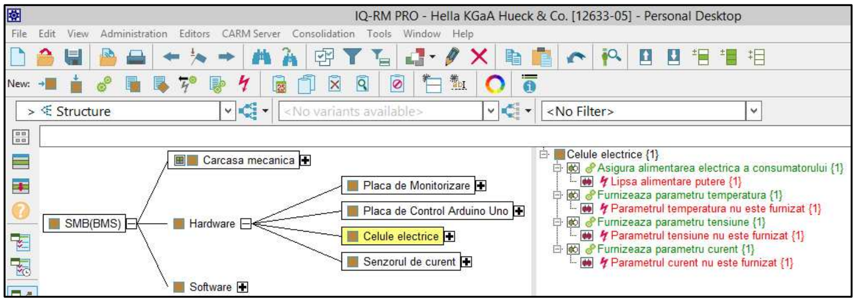
Within the "Mechanical housing" element, its 3 functions and 4 potential failure modes were documented according to figure 3.6:



- Carcasa mecanica {1}
  - Asigura pozitionarea si alinierea intre placa de monitorizare si placa de control {1}
    - Pinii de interfata intre cele doua placi sint tensionati {1}
    - Ansamblul de placi electronice nu este fixat in carcasa {1}
  - Asigura etanseitatea ansamblului conform clasei IP67 {1}
    - Protectia impotriva prafului si umiditatii nu este realizata {1}
  - Asigura pozitionarea si alinierea clipsurilor {1}
    - Clipsurile nu strang ferm carcasa {1}

Fig. 3.6 The functions and defects of the *mechanical casing* subsystem

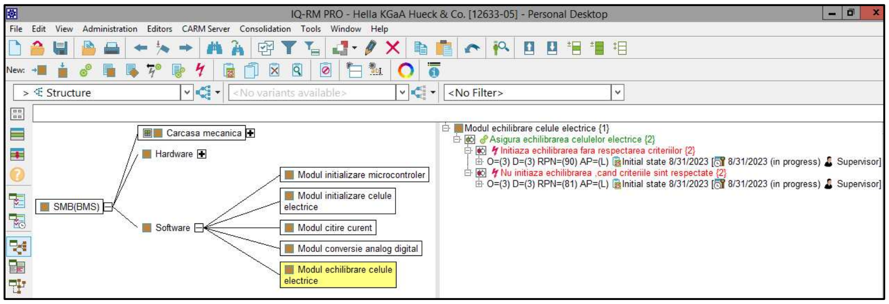
Within the "Hardware" element, the 4 basic electronic sub-components were structured: the cell monitoring board, the microcontroller control board, the electric cells and the current sensor, each sub-element having its functions and potential failure modes documented according to the figure 3.7.



- Celule electrice {1}
  - Asigura alimentarea electrica a consumatorului {1}
    - Lipsa alimentare putere {1}
  - Furnizeaza parametru temperatura {1}
    - Parametrul temperatura nu este furnizat {1}
  - Furnizeaza parametru tensiune {1}
    - Parametrul tensiune nu este furnizat {1}
  - Furnizeaza parametru curent {1}
    - Parametrul curent nu este furnizat {1}

Fig. 3.7. Functions and defects of electronic subsystems

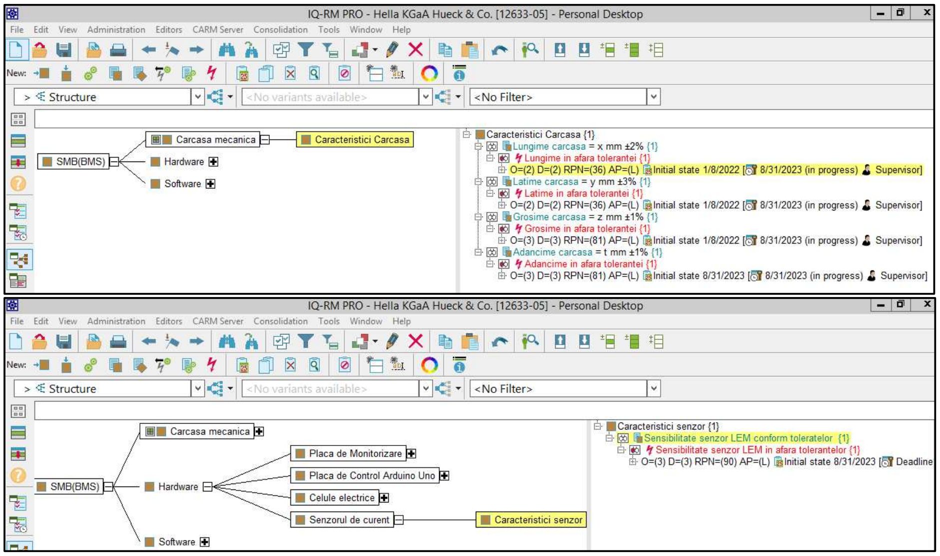
Within the "Software" element, the 5 basic logical sub-components were structured: the microcontroller initialization module, the electric cell initialization module, the current reading module, the analog-digital conversion module, the electric cell balancing module, each element having its functions and failure modes documented potentials according to figure 3.8.



Modul echilibrare celule electrice {1}
Asigura echilibrarea celulelor electrice {2}
Initiaza echilibrarea fara respectarea criteriilor {2}
O=(3) D=(3) RPN=(90) AP=(L) Initial state 8/31/2023 [8/31/2023 (in progress) Supervisor]
Nu initiaza echilibrarea ,cand criteriile sint respectate {2}
O=(3) D=(3) RPN=(81) AP=(L) Initial state 8/31/2023 [8/31/2023 (in progress) Supervisor]

Fig. 3.8. Functions and defects of software modules

Within the last root level, the rightmost in the analysis order, the functions of the primary components are called functional characteristics at the mechanical and hardware level. Each feature of the components has a tolerance according to the requirements of the interested parties or the catalog sheets. Figure 3.9 lists the characteristics of the mechanical and hardware components in turquoise color according to APIS IQ-RM default settings.



Caracteristici Carcasa {1}
Lungime carcasa = x mm ±2% {1}
Lungime in afara tolerantei {1}
O=(2) D=(2) RPN=(36) AP=(L) Initial state 1/8/2022 [8/31/2023 (in progress) Supervisor]
Latime carcasa = y mm ±3% {1}
Latime in afara tolerantei {1}
O=(2) D=(2) RPN=(36) AP=(L) Initial state 1/8/2022 [8/31/2023 (in progress) Supervisor]
Grosime carcasa = z mm ±1% {1}
Grosime in afara tolerantei {1}
O=(3) D=(3) RPN=(81) AP=(L) Initial state 1/8/2022 [8/31/2023 (in progress) Supervisor]
Adancime carcasa = t mm ±1% {1}
Adancime in afara tolerantei {1}
O=(3) D=(3) RPN=(81) AP=(L) Initial state 8/31/2023 [8/31/2023 (in progress) Supervisor]

Caracteristici senzor {1}
Sensibilitate senzor LEM conform toleratelor {1}
Sensibilitate senzor LEM in afara tolerantelor {1}
O=(3) D=(3) RPN=(90) AP=(L) Initial state 8/31/2023 [Deadline

Fig. 3.9. Characteristics and defects of mechanical and electronic components

3.3.3 Analysis of BMS failure modes

After we have structurally and functionally analyzed the BMS, the failure mode analysis stage follows for each of the functions analyzed in the previous step. The purpose of design failure mode analysis is to identify causes of failure modes and their effects including the relationships between them to enable risk assessment. The main objectives of a design failure analysis are: establishing the failure chain, potential failure effects, failure modes, failure causes for each product function.

After running the function and failure links in the analysis tree in APIS IQ-RM, the function network and failure mode network are obtained as in Figures 3.10 and 3.11. Thus one can observe the refinement at the function level as well as the multiple root causes that may imply a failure effect at the system level. The snapshot in Figure 3.10 shows the decomposition of a system-level function into all functions at the next level that compete to implement the system-level function.

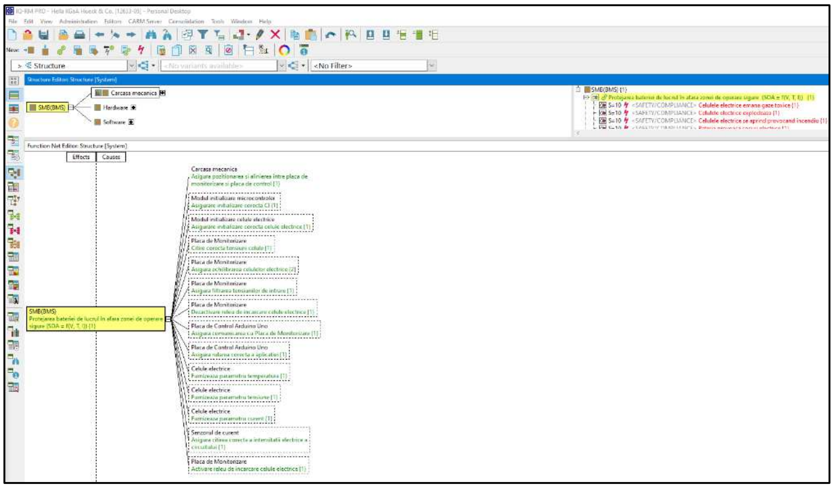


Fig. 3.10. Functional network at the system level

The snapshot in Figure 3.11 shows the direct and indirect causes that can determine the system-level effect. The analyzed causes and effects are functionally and structurally mapped onto functions and related structure elements. Each effect, failure mode and cause are marked with attributes and maximum severity from the defect network. The example focuses on a critical system-wide effect rated at maximum severity due to the impact.

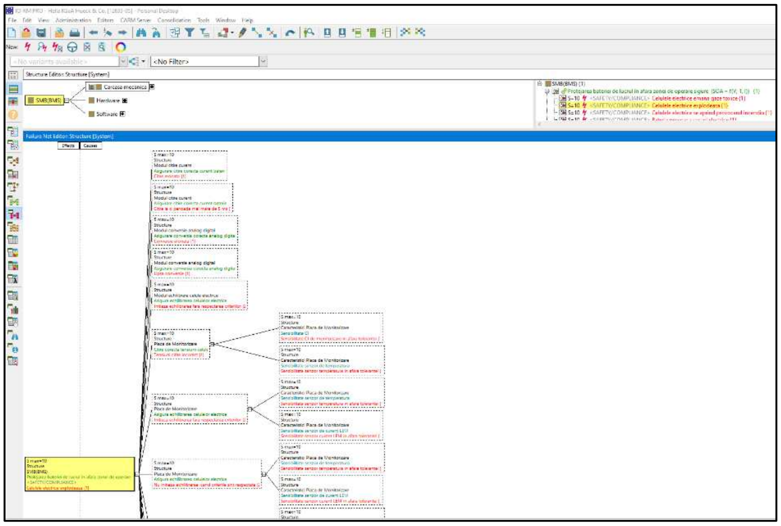
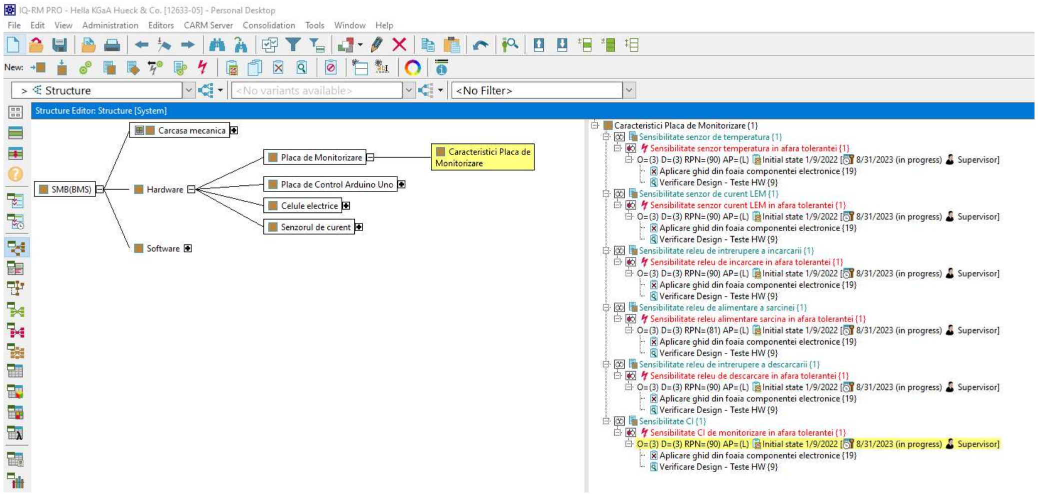


Fig. 3.11. Network of system-level failure modes

3.3.4 Analysis of preventive and detective actions

Preventive controls relate to performance requirements. For items that have been designed out of context and are purchased as stock or catalog items from a supplier, the preventive control should document a specific reference to how the item meets the requirement. This may be a reference to a specification sheet in a catalogue. Current preventive controls must be clearly and comprehensively described, with references cited.

Figure 3.12 shows the current preventive and detective actions for a particular case of a hardware component, where, in addition to evaluating the Occurrence and Detection parameters, APIS IQ-RM also documents the time limit until the implementation of the actions as well as the responsible person, information that can be used to perform various in-app filters to control, track and prioritize actions.



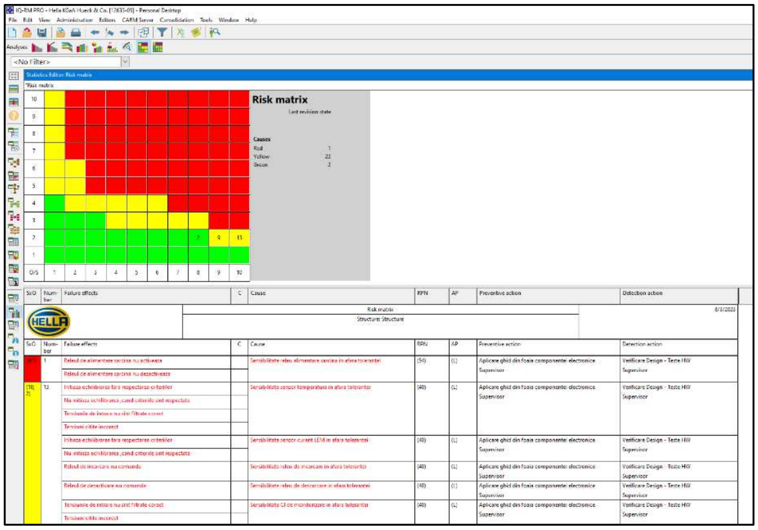
```
Caracteristici Placa de Monitorizare {1}
  Sensibilitate senzor de temperatura {1}
    Sensibilitate senzor temperatura in afara tolerantei {1}
      O=(3) D=(3) RPN=(90) AP=(L) Initial state 1/9/2022 [ 8/31/2023 (in progress) Supervisor]
        Aplicare ghid din foaia componentei electronice {19}
        Verificare Design - Teste HW {9}
  Sensibilitate senzor de curent LEM {1}
    Sensibilitate senzor curent LEM in afara tolerantei {1}
      O=(3) D=(3) RPN=(90) AP=(L) Initial state 1/9/2022 [ 8/31/2023 (in progress) Supervisor]
        Aplicare ghid din foaia componentei electronice {19}
        Verificare Design - Teste HW {9}
  Sensibilitate releu de intrerupere a incarcarii {1}
    Sensibilitate releu de incarcare in afara tolerantei {1}
      O=(3) D=(3) RPN=(90) AP=(L) Initial state 1/9/2022 [ 8/31/2023 (in progress) Supervisor]
        Aplicare ghid din foaia componentei electronice {19}
        Verificare Design - Teste HW {9}
  Sensibilitate releu de alimentare a sarcinei {1}
    Sensibilitate releu alimentare sarcina in afara tolerantei {1}
      O=(3) D=(3) RPN=(81) AP=(L) Initial state 1/9/2022 [ 8/31/2023 (in progress) Supervisor]
        Aplicare ghid din foaia componentei electronice {19}
        Verificare Design - Teste HW {9}
  Sensibilitate releu de intrerupere a descarcarii {1}
    Sensibilitate releu de descarcare in afara tolerantei {1}
      O=(3) D=(3) RPN=(90) AP=(L) Initial state 1/9/2022 [ 8/31/2023 (in progress) Supervisor]
        Aplicare ghid din foaia componentei electronice {19}
        Verificare Design - Teste HW {9}
  Sensibilitate CI {1}
    Sensibilitate CI de monitorizare in afara tolerantei {1}
      O=(3) D=(3) RPN=(90) AP=(L) Initial state 1/9/2022 [ 8/31/2023 (in progress) Supervisor]
        Aplicare ghid din foaia componentei electronice {19}
        Verificare Design - Teste HW {9}
```

Fig. 3.12. Preventive and detective actions at the root cause level

3.3.5 BMS risk matrix generation

Generating the risk matrix in AMDE analysis involves using severity (S), occurrence (O) and detectability (D) scores to assess the risk associated with each failure mode in the analyzed BMS. The risk score (IPR / RPN - Risk Priority Number) is calculated for each failure mode by multiplying the severity (S), occurrence (O) and detectability (D) scores so that IPR (RPN) = S x O x D.nMatrix of risk in AMDE automatically generated by the APIS IQ-RM application will contain detailed information about each failure mode analyzed, including S, O, D and IPR / RPN scores, helping to understand the associated risks for their prioritization. In figure 3.13, an instance of the risk matrix appears in the upper part and a prioritization of the root causes in tabular form in the lower part of the image.

The APIS IQ-RM application is also capable of another method of risk analysis, namely Pareto analysis. Pareto analysis in AMDE analysis is a technique used to identify and prioritize the failure modes or faults that have the greatest impact on the analyzed system. This technique is based on the Pareto principle, according to which a significant proportion of effects or consequences are generated by a small number of causes. Pareto analysis in AMDE enables quick and efficient identification of the main risks and helping to focus efforts on the most critical aspects to improve the safety and reliability of the BMS. Figure 3.14 shows a snapshot of the Pareto analysis where it is observed that 11 causes out of the 25 listed have the greatest impact in BMS design.



Risk matrix

Last revision state

Causes

Red	1
Yellow	22
Green	2

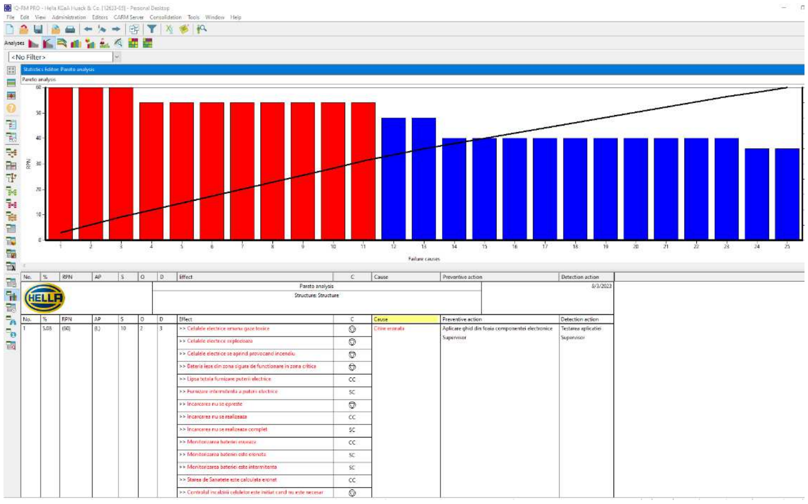
Risk matrix

Structure: Structure

8/3/2023

SxO	Number	Failure effects	C	Cause	RPN	AP	Preventive action	Detection action
[illegible]	1	Releul de alimentare sarcina nu activeaza		Sensibilitate releu alimentare sarcina in afara tolerantei	(54)	(L)	Aplicare ghid din foaia componentei electronice Supervisor	Verificare Design - Teste HW Supervisor
		Releul de alimentare sarcina nu dezactiveaza						
(10, 2)	13	Initiaza echilibrarea fara respectarea criteriilor		Sensibilitate senzor temperatura in afara tolerantei	(40)	(L)	Aplicare ghid din foaia componentei electronice Supervisor	Verificare Design - Teste HW Supervisor
		Nu initiaza echilibrarea ,cand criteriile sint respectate						
		Tensiunile de intrare nu sint filtrate corect						
		Tensiuni citite incorect						
		Initiaza echilibrarea fara respectarea criteriilor		Sensibilitate senzor curent LEM in afara tolerantei	(40)	(L)	Aplicare ghid din foaia componentei electronice Supervisor	Verificare Design - Teste HW Supervisor
		Nu initiaza echilibrarea ,cand criteriile sint respectate						
		Releul de incarcare nu comanda		Sensibilitate releu de incarcare in afara tolerantei	(40)	(L)	Aplicare ghid din foaia componentei electronice Supervisor	Verificare Design - Teste HW Supervisor
		Releul de descarcare nu comanda		Sensibilitate releu de descarcare in afara tolerantei	(40)	(L)	Aplicare ghid din foaia componentei electronice Supervisor	Verificare Design - Teste HW Supervisor
		Tensiunile de intrare nu sint filtrate corect		Sensibilitate CI de monitorizare in afara tolerantei	(40)	(L)	Aplicare ghid din foaia componentei electronice Supervisor	Verificare Design - Teste HW Supervisor
		Tensiuni citite incorect						

Fig. 3.13. BMS risk matrix



Pareto analysis

Structure: Structure

8/3/2023

No.	%	RPN	AP	S	O	D	Effect	C	Cause	Preventive action	Detection action
1	5.08	(60)	(L)	10	2	3	>> Celulele electrice emana gaze toxice	○	Citire eronata	Aplicare ghid din foaia componentei electronice Supervisor	Testarea aplicatiei Supervisor
							>> Celulele electrice explodeaza	○			
							>> Celulele electrice se aprind provocand incendiu	○			
							>> Bateria iese din zona sigura de functionare in zona critica	○			
							>> Lipsa totala furnizare puterii electrice	CC			
							>> Furnizare intermitenta a puterii electrice	SC			
							>> Incarcarea nu se opreste	○			
							>> Incarcarea nu se realizeaza	CC			
							>> Incarcarea nu se realizeaza complet	SC			
							>> Monitorizarea bateriei eseaza	CC			
							>> Monitorizarea bateriei este eronata	SC			
							>> Monitorizarea bateriei este intermitenta	SC			
							>> Starea de Sanatete este calculata eronat	CC			
							>> Controlul incalzirii celulelor este initiat cand nu este necesar	○			

Fig. 3.14. Pareto chart of BMS

3.4 DESIGN AND SIMULATION OF BMS THROUGH COMPUTER AIDED APPLICATIONS

The activity of synthesis and functional simulation of the BMS was done with the help of the SimulIDE design assistance application. SimulIDE is an open and free interactive simulation software that is mainly used to design and test digital and analog electronic circuits. It is especially used in education and in prototyping small to complex electronic projects. SimulIDE provides a virtual development environment to test and validate electronic circuits before physically implementing them on printed circuit boards or other electronic devices [46].

In conjunction with the SimulIDE environment, we also used the Arduino development environment to implement the BMS control application. The Arduino platform is an open-source prototyping and development platform for electronics, programming, and robotics projects. Arduino is a popular choice due to its ease of use and active support and development community. The Arduino platform includes the following main components: Arduino Boards, Arduino MID / IDE (Integrated Development Environment), Arduino Programming Language, Libraries, Arduino Community.

3.4.1 Computer Aided Design of BMS with SimulIDE application

With the help of the SimulIDE environment version 0.4.15, the virtual architecture of the BMS was implemented, and in the MID / IDE Arduino version 1.8.19, the control application was created, whose detailed source code is documented in the appendix of the thesis. The graphical interface of SimulIDE is shown in figure 3.15, it being configurable, other sections can be added, for example the microcontroller communication monitoring window.

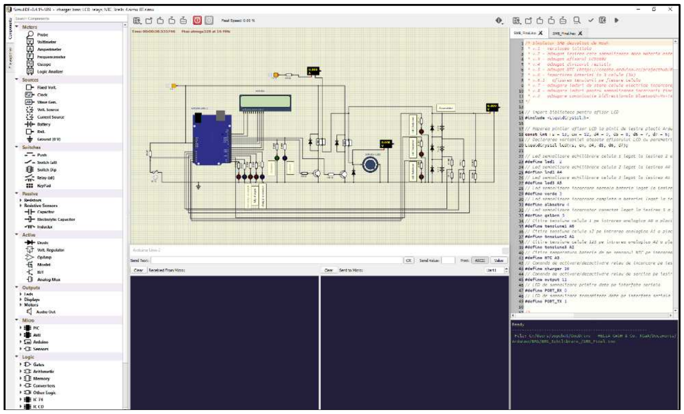
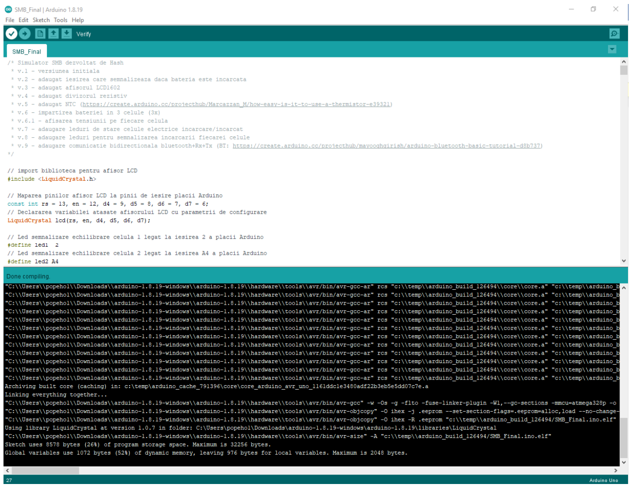


Fig. 3.15. SimulIDE simulation environment

The Arduino environment interface has a simple and easy-to-use structure, designed to allow users to write, compile, and upload code to the Arduino board to control various electronic devices and projects, as shown in Figure 3.16.



```
/* Simulator SMB dezvoltat de Hash
 * v.1 - versiunea initiala
 * v.2 - adaugat iesirea care semnalizeaza daca bateria este incarcata
 * v.3 - adaugat afisorul LCD1602
 * v.4 - adaugat divizorul rezistiv
 * v.5 - adaugat NTC (https://create.arduino.cc/projecthub/Marcazzan_M/how-easy-is-it-to-use-a-thermistor-e39321)
 * v.6 - impartirea bateriei in 3 celule (3x)
 * v.6.1 - afisarea tensiunii pe fiecare celula
 * v.7 - adaugare leduri de stare celule electrice incarcare/incarcat
 * v.8 - adaugare leduri pentru semnalizarea incarcarii fiecarei celule
 * v.9 - adaugare comunicatie bidirectionala bluetooth+Rx+Tx (BT: https://create.arduino.cc/projecthub/mayooghgirish/arduino-bluetooth-basic-tutorial-d8b737)
*/

// import biblioteca pentru afisor LCD
#include <LiquidCrystal.h>

// Maparea pinilor afisor LCD la pinii de iesire placii Arduino
const int rs = 13, en = 12, d4 = 9, d5 = 8, d6 = 7, d7 = 6;
// Declararea variabilei atasate afisorului LCD cu parametrii de configurare
LiquidCrystal lcd(rs, en, d4, d5, d6, d7);

// Led semnalizare echilibrare celula 1 legat la iesirea 2 a placii Arduino
#define led1  2
// Led semnalizare echilibrare celula 2 legat la iesirea A4 a placii Arduino
#define led2 A4
```

Done compiling.

```
"C:\\Users\\popehol\\Downloads\\arduino-1.8.19-windows\\arduino-1.8.19\\hardware\\tools\\avr/bin/avr-gcc-ar" rcs "c:\\temp\\arduino_build_126494\\core\\core.a" "c:\\temp\\arduino_b
"C:\\Users\\popehol\\Downloads\\arduino-1.8.19-windows\\arduino-1.8.19\\hardware\\tools\\avr/bin/avr-gcc-ar" rcs "c:\\temp\\arduino_build_126494\\core\\core.a" "c:\\temp\\arduino_b
"C:\\Users\\popehol\\Downloads\\arduino-1.8.19-windows\\arduino-1.8.19\\hardware\\tools\\avr/bin/avr-gcc-ar" rcs "c:\\temp\\arduino_build_126494\\core\\core.a" "c:\\temp\\arduino_b
"C:\\Users\\popehol\\Downloads\\arduino-1.8.19-windows\\arduino-1.8.19\\hardware\\tools\\avr/bin/avr-gcc-ar" rcs "c:\\temp\\arduino_build_126494\\core\\core.a" "c:\\temp\\arduino_b
"C:\\Users\\popehol\\Downloads\\arduino-1.8.19-windows\\arduino-1.8.19\\hardware\\tools\\avr/bin/avr-gcc-ar" rcs "c:\\temp\\arduino_build_126494\\core\\core.a" "c:\\temp\\arduino_b
"C:\\Users\\popehol\\Downloads\\arduino-1.8.19-windows\\arduino-1.8.19\\hardware\\tools\\avr/bin/avr-gcc-ar" rcs "c:\\temp\\arduino_build_126494\\core\\core.a" "c:\\temp\\arduino_b
"C:\\Users\\popehol\\Downloads\\arduino-1.8.19-windows\\arduino-1.8.19\\hardware\\tools\\avr/bin/avr-gcc-ar" rcs "c:\\temp\\arduino_build_126494\\core\\core.a" "c:\\temp\\arduino_b
"C:\\Users\\popehol\\Downloads\\arduino-1.8.19-windows\\arduino-1.8.19\\hardware\\tools\\avr/bin/avr-gcc-ar" rcs "c:\\temp\\arduino_build_126494\\core\\core.a" "c:\\temp\\arduino_b
"C:\\Users\\popehol\\Downloads\\arduino-1.8.19-windows\\arduino-1.8.19\\hardware\\tools\\avr/bin/avr-gcc-ar" rcs "c:\\temp\\arduino_build_126494\\core\\core.a" "c:\\temp\\arduino_b
"C:\\Users\\popehol\\Downloads\\arduino-1.8.19-windows\\arduino-1.8.19\\hardware\\tools\\avr/bin/avr-gcc-ar" rcs "c:\\temp\\arduino_build_126494\\core\\core.a" "c:\\temp\\arduino_b
"C:\\Users\\popehol\\Downloads\\arduino-1.8.19-windows\\arduino-1.8.19\\hardware\\tools\\avr/bin/avr-gcc-ar" rcs "c:\\temp\\arduino_build_126494\\core\\core.a" "c:\\temp\\arduino_b
"C:\\Users\\popehol\\Downloads\\arduino-1.8.19-windows\\arduino-1.8.19\\hardware\\tools\\avr/bin/avr-gcc-ar" rcs "c:\\temp\\arduino_build_126494\\core\\core.a" "c:\\temp\\arduino_b
Archiving built core (caching) in: c:\temp\arduino_cache_791396\core\core_arduino_avr_uno_1161ddc1e3480adf22b3eb5e5dd07c7e.a
Linking everything together...
"C:\\Users\\popehol\\Downloads\\arduino-1.8.19-windows\\arduino-1.8.19\\hardware\\tools\\avr/bin/avr-gcc" -w -Os -g -flto -fuse-linker-plugin -Wl,--gc-sections -mmcu=atmega328p -o
"C:\\Users\\popehol\\Downloads\\arduino-1.8.19-windows\\arduino-1.8.19\\hardware\\tools\\avr/bin/avr-objcopy" -O ihex -j .eeprom --set-section-flags=.eeprom=alloc,load --no-change-
"C:\\Users\\popehol\\Downloads\\arduino-1.8.19-windows\\arduino-1.8.19\\hardware\\tools\\avr/bin/avr-objcopy" -O ihex -R .eeprom "c:\\temp\\arduino_build_126494/SMB_Final.ino.elf"
Using library LiquidCrystal at version 1.0.7 in folder: C:\Users\popehol\Downloads\arduino-1.8.19-windows\arduino-1.8.19\libraries\LiquidCrystal
"C:\\Users\\popehol\\Downloads\\arduino-1.8.19-windows\\arduino-1.8.19\\hardware\\tools\\avr/bin/avr-size" -A "c:\\temp\\arduino_build_126494/SMB_Final.ino.elf"
Sketch uses 8578 bytes (26%) of program storage space. Maximum is 32256 bytes.
Global variables use 1072 bytes (52%) of dynamic memory, leaving 976 bytes for local variables. Maximum is 2048 bytes.
```

Fig. 3.16. Arduino Integrated Development Environment

For the implementation of the BMS functionalities, from the hardware point of view, the following blocks formed by the components of the SimulIDE library were used, listed from left to right according to the architecture in figure 3.17:

- Battery temperature sensor;
- Development board based on Arduino Uno microcontroller;
- LCD display;
- Communication or BMS status information LEDs;
- Battery charger coupling/uncoupling relay;
- Battery load disconnect coupling relay;
- BMS load;
- Cell balancing information LEDs;
- Balancing diodes of the 3 electric cells in the battery;
- Voltage dividers.

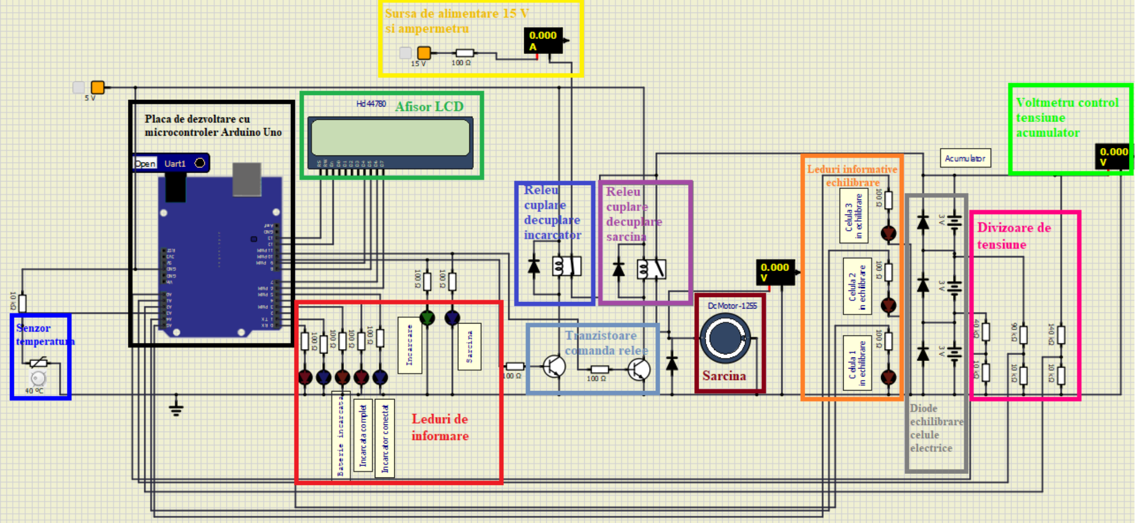


Fig. 3.17. BMS hardware architecture

The left side of the board uses the following inputs/outputs listed from top to bottom:

- 5 V power input;
- Analog input A0 connected to the frequency divider of the first cell;
- Analog input A1 connected to the frequency divider of the second cell;
- Analog input A2 connected to the frequency divider of the third cell;
- Analog input A3 linked to the temperature sensor;
- Analogue output A4 linked to cell 2 balancing signaling LED;
- Analogue output A5 linked to cell 3 balancing signaling LED;

The following inputs listed from bottom to top are used on the right side of the board:

- The Rx output linked to the data reception signaling LED that activates when data is received on the serial interface;
- The Tx output linked to the data sending signal LED that activates when data is transmitted on the serial interface;
- PWM output 3 controls the LED indicating the state of battery charge;
- Digital output 4 that controls the LED signaling the state of full charge of the battery;

- PWM output 5 controls the LED indicating the connection of the external battery charger;
- PWM output 6 connected to pin D7 of the LCD display;
- Digital output 7 connected to pin D6 of the LCD display;
- Digital output 8 connected to pin D5 of the LCD display;
- PWM output 9 connected to pin D4 of the LCD display;
- PWM output 10 connected to the control transistor of the external battery charger connection / disconnection relay;
- PWM output 11 connected to the control transistor of the external load connection / disconnection relay of the battery;
- Digital output 12 connected to pin En of the LCD display;
- Digital output 13 connected to the RS pin of the LCD display;

3.4.2 BMS control application algorithm and architecture

The architecture of a program for Arduino Uno is based on the Arduino programming language and the Arduino IDE (Integrated Development Environment). Thus, the software architecture with main components of a program for Arduino Uno is presented in detail in figure 3.18:

- The setup() function: This is an essential function in any Arduino program, the code in the setup() function runs only once when the Arduino board is powered on and is used for initial initializations such as setting up pins, setting up serial communication or setting parameters important;
- The loop() function: This is where most of the code will be placed. The code in the loop() function loops indefinitely, continuously. This is where repetitive logic or constant monitoring is implemented, being called continuously and executed in an infinite loop once the program has been started on the Arduino board;
- Functions and Variables: You can define your own functions and variables in the Arduino program to organize the code and make the logic easier to understand, variables can be used to store temporary data or pass information between different parts of the program.

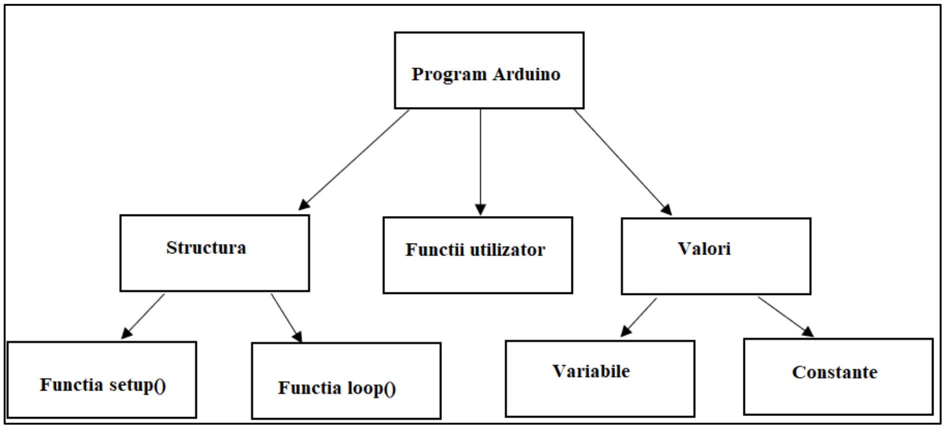


Fig. 3.18. General softw

Based on the above, the BMS control program architecture has 3 distinct sections as follows and are sketched in figure 3.19:

- Data declaration area;
- Initialization module *setup()*;
- Looping module *loop()*;

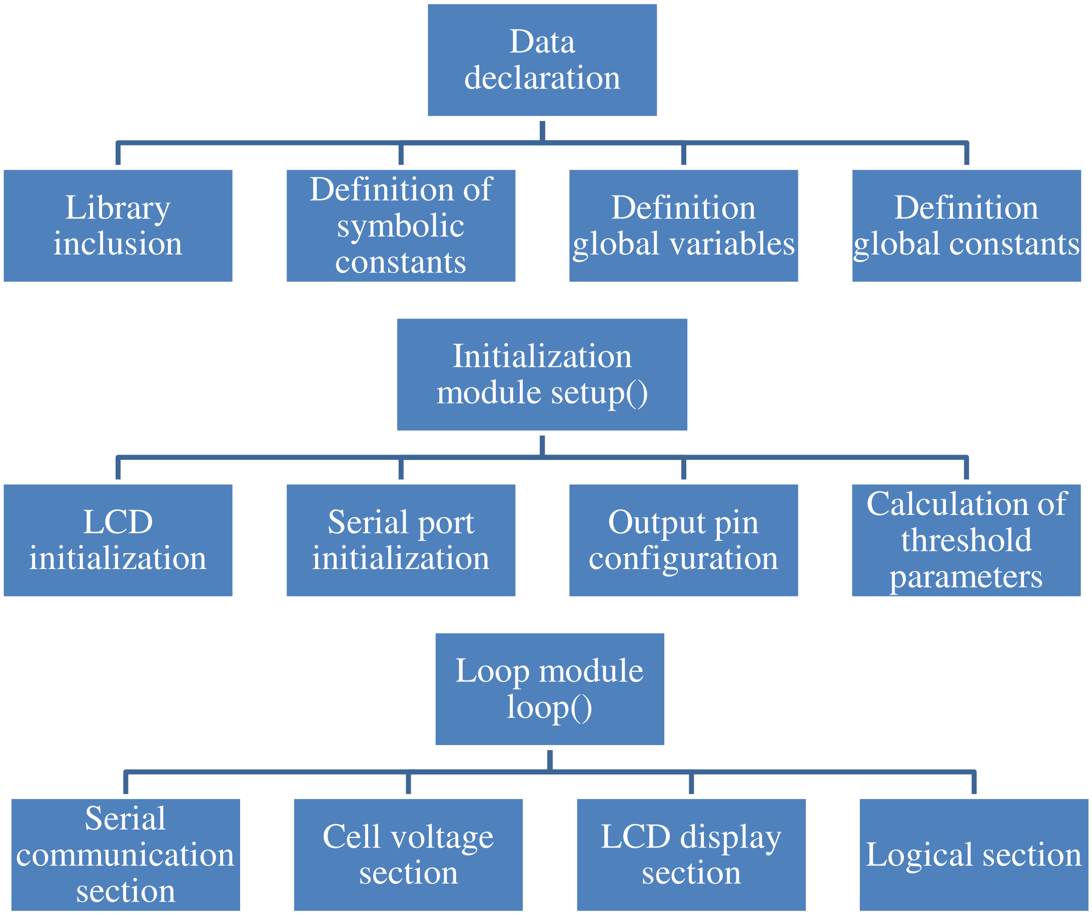


Fig. 3.19 The architecture of the BMS control program

The control logic in the *loop()* function starts with checking the availability of the serial port for communication, if it is ready for use, the data is read from the serial interface and signaled visually by the data reception LED on the Rx port. The data is manually transmitted in the communication window of the SimulIDE environment by the user and represents commands to display various information: the voltage of the 3 cells, information messages if the cells are overcharged and need to be balanced, the state of charge of the battery with connecting / not connecting the charger or load depending on the conditions met BMS parameters, temperature and information or warning messages. The requested data is transmitted to the serial console to the user and the activity on the Tx data transmission port is visually signaled by the LED. The commands received for displaying data are natural numbers between 1 and 4 representing requests, in order, to display information about electric cells 1,2,3 and temperature.

The algorithm continues with reading the data from the voltage dividers and calculating the voltage drops on each of the 3 electrical cells necessary for balancing action decisions. Next comes the preparation of the display data on the LCD screen, namely sequentially every 3 seconds the following information: battery voltage, electric cell voltage and balancing status, temperature and warning messages if applicable.

The last part of the algorithm contains the implementation of the state machine of the BMS that ensures the transition in different states depending on the values of the system parameters in relation to the accepted operating limits in the safe area of the system. If the battery temperature exceeds the BMS configurable limit, the BMS status changes from normal heated to overheated and the warning LEDs are activated. The logic scheme that implements the control of program flows in the *loop()* loop is presented in figure 3.20. In order to increase the readability of the logic scheme, a scalable vector file has been integrated as an image that allows the image enlargement function without losing content details.

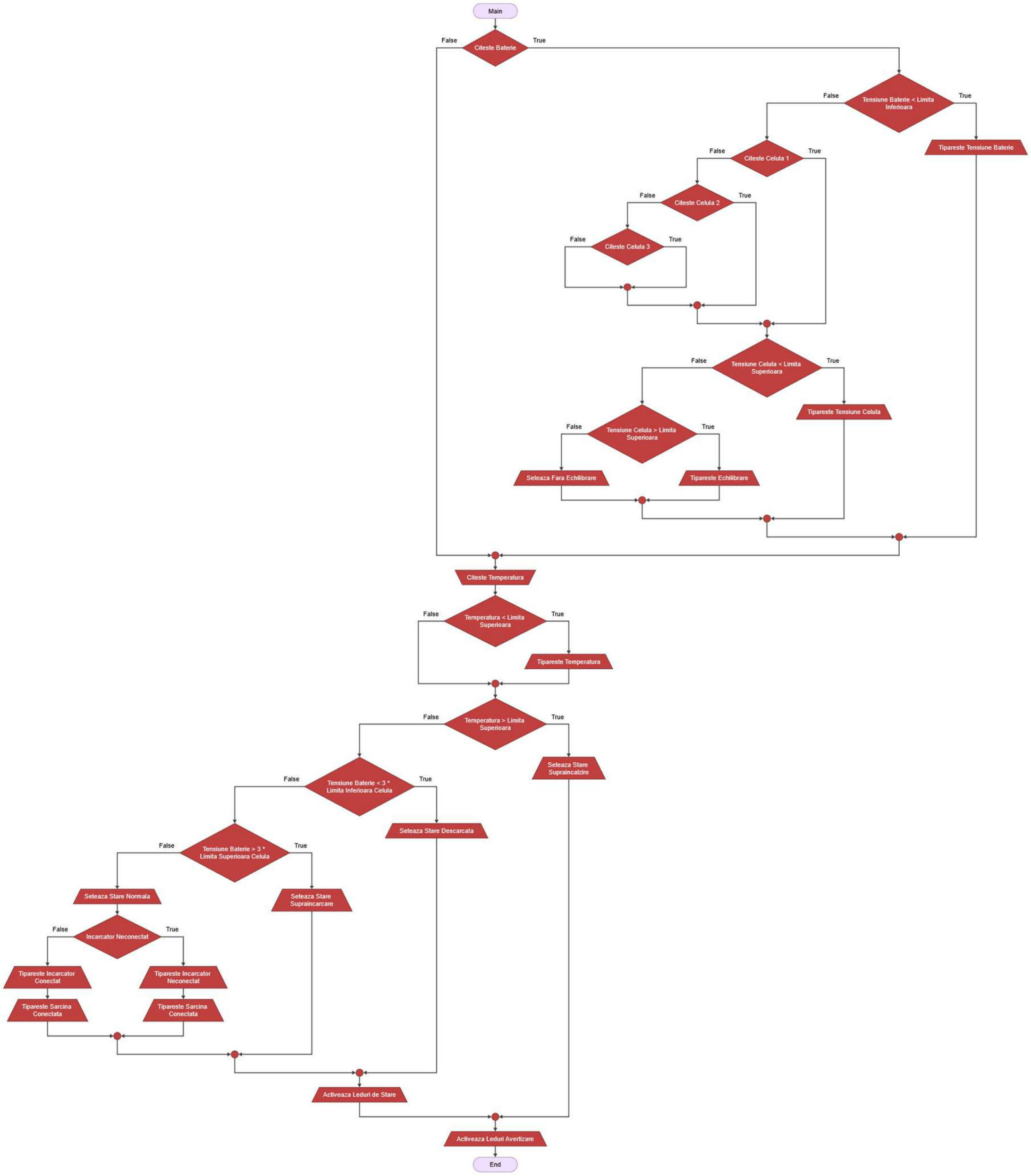
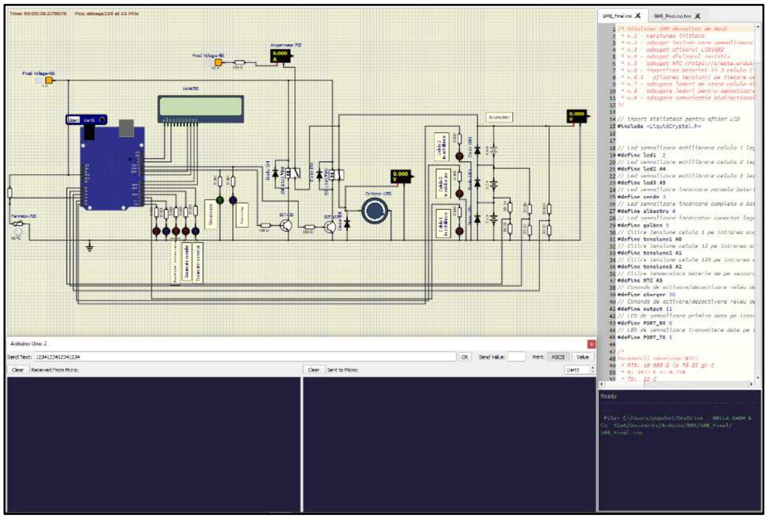


Fig. 3.20. The logic diagram of loop*()*

3.4.3 Computer-aided simulation of BMS with the SimulIDE application

Assisted by the ScreenRecorder utility, I recorded the simulation of the BMS operation from the SimulIDE application and integrated it in this chapter in figure 3.21, for running the *.wmv video file, the control key (Ctrl) and the left mouse button must be pressed simultaneously. The approximately 4-minute recording contains the demonstration of various functional states of the BMS as follows:

- BMS simulation in normal operating state, with parameter values that ensure a safe zone, battery temperature set around 50o C, electric cell voltages around 3.7 V nominal value, which will lead to a total battery voltage of approximately 11.1 V resulting in the activation of the 2 relays connecting the charger and the load simultaneously, the status information being displayed on the LCD screen and transmitted on the serial interface;
- At the 33rd second, the temperature parameter is changed by means of the thermistor potentiometer to the value of 65o C without changing the voltages of the electric cells, an action that will lead to the disconnection of the charger and the external load by deactivating the 2 relays, the status information and overheating warning being displayed on the LCD screen and transmitted on the serial interface;
- At the 50th second, the temperature parameter is changed by means of the thermistor potentiometer to the value of 50o C and the voltages of the 3 electric cells are set to a value of 3.0 V in order to meet the conditions of deep discharge of the battery under the minimum voltage of 3.2 V per electric cell, which will lead to the disconnection of the load through the corresponding relay and the LED warning of connecting the charger;
- At second 120, the voltages of the 3 electric cells are set to values of 3.5 V to meet the conditions of normal battery charging above the minimum voltage of 3.2 V per electric cell but below the nominal voltage of 3.7 V, which will lead to the connection of the load through the corresponding relay, the charger remaining connected and the information through LEDs and on the LCD screen of the connection of the load;
- At second 165, the voltages of the 3 electric cells are set to values of 4.7 V in order to meet the battery overload conditions above the maximum voltage of 4.2 V per electric cell, meeting the balancing conditions, which will lead to the disconnection of the charger through the corresponding relay, the load staying connected, the diodes parallel to the cells will be activated to take over the excess load from the electric cells, generating information through balancing LEDs as well as on the LCD screen of the connection of the load and the disconnection of the charger;
- At the 165th second, a multiple set of "1234" commands will be sent in a burst of 4, generating the information through balancing LEDs, on the LCD screen as well as through the serial interface of the overload status and the balancing process; it is observed in this last simulation case how the communication LEDs on both Rx and Tx representing the reception and transmission of data on the serial interface flash to inform the user about the data transfer;



```
// import biblioteca pentru afisor LCD
#include <LiquidCrystal.h>


// Led semnalizare echilibrare celula 1 leg
#define led1  2
// Led semnalizare echilibrare celula 2 leg
#define led2 A4
// Led semnalizare echilibrare celula 3 leg
#define led3 A5
// Led semnalizare incarcare normala bater
#define verde 3
// Led semnalizare incarcare completa a bat
#define albastru 4
// Led semnalizare incarcator conectat leg
#define galben 5
// Citire tensiune celula 1 pe intrarea an
#define tensiune1 A0
// Citire tensiune celule 12 pe intrarea a
#define tensiune2 A1
// Citire tensiune celule 123 pe intrarea 
#define tensiune3 A2
// Citire temperatura baterie de pe senzor
#define NTC A3
// Comanda de activare/dezactivare releu de
#define charger 10
// Comanda de activare/dezactivare releu de
#define output 11
// LED de semnalizare primire date pe inte
#define PORT_RX 0
// LED de semnalizare transmitere date pe 
#define PORT_TX 1
```

Fig. 3.21. BMS functionality simulation

3.4.4 BMS use cases testing

Testing the simulated battery management system with a temperature sensor and three electric cells involves checking and validating the functionality and safety of the system under different conditions. In order to develop the test cases, the values of the temperature and voltage parameters for the 3 electrical cells must be taken into account. Thus, the maximum operating temperature in the safe zone was set in the control program to 60o C, the minimum voltage of the electrical cell is 3.2 V, the nominal voltage 3.7 V, the maximum voltage 4.2 V when the balancing function must be triggered. The lower voltage limit of the whole battery to be considered discharged is 3 times the minimum voltage of an electric cell so if it is lower than 9.6 V. The test cases we consider for BMS are as follows:

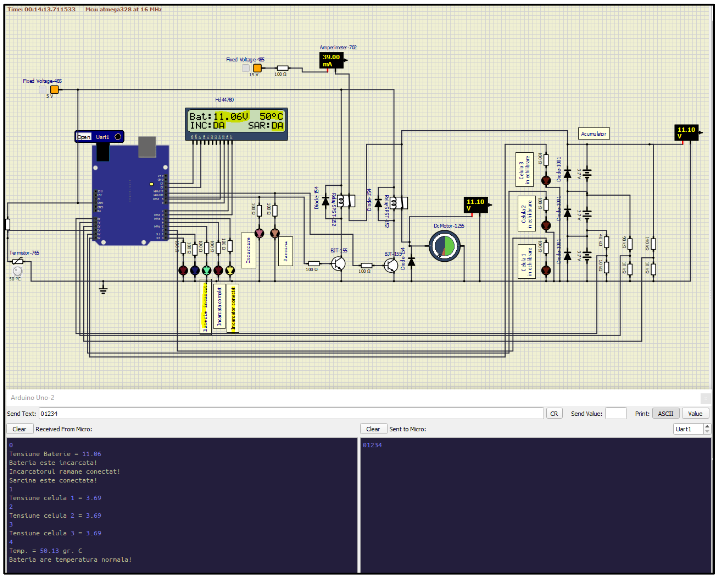
- Testing the upload and download functionality;
- Testing the balancing function;
- Temperature sensor testing;
- Safety testing:
- Load management testing:
- Download management testing;
- Communications and interface testing;
- Testing in extreme environments:

The results of each test case will be documented and analyzed to ensure that the battery management system is working properly, safely and according to project specifications and requirements, exemplified by snapshots from the SimulIDE simulation application.

Test case 1: checking the normal operation state of the BMS, the temperature set to 50o C and the voltages of the 3 electric cells set to 3.7 V. The expected result of the BMS simulation is to activate the load and the load through the 2 relays, the correct display on the LCD screen of the parameters and status of the relays as well as on the serial interface, the activation of the 2 information LEDs Battery charged and Charger connected. As exemplified in figure 3.22, this test passed successfully in the simulation.

Test case 2: checking the overheat condition of the battery, the temperature set to 75o C and the voltages of the 3 electric cells set to 3.7 V. The expected result of the BMS simulation is to disable the load and the load through the 2 relays, the correct display on the screen LCD of parameters and status of relays as well as on the serial interface, deactivation of all information LEDs, display of warning messages of overheating status on the LCD as well as on the serial interface. As exemplified in figure 3.23, this test passed successfully in the simulation.

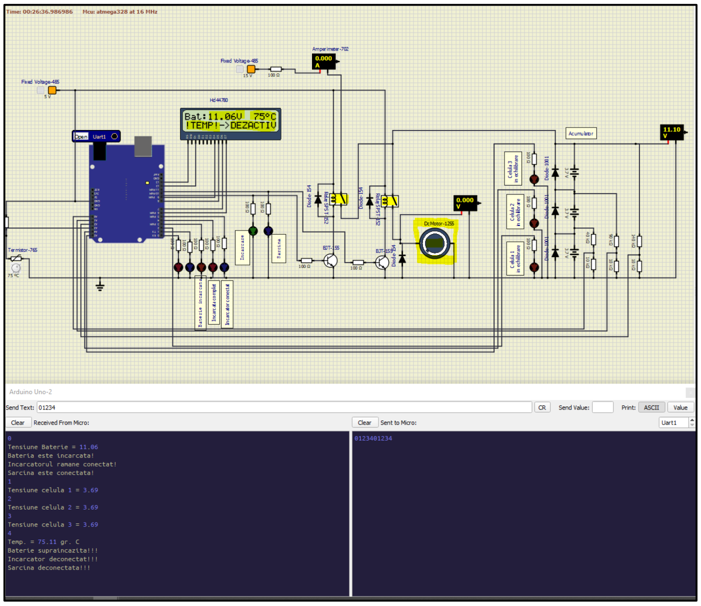
Test case 3: checking the undercharge status of the battery, the temperature set to 50o C and the voltages of the 3 electric cells set to 3.2 V. The expected result of the BMS simulation is to activate the load and deactivate the load through the 2 relays, the correct display on the LCD screen as well as on the serial interface of the parameters, the status of the relays and the warning messages of the undercharge state, the activation of the connected Charger information LED. As exemplified in figure 3.24, this test passed successfully in the simulation.



```
0
Tensiune Baterie = 11.06
Bateria este incarcata!
Incarcatorul ramane conectat!
Sarcina este conectata!
1
Tensiune celula 1 = 3.69
2
Tensiune celula 2 = 3.69
3
Tensiune celula 3 = 3.69
4
Temp. = 50.13 gr. C
Bateria are temperatura normala!
```

```
01234
```

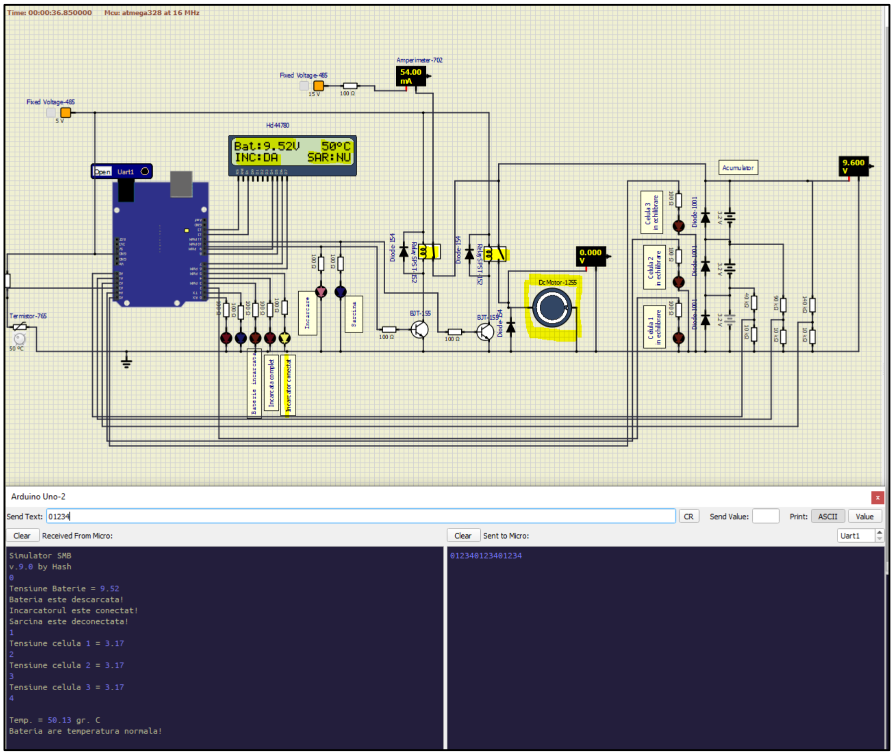
Fig. 3.22. Test case 1



```
0
Tensiune Baterie = 11.06
Bateria este incarcata!
Incarcatorul ramane conectat!
Sarcina este conectata!
1
Tensiune celula 1 = 3.69
2
Tensiune celula 2 = 3.69
3
Tensiune celula 3 = 3.69
4
Temp. = 75.11 gr. C
Baterie supraincazita!!!
Incarcator deconectat!!!
Sarcina deconectata!!!
```

```
0123401234
```

Fig. 3.23. Test case 2



```
Simulator SMB
v.9.0 by Hash
0
Tensiune Baterie = 9.52
Bateria este descarcata!
Incarcatorul este conectat!
Sarcina este deconectata!
1
Tensiune celula 1 = 3.17
2
Tensiune celula 2 = 3.17
3
Tensiune celula 3 = 3.17
4

Temp. = 50.13 gr. C
Bateria are temperatura normala!
```

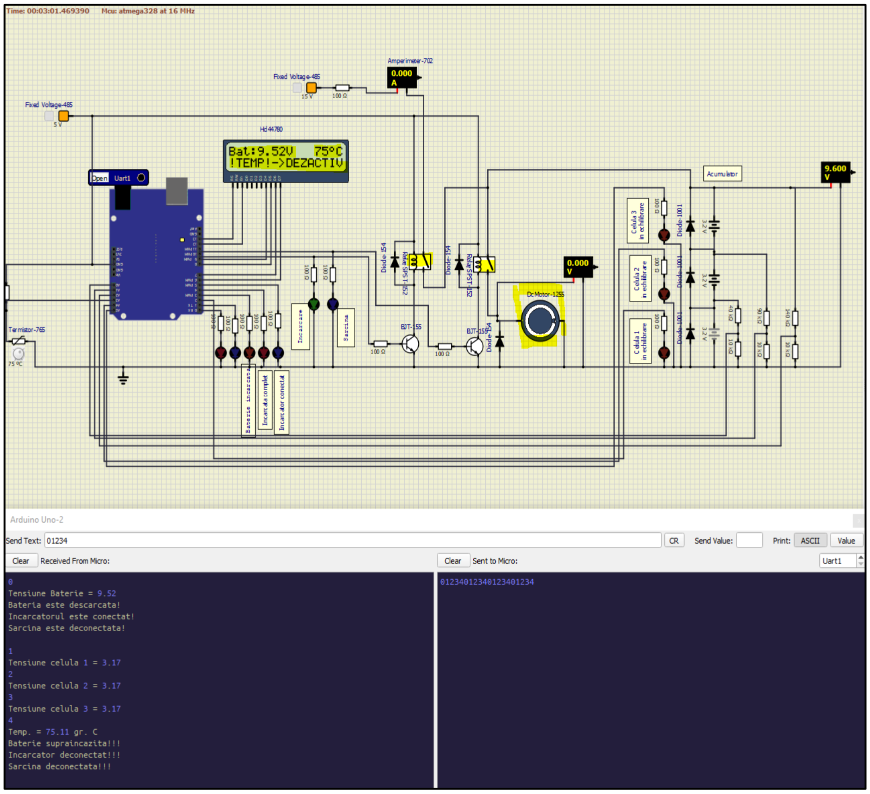
```
012340123401234
```

Fig. 3.24. Test case 3

Test case 4: checking the undercharge and overheat status of the battery, the temperature set to 75o C and the voltages of the 3 electric cells set to 3.2 V. The expected result from the BMS simulation is to disable the load and disable the load through the 2 relays, the display correct on the LCD screen as well as on the serial interface of the parameters, the status of the relays and the warning messages of the undercharge and overheat condition, the deactivation of all the information LEDs. As exemplified in figure 3.25, this test passed successfully in the simulation.

Test case 5: checking the undercharge condition on a subset of electric cells but with the total battery voltage above the lower limit of 9.6 V, the temperature set to 50o C and the voltages of 2 electric cells set to the nominal 3.7 V and the cell to the voltage of undercharge of 3.2 V resulting in a battery voltage of 10.6 V. The expected output from the BMS simulation is load activation and load activation through the 2 relays, correct display on the LCD screen as well as on the serial interface of the parameters, the status of the relays and message information LEDs Battery Charged and Charger Connected Undercharge and Overheat. As exemplified in figure 3.26, this test passed successfully in the simulation.

Test case 6: checking the overload condition of some electric cells, the temperature set at 50^{o} C and the voltage of 2 electric cells set to values above the upper limit of 4.2 V and the voltage of one electric cell set below this upper limit. The expected result of the BMS simulation is deactivation of the load and activation of the load through the 2 relays, the correct display on the LCD screen as well as on the serial interface of the parameters, the status of the relays and the information messages Fully loaded and warning of the overload status of 2 electrical cells which leads to the activation of balancing on the 2 cells, an event signaled by the balancing information LEDs. As exemplified in figure 2.27, this test passed successfully in the simulation.

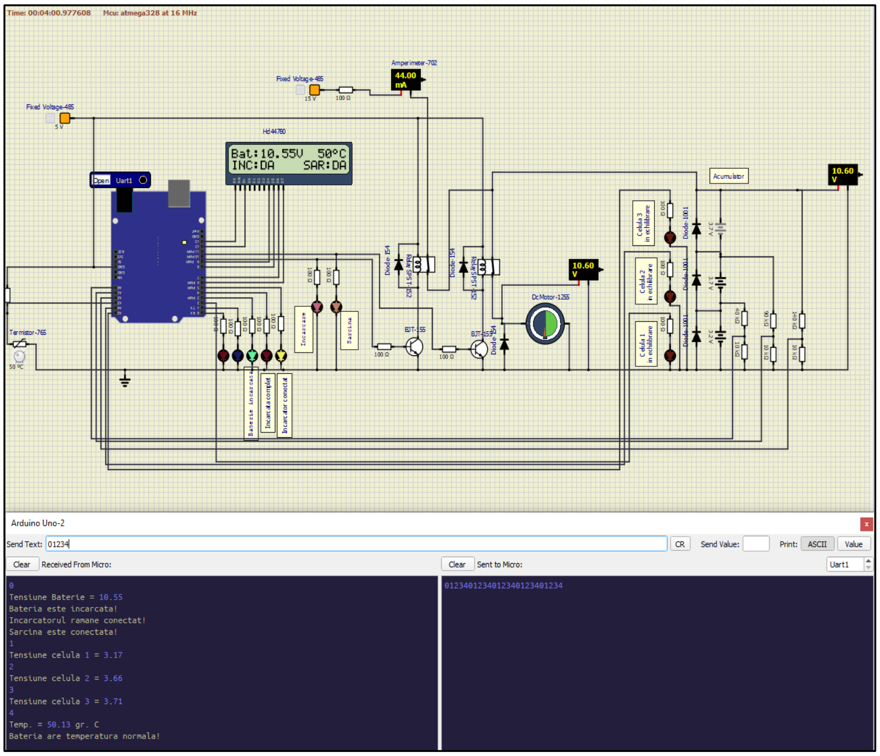


```
0
Tensiune Baterie = 9.52
Bateria este descarcata!
Incarcatorul este conectat!
Sarcina este deconectata!

1
Tensiune celula 1 = 3.17
2
Tensiune celula 2 = 3.17
3
Tensiune celula 3 = 3.17
4
Temp. = 75.11 gr. C
Baterie supraincazita!!!
Incarcator deconectat!!!
Sarcina deconectata!!!
```

```
01234012340123401234
```

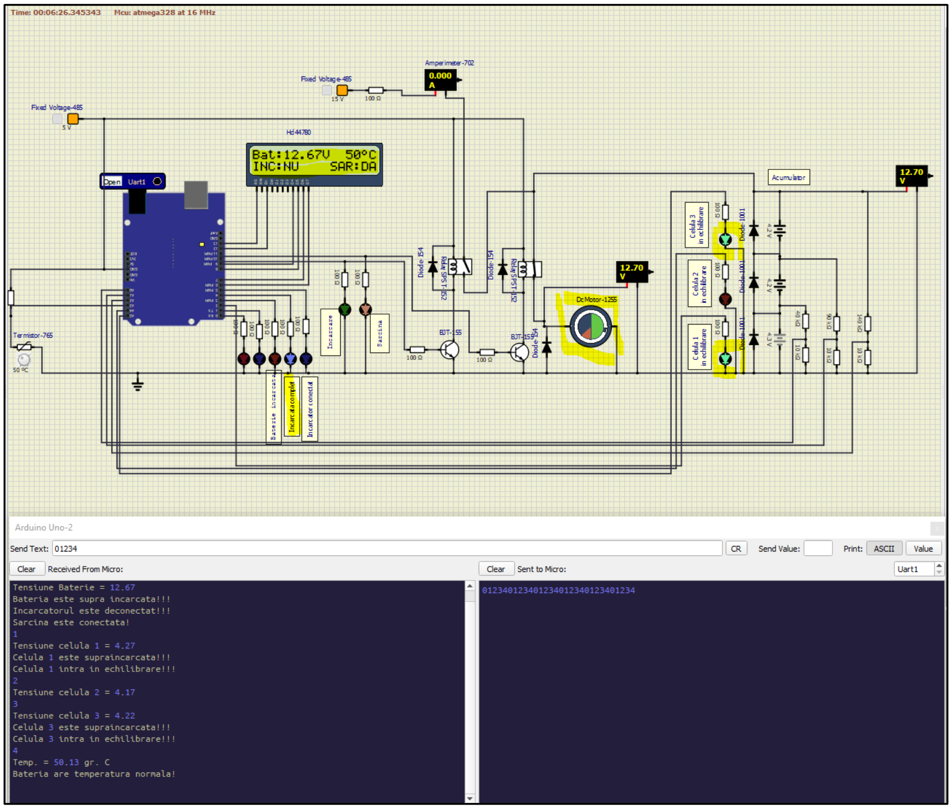
Fig. 3.25. Test case 4



```
0
Tensiune Baterie = 10.55
Bateria este incarcata!
Incarcatorul ramane conectat!
Sarcina este conectata!
1
Tensiune celula 1 = 3.17
2
Tensiune celula 2 = 3.66
3
Tensiune celula 3 = 3.71
4
Temp. = 50.13 gr. C
Bateria are temperatura normala!
```

```
0123401234012340123401234
```

Fig. 3.26. Test case 5



```
Bat:12.67V  50°C
INC:NU    SAR:DA
```

Send Text: 01234

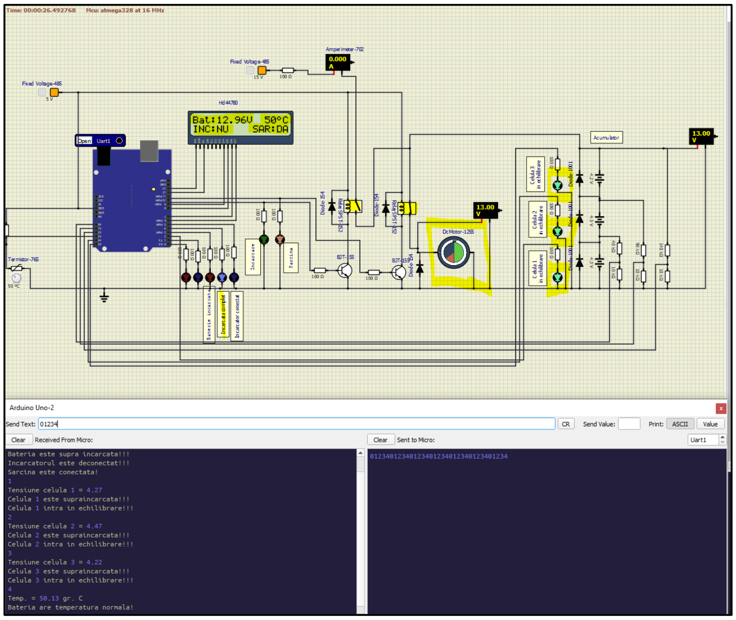
```
Tensiune Baterie = 12.67
Bateria este supra incarcata!!!
Incarcatorul este deconectat!!!
Sarcina este conectata!
1
Tensiune celula 1 = 4.27
Celula 1 este supraincarcata!!!
Celula 1 intra in echilibrare!!!
2
Tensiune celula 2 = 4.17
3
Tensiune celula 3 = 4.22
Celula 3 este supraincarcata!!!
Celula 3 intra in echilibrare!!!
4
Temp. = 50.13 gr. C
Bateria are temperatura normala!
```

```
0123401234012340123401234
```

Fig. 3.27. Test case 6

Test case 7: checking the overload condition of the 3 electric cells, the temperature set to 50º C and the electric cell voltage set to values above the upper limit of 4.2 V. The expected result from the BMS simulation is to disable the load and activate the load by the 2 relays, the correct display on the LCD screen as well as on the serial interface of the parameters, the state of the relays and the information messages Fully charged and warning of the overload state of the 3 electric cells which leads to the activation of balancing on them, an event signaled by balancing information LEDs. As exemplified in figure 2.28, this test passed successfully in the simulation.

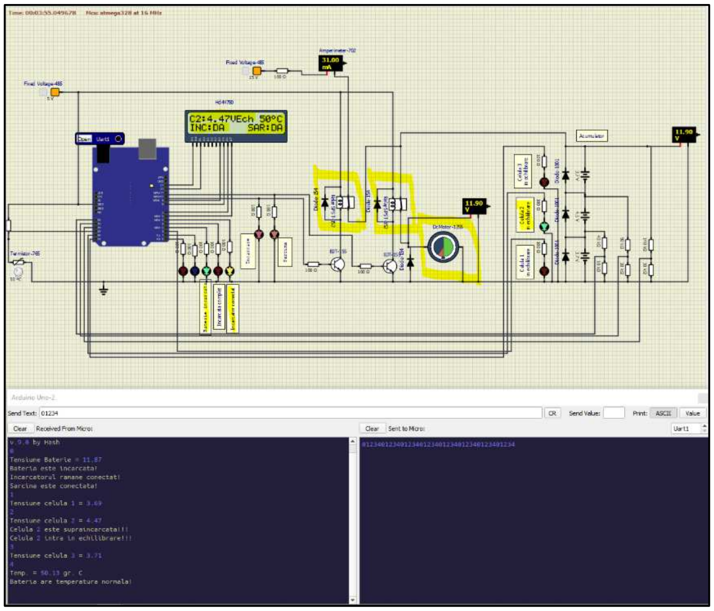
Test case 8: checking the overload condition of one electric cell out of the 3, the temperature set to 50º C and the voltage of one electric cell set to values above the upper limit of 4.2 V and the other 2 cells set to the nominal voltage of 3.7 V. Expected result from the BMS simulation is to activate the load and activate the load through the 2 relays, the correct display on the LCD screen as well as on the serial interface of the parameters, the status of the relays and the information messages Battery charged and Charger connected as well as the warning message of the state of overload of the electric cell, which leads to the activation of balancing on it, an event signaled by the information LED of the balancing of the overloaded cell. As exemplified in figure 3.29, this test passed successfully in the simulation.



```
Bateria este supra incarcata!!!
Incarcatorul este deconectat!!!
Sarcina este conectata!
1
Tensiune celula 1 = 4.27
Celula 1 este supraincarcata!!!
Celula 1 intra in echilibrare!!!
2
Tensiune celula 2 = 4.47
Celula 2 este supraincarcata!!!
Celula 2 intra in echilibrare!!!
3
Tensiune celula 3 = 4.22
Celula 3 este supraincarcata!!!
Celula 3 intra in echilibrare!!!
4
Temp. = 50.13 gr. C
Bateria are temperatura normala!
```

```
01234012340123401234012340123401234
```

Fig. 3.28. Test case 7

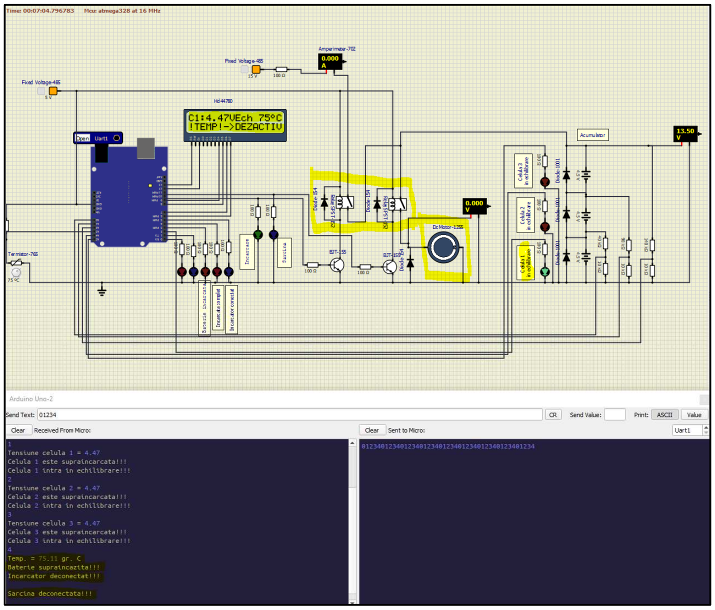


```
v.0.0 by Hash
0
Tensiune Baterie = 11.87
Bateria este incarcata!
Incarcatorul ramane conectat!
Sarcina este conectata!
1
Tensiune celula 1 = 3.69
2
Tensiune celula 2 = 4.47
Celula 2 este supraincarcata!!!
Celula 2 intra in echilibrare!!!
3
Tensiune celula 3 = 3.71
4
Temp. = 50.13 gr. C
Bateria are temperatura normala!
```

```
01234012340123401234012340123401234
```

Fig. 3.29. Test case 8

Test case 9: checking the overload condition of the 3 electric cells in case of overheating of the battery which is set to 75° C, the voltage of the electric cells set to values above the upper limit of 4.2 V. The expected result from the BMS simulation is to disable the loading and deactivation of the load through the 2 relays because the system is outside the safe operating zone, the correct display on the LCD screen as well as on the serial interface of the parameters, the status of the relays and the warning message Battery overheated and Charger disconnected as well as the message of information on the state of overloading of the electric cells, which leads to the activation of balancing on them, an event signaled by information LEDs of the balancing of overloaded cells. As exemplified in figure 3.30, this test passed successfully in the simulation.



```
C1:4.47VEch 75°C
!TEMP!->DEZACTIV
```

Send Text: 01234

Received From Micro:

```
1
Tensiune celula 1 = 4.47
Celula 1 este supraincarcata!!!
Celula 1 intra in echilibrare!!!
2
Tensiune celula 2 = 4.47
Celula 2 este supraincarcata!!!
Celula 2 intra in echilibrare!!!
3
Tensiune celula 3 = 4.47
Celula 3 este supraincarcata!!!
Celula 3 intra in echilibrare!!!
4
Temp. = 75.11 gr. C
Baterie supraincazita!!!
Incarcator deconectat!!!

Sarcina deconectata!!!
```

Sent to Micro:

```
01234012340123401234012340123401234012340123401234
```

Fig. 3.30. Test case 9

As a summary of the functional testing of the BMS in the various scenarios, the 9 test cases are detailed in Table 3.1, containing relevant information about the battery temperature and cell voltage parameter values in various configurations important for influencing the BMS states following as after the simulation with the success of the BMS let's move on to the next chapter to its implementation.

Table 3.1

Summary of simulated BMS test cases

Test case	Temperature ºC	Voltage for cells 1, 2, 3 V	Serial command	Expected behaviour	Actual behaviour	Test Result
1	50.13	3.69, 3.69, 3.69	01234	Charger connected, Load connected, Led Battery charged active, Led Charger connected active, Rx, Tx LEDs active during data transfer, Parameter values and information messages displayed on the serial interface	Figure 61	Passed
2	75.11	3.69, 3.69, 3.69	01234	Charger disconnected, Load disconnected, Information LEDs disabled, Rx LEDs, Tx active when transferring data, Parameter values and information and warning messages displayed on the serial interface	Figure 62	Passed
3	50.13	3.17, 3.17, 3.17	01234	Charger connected, Load disconnected, Led Charger connected, Rx, Tx LEDs active during data transfer, Parameter values and information and warning messages displayed on the serial interface	Figure 63	Passed
4	75.11	3.17, 3.17, 3.17	01234	Charger disconnected, Load disconnected, Information LEDs disabled, Rx LEDs, Tx active when transferring data, Parameter values and information and warning messages displayed on the serial interface	Figure 64	Passed

5	50.13	3.17, 3.66, 3.17	01234	Charger connected, Load connected, Information LEDs Battery charged, Charger connected. Load, Load enabled, Rx LEDs, Tx active during data transfer, Parameter values and information messages displayed on the serial interface	Figure 65	Passed
6	50.13	4.27, 4.17, 4.22	01234	Charger disconnected, Load connected, Information LEDs Fully charged, Load, Cell 1 in balancing, Cell 3 in balancing activated, Rx, Tx LEDs active during data transfer, Parameter values and information messages displayed on the serial interface	Figure 66	Passed
7	50.13	4.27, 4.47, 4.22	01234	Charger disconnected, Load connected, Information LEDs Fully charged, Load, Cell 1 in balancing, Cell 2 in balancing, Cell 3 in balancing activated, Rx, Tx LEDs active during data transfer, Parameter values and information messages displayed on the serial interface	Figure 67	Passed
8	50.13	3.69, 4.47, 3.71	01234	Charger connected, Load connected, Information LEDs Battery charged, Charger connected, Charging, Load, , Cell 2 in balancing activated, Rx, Tx LEDs active during data transfer, Parameter values and information messages displayed on the serial interface	Figure 68	Passed
9	75.11	4.47, 4.47, 4.47	01234	Charger disconnected, Load disconnected, Information LEDs disabled, Rx LEDs, Tx active when transferring data, Balance LEDs active, Parameter values and information and warning messages displayed on the serial interface	Figure 69	Passed

3.5 BMS IMPLEMENTATION

3.5.1 Hardware schematic drawing assisted by EAGLE application

EAGLE (acronym for Easily Applicable Graphical Layout Editor) is a software application used for schematic and printed circuit board (PCB) design. Developed by the CadSoft company that was later acquired by Autodesk, EAGLE is one of the most popular and well-known design solutions for electronics, engineers and hobbyists. EAGLE is a versatile and powerful tool for printed circuit design and is used in a wide range of fields, from hobbyist electronics to commercial product development [47].

Figure 3.31 shows the functional blocks of the BMS hardware architecture as well as the schematic of the implemented system using the color code. The block structure of the BMS underwent some optimization changes compared to the simulated version presented in the previous chapter, thus a device with 2 integrated relays was used instead of the independent load and interruption relays, and instead of the UART serial interface we chose a communication module without buetooth wire for information transfer. Another important change is the use of an interface that uses the I2C protocol to display status and warning data on the LCD screen, thus using only 2 control pins instead of the 6 pins used in the simulated version. The detailed description of the functional blocks for the hardware implementation of the BMS is as follows:

- **Arduino Nano 3.0 development board**;
- **Bluetooth module HC-05**;
- **5 V voltage stabilizer**;
- **Current limiter** based on the LM317 circuit;;
- **Balancing LEDs LED1, LED2, LED3**;
- **Battery status LEDs LED4, LED5, LED6**;
- I2C (Inter-Integrated Circuit) interface for the LCD screen;
- **The Charger and load relay device** module, Relay-2-SRD, is an electronic device that contains two SRD (Single Relay Driver) type relays;
- **LCD screen**, module "HD44780LCD-1602";
- The **Voltage Dividers** section contains the 3 voltage dividers needed to collect the 3 voltages from electric cell 1, from the combination of cells 1 and 2 and from electric cells 1, 2 and 3;
- **Voltage Balancing Module** block;
- The **Electric Cells** block contains the 3 electric cells implemented using Li-Ion 18650 batteries with a nominal voltage of 3.7 V and a capacity of 8800 mAh;
- The Temperature Sensor block is implemented by means of the Siemens B57164 NTC thermistor;

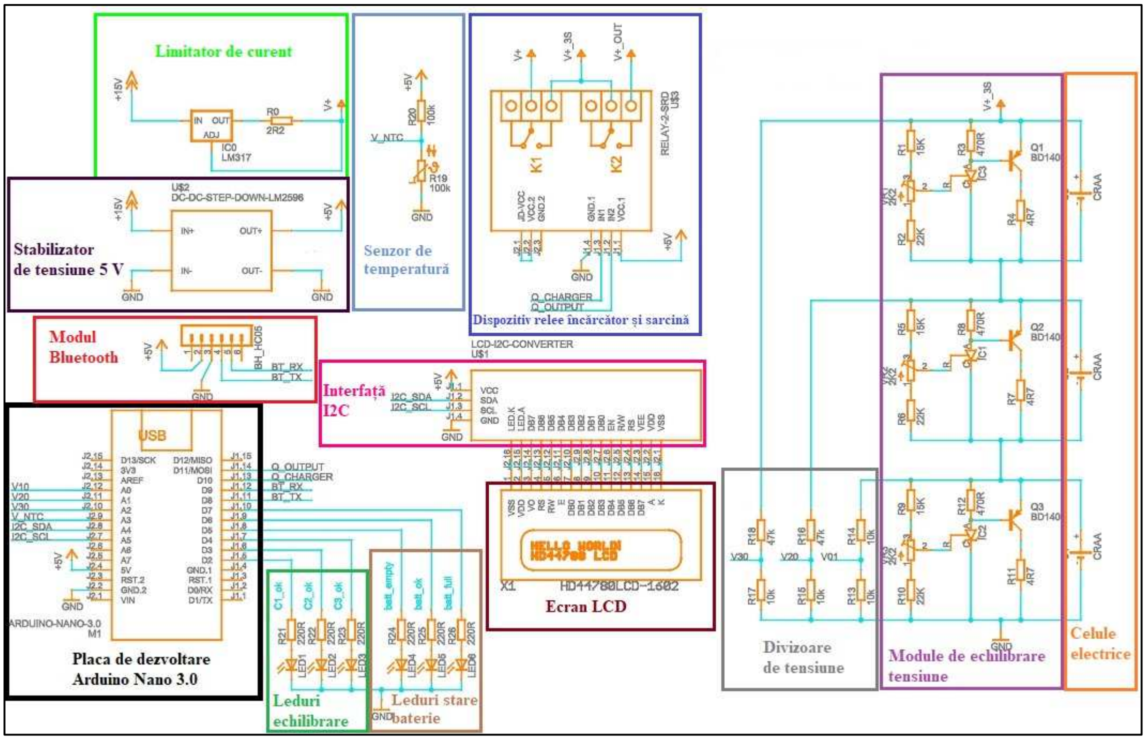


Fig. 3.31. Hardware architecture and BMS schematic

3.5.2 List of electrical / electronic components of BMS (BOM)

To create the bill of materials (BOM) in Autodesk Eagle, I used the BOM tool, which automatically generated a BOM based on the parts I placed in the schematic design. The steps to generate the list in .csv format are as follows:

- Open the schematic file (.sch) from the Autodesk EAGLE Control Panel;
- Select the ULP tool from the top of the interface and choose bom.ulp file from the list of available ULPs;
- The BOM tool will automatically generate a LM / BOM based on the parts we placed in the schematic design.

The generated .csv file is embedded in Table 3.2:

Table 3.2

List of components generated from the BMS schematic

Componenta	Valoare	Dispozitivul	Capsulă	Descriere
BH_HC05		MA06-1	MA06-1	CONNECTOR WITH PINS
C1	CRAA	CRAA	CRAA	LI-ION VARTA BATTERY
C2	CRAA	CRAA	CRAA	LI-ION VARTA BATTERY
C3	CRAA	CRAA	CRAA	LI-ION VARTA BATTERY
IC0	LM317	LM317-TO3	TO3-K02	VOLTAGE REGULATOR
IC1		TL431CLP	TO92-CLP	VOLTAGE REGULATOR
IC2		TL431CLP	TO92-CLP	VOLTAGE REGULATOR
IC3		TL431CLP	TO92-CLP	VOLTAGE REGULATOR
LED1		LED5MM	LED5MM	LED
LED2		LED5MM	LED5MM	LED
LED3		LED5MM	LED5MM	LED
LED4		LED5MM	LED5MM	LED
LED5		LED5MM	LED5MM	LED
LED6		LED5MM	LED5MM	LED
M1	ARDUINO-NANO-3.0	ARDUINO-NANO-3.0	ARDUINO-NANO-3.0	ARDUINO NANO 3.0
Q1	BD140	BD140	TO126AV	PNP TRANSISTOR
Q2	BD140	BD140	TO126AV	PNP TRANSISTOR
Q3	BD140	BD140	TO126AV	PNP TRANSISTOR
R0	2R2	R-EU_0204/7	0204/7	RESISTOR, European symbol
R1	15K	R-EU_0204/7	0204/7	RESISTOR, European symbol
R2	22K	R-EU_0204/7	0204/7	RESISTOR, European symbol
R3	470R	R-EU_0204/7	0204/7	RESISTOR, European symbol
R4	4R7	R-EU_0204/7	0204/7	RESISTOR, European symbol
R5	15K	R-EU_0204/7	0204/7	RESISTOR, European symbol
R6	22K	R-EU_0204/7	0204/7	RESISTOR, European symbol
R7	4R7	R-EU_0204/7	0204/7	RESISTOR, European symbol
R8	470R	R-EU_0204/7	0204/7	RESISTOR, European symbol
R9	15K	R-EU_0204/7	0204/7	RESISTOR, European symbol
R10	22K	R-EU_0204/7	0204/7	RESISTOR, European symbol
R11	4R7	R-EU_0204/7	0204/7	RESISTOR, European symbol
R12	470R	R-EU_0204/7	0204/7	RESISTOR, European symbol
R13	10k	R-EU_0204/7	0204/7	RESISTOR, European symbol
R14	10k	R-EU_0204/7	0204/7	RESISTOR, European symbol
R15	10k	R-EU_0204/7	0204/7	RESISTOR, European symbol
R16	47k	R-EU_0204/7	0204/7	RESISTOR, European symbol
R17	10k	R-EU_0204/7	0204/7	RESISTOR, European symbol

R18	47k	R-EU_0204/7	0204/7	RESISTOR, European symbol
R19	100k	B57164	B57164	SIEMENS NTC THERMISTOR
R20	100k	R-EU_0204/7	0204/7	RESISTOR, European symbol
R21	220R	R-EU_0204/7	0204/7	RESISTOR, European symbol
R22	220R	R-EU_0204/7	0204/7	RESISTOR, European symbol
R23	220R	R-EU_0204/7	0204/7	RESISTOR, European symbol
R24	220R	R-EU_0204/7	0204/7	RESISTOR, European symbol
R25	220R	R-EU_0204/7	0204/7	RESISTOR, European symbol
R26	220R	R-EU_0204/7	0204/7	RESISTOR, European symbol
U$1	LCD-I2C-CONVERTER	LCD-I2C-CONVERTER	LCD-I2C-CONVERTER	I2C bus to parallel interface 4-bit LCD with LED backlight driver
U$2	DC-DC-STEP-DOWN-LM2596	DC-DC-STEP-DOWN-LM2596	DC-DC-STEP-DOWN-LM2596	DC/DC Step-Down Regulator based on the LM2596-ADJ chip
U$3	RELAY-2-SRD	RELAY-2-SRD	RELAY-2-SRD	2-channel relay module based on SRD-05VDC-SL-C relays
VR1	2K2	R-TRIMM64P	RTRIM64P	Adjustment resistor
VR2	2K2	R-TRIMM64P	RTRIM64P	Adjustment resistor
VR3	2K2	R-TRIMM64P	RTRIM64P	Adjustment resistor
X1	HD44780 LCD-1602	HD44780 LCD-1602	LCD1602	HD44780 liquid crystal display

3.5.3 Hardware implementation of BMS

Based on the hardware architecture and the schematic, the list of components was purchased through the ArduinoShop platform, in order to integrate them on the circuit board to achieve the hardware implementation as in figure 3.32.

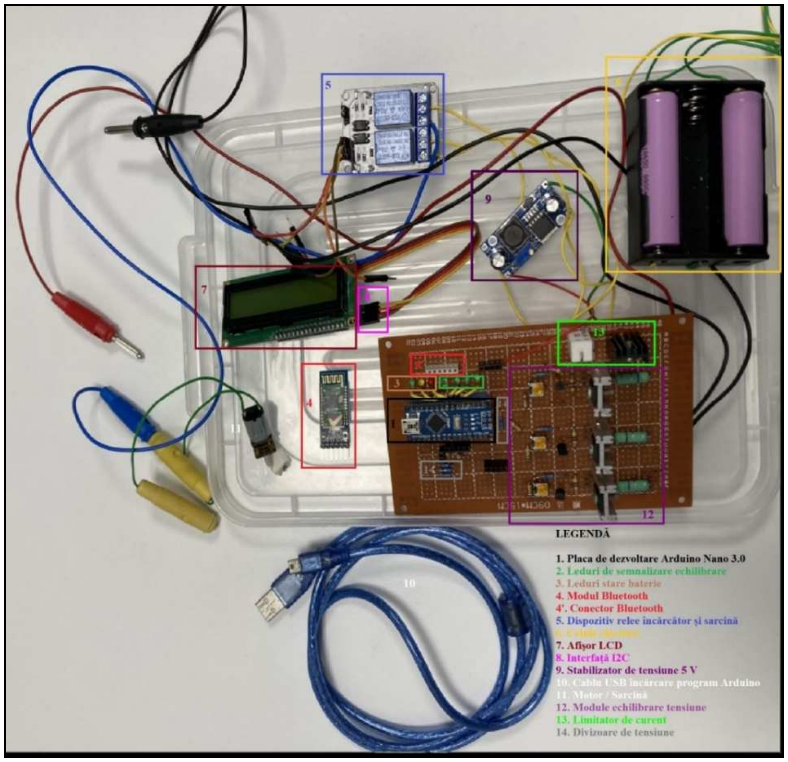


Fig. 3.32. Hardware implementation of BMS

To ensure traceability between the physical and abstract components of the schematic in figure 3.32, we have kept the same color code for highlighting the functional blocks on the circuit as well as in their documentation on the legend. On the actual circuit there are 2 items in addition to the schematic that are documented in white color, it is the USB cable to ensure the transfer of the control program from the Arduino IDE programming environment to the Arduino Nano 3.0 development board numbered 10 and the motor that plays the role load numbered 11.

Following the schematic, the purchased components were integrated on the circuit board respecting their correct orientation and polarization, the connections being made by soldering or wires. After assembly, connection errors or short circuits were checked by means of a digital multimeter. Following the integration of the electrical and electronic components on the wiring board as well as the connection of the wires to the specific interfaces, the integrated system is obtained as in figure 3.33. Compared to figure 3.34, the connection to the specific interfaces of the following components can be observed: the LCD display through the I2C interface, the system battery consisting of the 3 electric cells in series, the bluetooth module for wireless serial communication, the device with the 2 relays for connecting or disconnecting of the external charger and the load, the temperature sensor implemented through the NTC thermistor from Siemens.

The system thus integrated was subjected to the Smoke Test, which is a quick and simple initial test of the BMS to check that it starts up correctly and that there are no major errors. This test does not explore all BMS functionality in detail, but only checks that the system "starts" without obvious problems. Connected the BMS to an external 15V power supply with a current limit of 1A for protection and checked the lights on the active components, the system temperature to identify any heat dissipation or overload problems.

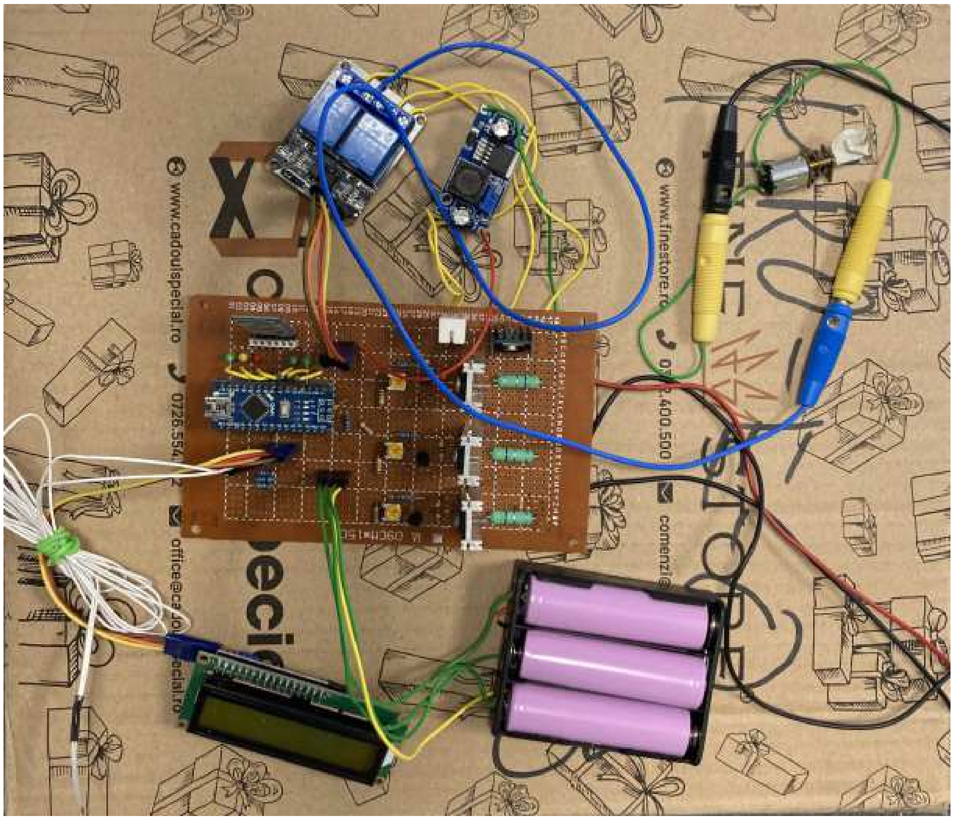


Fig. 3.33. BMS integrated hardware system

3.5.4 BMS Software implementation of BMS dynamic behavior

The software architecture of the hardware implementation variant of the BMS is similar to the software architecture of the simulated BMS in the SimulIDE application. The logic part of the loop() loop has been adjusted with some changes that consider replacing UART wired serial communication with bluetooth wireless serial communication and using temporary flags to ensure actuators are actuated after a period of time necessary to eliminate transients and avoiding making false decisions. Figure 3.34 shows the logic diagram of the control flows of the loop() loop and the detailed implementation in the Arduino C programming language is documented in the Appendix with explanatory comments for each line of code.

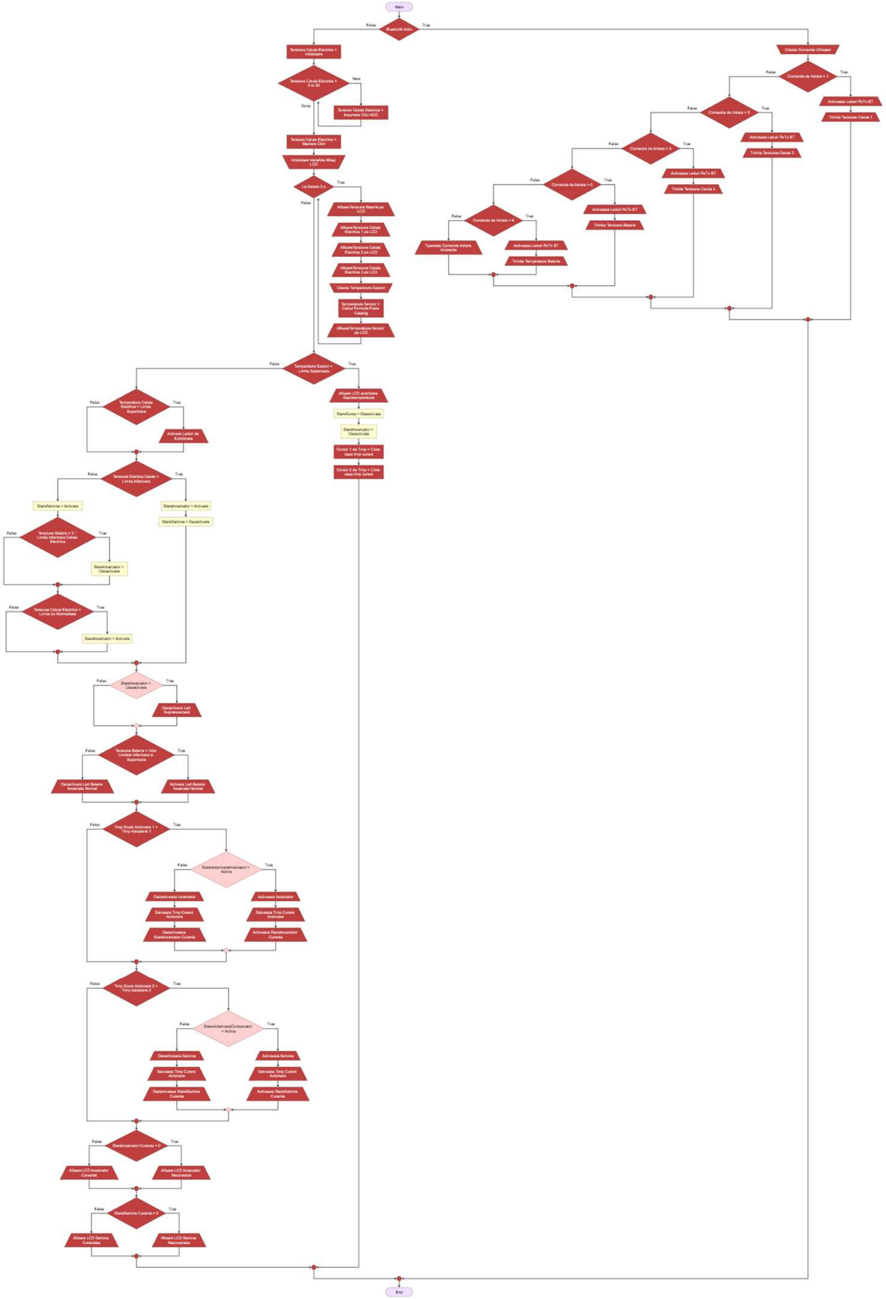
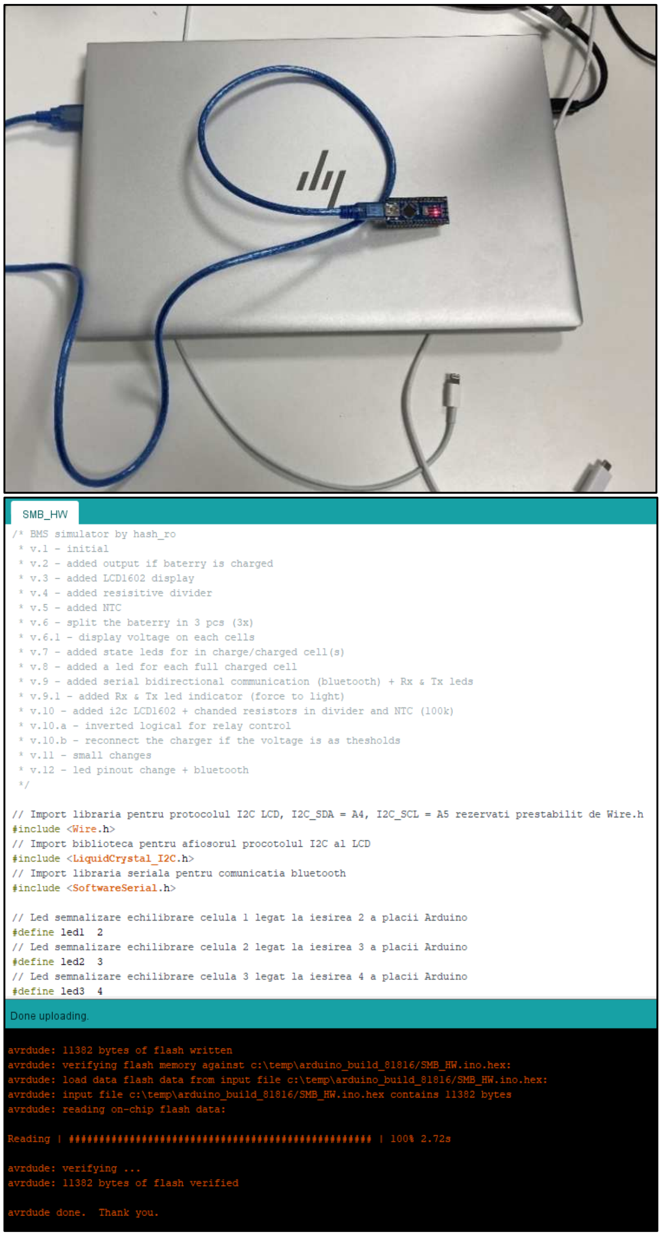


Fig. 3.34. BMS hardware implementation loop logic diagram

Once the software application is implemented and syntactically verified by compilation, it is necessary to download it to the Arduino Nano 3.0 development board. Thus, the Arduino Uno 3.0 board is connected to the computer using a USB cable, item number 10 in table 3.2. Open the Arduino IDE environment and select the type of board we use from the "Tools" -> "Board" menu, in this case, select "Arduino Nano 3.0". Also, from the "Tools" -> "Port" menu, select the corresponding serial port to which the Arduino board is connected, in our case COM7. After the program is checked for errors by the Verify or Compile option, we use the Upload button (or the arrows next to it) to upload the program to the Arduino board, an option that will compile the program and transfer it to the board. After the program is successfully loaded as shown in Figure 3.35, we can disconnect the Arduino board from the computer.



```
/* BMS simulator by hash_ro
 * v.1 - initial
 * v.2 - added output if baterry is charged
 * v.3 - added LCD1602 display
 * v.4 - added resisitive divider
 * v.5 - added NTC
 * v.6 - split the baterry in 3 pcs (3x)
 * v.6.1 - display voltage on each cells
 * v.7 - added state leds for in charge/charged cell(s)
 * v.8 - added a led for each full charged cell
 * v.9 - added serial bidirectional communication (bluetooth) + Rx & Tx leds
 * v.9.1 - added Rx & Tx led indicator (force to light)
 * v.10 - added i2c LCD1602 + chanded resistors in divider and NTC (100k)
 * v.10.a - inverted logical for relay control
 * v.10.b - reconnect the charger if the voltage is as thesholds
 * v.11 - small changes
 * v.12 - led pinout change + bluetooth
 */

// Import libraria pentru protocolul I2C LCD, I2C_SDA = A4, I2C_SCL = A5 rezervati prestabilit de Wire.h
#include <Wire.h>
// Import biblioteca pentru afiosorul procotolul I2C al LCD
#include <LiquidCrystal_I2C.h>
// Import libraria seriala pentru comunicatia bluetooth
#include <SoftwareSerial.h>

// Led semnalizare echilibrare celula 1 legat la iesirea 2 a placii Arduino
#define led1  2
// Led semnalizare echilibrare celula 2 legat la iesirea 3 a placii Arduino
#define led2  3
// Led semnalizare echilibrare celula 3 legat la iesirea 4 a placii Arduino
#define led3  4
```

Done uploading.

```
avrdude: 11382 bytes of flash written
avrdude: verifying flash memory against c:\temp\arduino_build_81816/SMB_HW.ino.hex:
avrdude: load data flash data from input file c:\temp\arduino_build_81816/SMB_HW.ino.hex:
avrdude: input file c:\temp\arduino_build_81816/SMB_HW.ino.hex contains 11382 bytes
avrdude: reading on-chip flash data:

Reading | ################################################## | 100% 2.72s

avrdude: verifying ...
avrdude: 11382 bytes of flash verified

avrdude done.  Thank you.
```

Fig. 3.35. Download the control application on the Arduino Nano 3.0 development board

3.6 BMS VERIFICATION AND TESTING

Similar to paragraph 3.4.4, the results of each test case shall be documented and analyzed to ensure that the battery management system is operating properly, safely and according to project specifications and requirements, directly on the hardware implemented board of the BMS, exemplifying -se with snapshots from the testing process.

3.6.1 Development of test cases

Test Case 1: Checking the bluetooth wireless communication of the BMS at system startup and setting it correctly. The expected result is to display the command menu on the intelligent terminal connected to the BMS system, a menu that has been implemented in the system setting function and that must be displayed only once as information for the user when starting or resetting the BMS. As exemplified in figure 3.36 this test passed successfully, after resetting the BMS displaying the command menu from 0 to 4 as follows:
Orders accepted**;**

0 -> Print battery voltage
1 -> Printing electric cell voltage 1
2 -> Printing electric cell voltage 2
3 -> Printing electric cell voltage 3
4 -> Print battery temperature

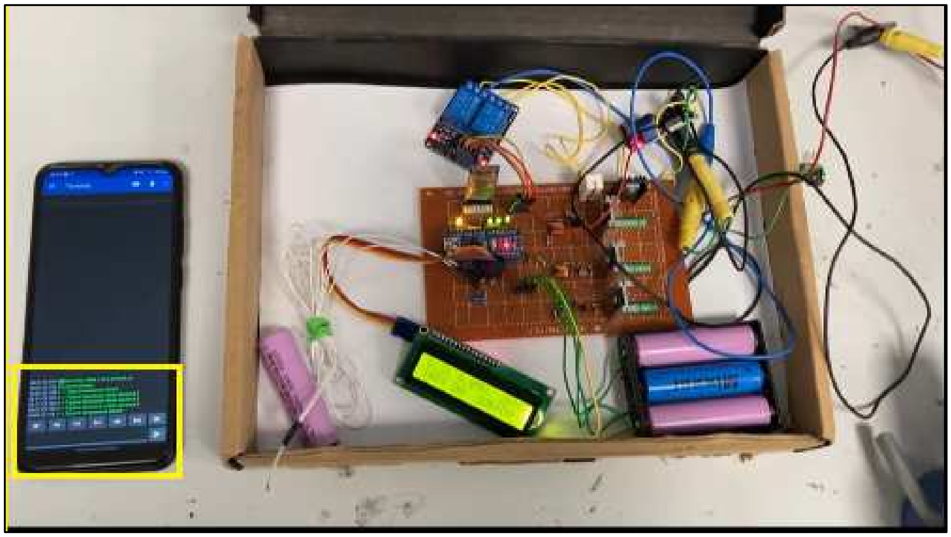


Fig. 3.36. Test case 1

Test case 2: Check the operation of bluetooth wireless communication of BMS at system start-up and information message in case of wrong input command, out of range 0-4. The expected result is to display the warning Incorrect command, allowed values: 0, 1, 2, 3, 4 on the smart terminal connected via bluetooth to the BMS, if an erroneous command is read. As exemplified in figure 3.37, this test passed successfully, after command 5, with the error command warning message being displayed:

Fig. 3.37. Test case 2

Test case 3: checking the normal operation state of BMS, ambient temperature 24° C and battery voltage 12.04 V, with the voltage distribution on the electric cells of 4.1 V, 3.9 V, 4.04 V. The expected result from the BMS is to activate the load and of the load through the 2 relays, the correct display on the LCD screen of the parameters and the status of the relays as well as on the bluetooth serial interface, the activation of the information LED Battery normally charged and Charger connected. As exemplified in figure 3.38, this test passed successfully.

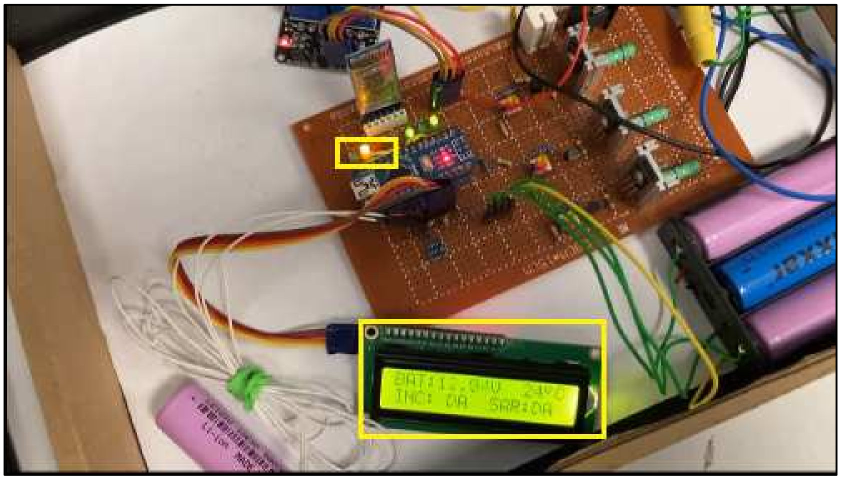


Fig. 3.38. Test case 3

Test case 4: verification of BMS electric cell balancing process, ambient temperature 24° C and battery voltage 12.04 V, with electric cell voltage distribution of 4.1 V, 3.9 V, 4.04 V. The expected result from BMS is to activate of the load and the load through the 2 relays, the correct display on the LCD screen of the parameters and the status of the relays as well as on the bluetooth serial interface, the activation of the information LEDs of the balancing of cells 1 and 2, the deactivation of the information LED of the balancing of the electrical cell 2. As it is exemplified in figure 3.39, this test passed successfully when running.

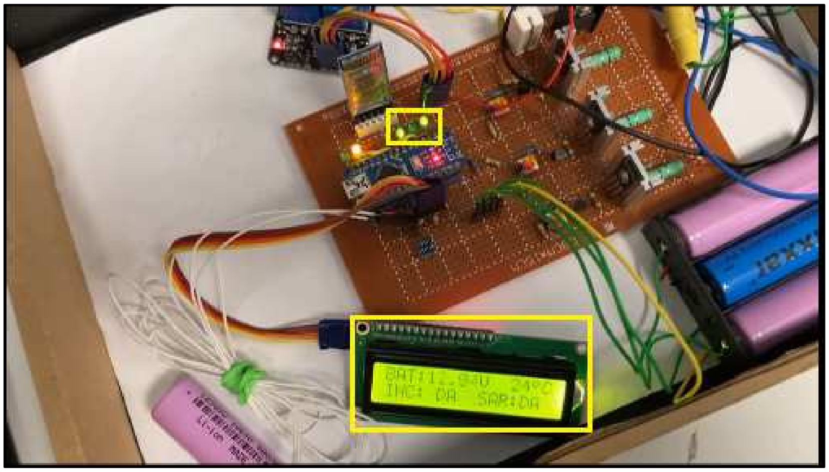


Fig. 3.39. Test case 4

Test case 5: verifying the correct display process of BMS parameters on the smart terminal using bluetooth BMS technology. The expected result from the BMS is the correct display on the screen of the smart terminal of the parameters battery voltage at command 0, voltage of electrical cell 1 at command 1, voltage of electrical cell 2 at command 2, voltage of electrical cell 3 at command 3, temperature NTC temperature sensor at command 4. As exemplified in figure 3.40, this test passed successfully at runtime.

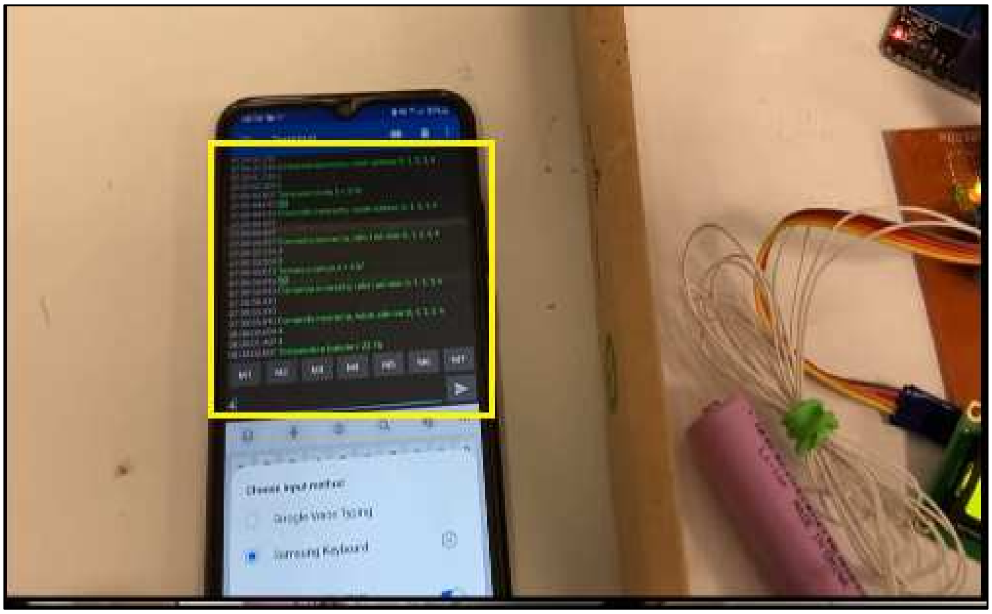


Fig. 3.40. Test case 5

Test case 6: checking the overtemperature process of the BMS when the sensor is heated above the threshold temperature of 60o C. The expected result from the BMS is the correct display on the smart terminal screen of the NTC temperature sensor temperature parameter at command 4 as well as the warning message on the LCD screen , disconnecting the external charger and the load until the sensor temperature drops below 60o C. As exemplified in figure 3.41 this test passed successfully to run.

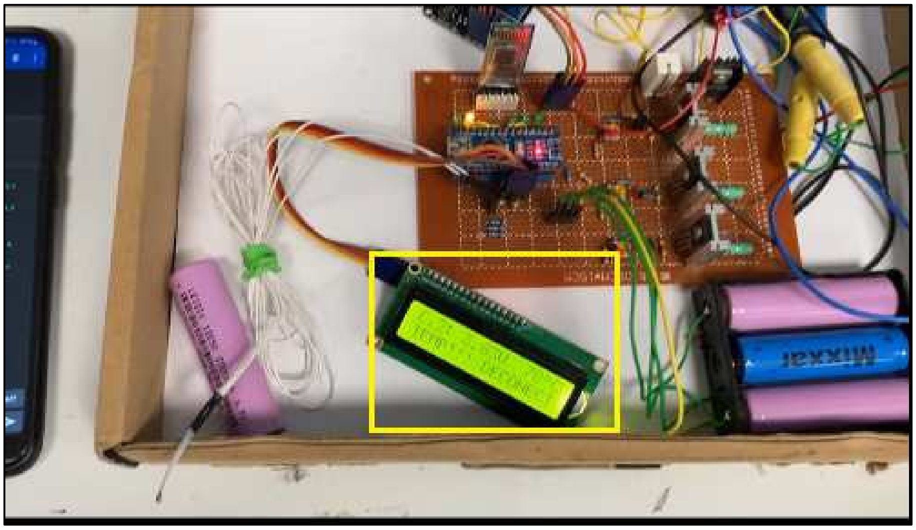


Fig. 3.41. Test case 6

Test case 7: checking the full charge process of the BMS battery and the balancing process of all 3 electric cells. The expected result from the BMS is the disconnection of the external charger and connection of the load, the activation of the green information LED of full battery charge, the correct display of the status of the external charger and the load on the LCD screen, and the activation of the green information LEDs of the balancing of the cells. As exemplified in figure 3.42, this test passed successfully.

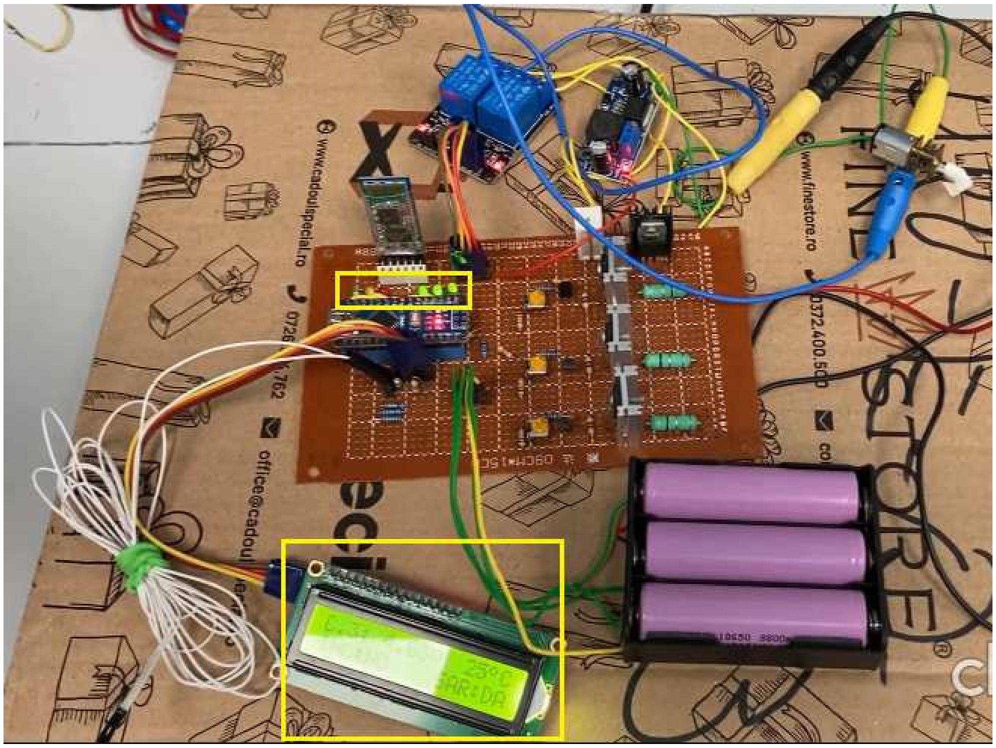


Fig. 3.42. Test case 7

As a summary of the functional testing of hardware-implemented BMS in the various scenarios, the 7 test cases are detailed in table 3.3, containing relevant information about the NTC sensor temperature and cell voltage parameter values in various important configurations for influencing the BMS states, successfully testing bluetooth wireless serial communication, displaying status information on both LCD screen and smart terminal connected to BMS, testing system reaction to over temperature condition, testing power cell balancing process, testing charger activation and deactivation external and pregnancy.

Table 3.3

HW Summary of HW implemented BMS test cases

Test Case	Temperature ºC	Voltage in V of cells 1, 2, 3	Serial command	Expected behaviour	Actual behaviour	Test verdict
1	-	-, -, -	-	Show command menu when starting or resetting the BMS via the smart terminal: Accepted orders: 0 -> *Print battery voltage* 1 -> *Printing electric cell voltage 1* 2 -> *Printing electric cell voltage 2* 3 -> *Printing electric cell voltage 3* 4 -> *Print battery temperature*	Figure 77	Succesfully
2	-	-, -, -	5	Display warning message on the smart terminal when entering an incorrect command: Incorrect command, allowed values: 0, 1, 2, 3, 4	Figure 78	Succesfully
3	24	4.10, 3.90, 4.04	-	Charger connected, Load connected, Yellow LED information Battery Normal Charged, parameter values and information messages correctly displayed on the LCD screen	Figure 79	Succesfully
4	24	4.10, 3.90, 4.04	-	Charger connected, Load connected, Power cell balance information LEDs 1 and 3 on, cell balance information LED 2 off, correct parameter values displayed on LCD	Figure 80	Succesfully
5	24	4.10, 3.90, 4.04	01234	Correct BMS parameter values displayed on the smart terminal connected to the BMS via bluetooth: print battery voltage at command 0, print cell 1 voltage at command 1, print cell 2 voltage at command 2, print cell 3 voltage at command 3, print temperature battery on order 4	Figure 81	Succesfully
6	78	4.10, 4.15, 4.22	-	Charger disconnected, Load disconnected, over temperature warning message displayed on LCD, correct temperature displayed on LCD	Figure 82	Succesfully
7	25	4.15, 4.17, 4.20	-	Charger disconnected, Load connected, Green battery fully active information LED, 3 active cell balancing green information LEDs, charger status and correct load information message displayed on the LCD screen	Figure 83	Succesfully

3.6.2 Running test cases and recording results

Assisted by the clideo.com utility, I recorded the running of the hardware-implemented BMS operation testing and integrated it in this chapter in figure 3.43, for running the *.wmv video file, the control key (Ctrl) and the left mouse button must be pressed simultaneously. The approximately 4 minute recording contains the actual run for various functional states of the BMS as follows:

- until the 15th second, the BMS was run in a normal operating state, with parameter values that ensure a safe zone, the ambient temperature around 24o C, the electric cell voltages around 4.0 V, which will lead to a total voltage on battery of approximately 12.0 V in normal state of charge, resulting in the activation of the 2 relays connecting the charger and the load simultaneously, the status information being displayed on the LCD screen;
- between second 16 and second 27, the Arduino Nano 3.0 development board is reset through the specific button, an action that will lead to setting the parameters of the development board and displaying the control panel on the smart terminal connected to the system via bluetooth;
- between seconds 28 and 77, the system parameters are displayed on the screen of the smart device connected via bluetooth to the BMS as follows: battery voltage at command 0, voltage of electric cell 1 at command 1, voltage of electric cell 2 at command 2, voltage of electric cell 3 at command 3, NTC sensor temperature at command 4;
- between seconds 78 and 139, the display of the system parameters on the LCD screen, battery voltage, electric cell voltage, NTC sensor temperature, the activation of the yellow LED for normal battery charging and the green LEDs for balancing the individual electric cells if they have reached the voltage threshold of balancing;
- at second 140, the Arduino Nano 3.0 development board is reset, following the execution of its setting function with the display of the command menu on the smart terminal connected via bluetooth to the BMS, the external source set to 15 V, indicating a consumption of 0.5 A of connected and active loads, the normal state of battery charge being indicated by the yellow LED, the electric cells being in balance according to the activated green LEDs and the voltages displayed on the LCD screen, the information message of connecting the external charger and the load appearing on the LCD display;
- at second 200, the process of external heating of the NTC temperature sensor begins in order to raise the temperature above the overheating threshold of 60 degrees, which will lead to the deactivation of the load and load relays as well as the display of the warning message on the LCD screen of overheating and disconnecting the charger and the load and displaying the temperature on the LCD screen and the smart terminal upon receiving the command 4 from the user;
- at second 218 when the temperature of the NTC sensor drops below the overheating temperature threshold of 60 degrees by deactivating the external heating source, the activation of the load and load relays is observed as well as the display of the information message on the LCD screen connecting the charger and the load, the external motor starting in rotation mode;
- at second 247, all 3 electric cells reach the voltage threshold for activating the balancing, the green LED of full battery charge being activated instead of the yellow one of normal charge, as well as the green LEDs of balancing information on all 3 electric cells;

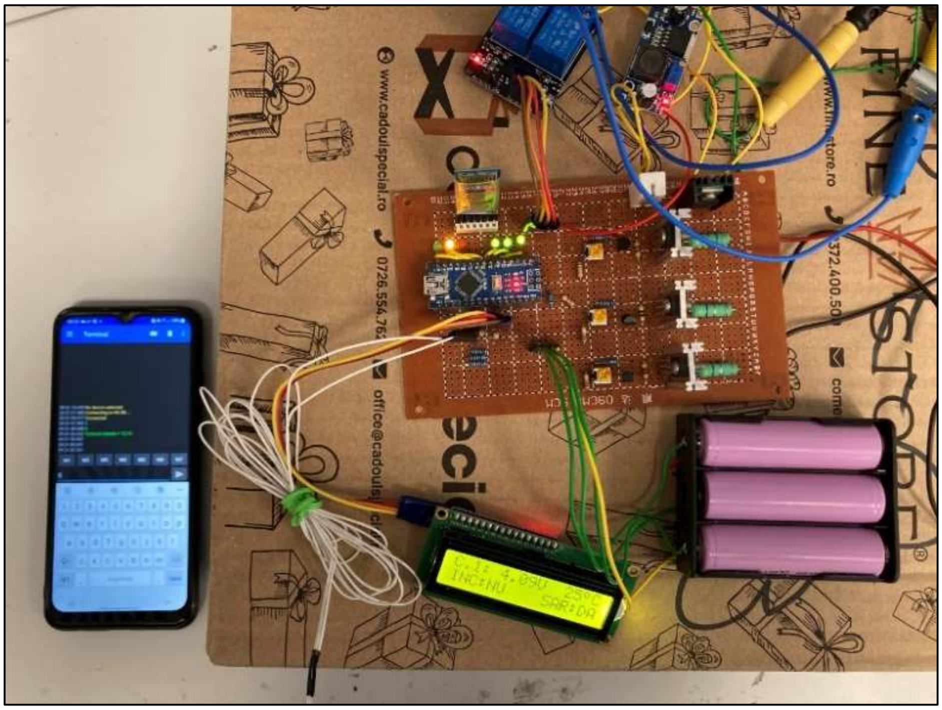


Fig. 3.43. Running hardware implemented BMS functionality tests

CHAPTER 4

CONCLUSIONS

Following the extensive analysis of wireless transfer in the context of electric cars and the implementation of a battery management system, the results and conclusions obtained highlight the significant importance of wireless technology in the development of electric vehicles and in the optimization of battery performance. This thesis provides a comprehensive look at the benefits, challenges and potential of wireless transfer in the electric car industry. The main conclusions include:

- Efficiency of wireless transfer: the analysis showed that wireless transfer is a promising way to charge electric car batteries, inductive and resonant charging systems can provide significant efficiency in energy transfer, reducing the need to physically connect to a power source;
- Simplifying the charging process: the implementation of wireless transfer can simplify the charging process of electric cars, drivers no longer need to worry about cables or sockets, which can improve the user experience and promote the adoption of electric vehicles;
- Optimizing the Battery Management System: developing and implementing a battery management system is essential to maximize battery life, optimize charging efficiency and monitor battery health, this system can significantly contribute to preventing premature battery degradation and maintaining performance optimum;
- Technical and technological challenges: However, there are technical and technological challenges associated with wireless transfer, such as reduced efficiency over long distances and the need to standardize technology to ensure interoperability;
- Socio-economic effects: the thesis also highlighted the positive socio-economic effects of implementing wireless transfer in electric cars, contributing to the reduction of greenhouse gas emissions, decreasing dependence on fossil fuels and promoting the sustainable development of automotive industry.

In conclusion, this thesis highlights that wireless transfer is a promising solution for charging electric cars, and the implementation of a battery management system is essential to optimize their operation. Although there are challenges to be overcome, the positive outlook in terms of efficiency, user comfort and sustainability make this technology a viable direction for the electric car industry.

4.1 SUMMARY OF ORIGINAL THESIS CONTRIBUTIONS

This chapter lists the main original contributions made by the author in this doctoral thesis:

- **Chapter 1** includes a comprehensive description of the current state of the global automotive industry, focusing on the 3 current global research trends that through the transition to electric mobility, autonomous driving and car digitization and personalization services, ensure the orientation towards friendly solutions the environment and reducing the carbon footprint of the industry and reducing greenhouse gas emissions. The distribution of the initiatives of the car market trends, the forecast of the allocation of the current traction technologies of the cars as well as of the electrical systems based on the voltages of the batteries in the current decade were analyzed. In addition, a survey of electric vehicle owners on the benefits of VH / EV wireless charging and the evolution of electric battery technologies was also highlighted;

- **Chapter 2** describes a brief history of the most important milestones in the evolution of wireless power transfer over the last century and a detailed classification of this technology with a major impact in multiple industries. It presents the architecture of the wireless power transfer system in electric vehicles, the main industry standards and operating parameters, as well as the most important market players in the field of research and commercial implementation of this research. The main parameters of wireless power transfer in electric vehicles and an analysis of the components of the transfer system are also mentioned. As a primary element of this thesis, the concept of electric battery management system is described in detail and the main architectures existing on the market are presented both at the system level and at the hardware and software level. In this chapter, emphasis is also placed on the load balancing function of the electric cells and on the importance of the technical risk analysis of the system, an important step in the effective and efficient design of a system of such complexity, introducing the concept of safety in the operation of a BMS and its application in failure mode analysis of a BMS. The last part of this chapter provides a detailed description of computer-aided design for the development of BMSs and an evolution of this new field of design support with major impact in decreasing development costs and implementation time, listing the main commercial platforms of the design assistance industry;
- **Chapter 3** brings as a new element the use of the V development model for both the hardware and the software side, the most used development model in the engineering industry, which ensures the iterative and incremental design and implementation of products. The first step of specification analysis in the V-development model is continued with technical risk analysis of BMS functions using the APIS IQ-RM computer aided application, which enables structural, functional and failure mode analysis in an efficient and controlled by the internal verification criteria of the software tool used, generating the system's risk matrix and Pareto analysis. Based on the risk matrix and the Pareto analysis, the root causes of the system defects with the greatest functional or safety impact are identified, implementing additional preventive and corrective actions to place the impact outside the critical area of operation. The chapter continues with BMS analysis and synthesis using the SimulIDE design and simulation application from the PAC / CAD family, thereby shortening product development time by quickly debugging and updating the digitized project. Thus we implemented the control application of the Arduino Uno development board, debugging and optimizing the logic control flows in the simulation-assisted environment, which greatly reduced the risk of effective failure in the implemented version of the BMS / BMS as well as its development time . Continuing the development steps of the V model, the BMS architecture is elaborated which is refined at the module level in both hardware and software domain, then the algorithm and control application of the BMS development board are implemented, the test cases are elaborated and perform system verification and validation. After the successful completion of the BMS simulation, validating through successful tests the functionality of the system, it continues with its hardware implementation using the same development model in V. An important technical contribution from this thesis appears in the control application of the physically implemented BMS, namely how to read the voltages of the voltage dividers on the electric cells, the instantaneous reading at a certain moment of time has been replaced to increase the accuracy of the values with a repeated reading of the values for a certain number, in the present case 20 consecutive readings, and the calculation averages of the readings to generate the final voltages used by the control application in making decisions. Another technical

element of contribution used in the control application with the aim of eliminating transient effects and synchronizing information and warning messages with the actual current state of the BMS is the use of dual state variables for load and load as well as the processing of raw data acquired by the system from external environment after a configurable timeout. Thus, for the control of the external charger, the pairs of variables tactionare1/tpaseptare1 are used, which ensure the verification of the current state of the charger after a configurable period of time compared to the previous actuation time. We proceeded similarly for the control of the external load by means of the variables tactionare2/tpaseptare2, ensuring the consistency between the real state of the system and the one processed by the control program. As for updating the calculated states of the external loader and load, we used a pair of variables load/load1 and consumer/consumer1 as control flags of the previous and current states, thus implementing a finite state machine that makes the state decision in the application next based on the previous state.

4.2 FUTURE RESEARCH DIRECTIONS

In recent decades, research and development in the field of electric cars and wireless transfer technology have made significant progress. This continuous evolution has opened the way to new perspectives and innovations in the direction of electric mobility, helping to reduce the impact on the environment and create a sustainable future in the automotive industry. In this context, exploring future research directions in the field of wireless transfer and battery management systems for electric cars plays a key role in defining technological evolution and sustainable development, considering the following directions:

- Improved wireless transfer efficiency: future research should focus on developing and optimizing wireless transfer technologies to improve efficiency and power transfer rate, investigating coil materials and geometries can help minimize losses and increase transmitted power, which would make wireless charging faster and more convenient;
- Development of dynamic charging technology: an interesting direction is the research and development of dynamic charging technology of electric vehicles while in motion, an approach that would eliminate the need to stop to charge the battery and allow automobiles to charge while driving on highways or in cities, thus extending the autonomy of electric vehicles;
- Artificial Intelligence and data analysis for Battery Management Systems: the implementation of artificial intelligence (AI) technologies and advanced data analysis can contribute to the development of more sophisticated battery management systems, systems that can predict battery status, optimize charging and discharge to extend battery life and can adapt operating parameters to driver needs and traffic conditions;
- Technological standardization and interoperability: research should move towards establishing technological standards for wireless transfer and battery management systems in electric cars, with interoperability between different systems and devices being essential to ensure a coherent and efficient charging infrastructure;
- Miniaturization and integration of wireless transfer technology: another interesting direction is the development of wireless transfer technologies that allow integration into road or parking infrastructure, which could eliminate the need for separate charging stations and make charging an invisible part and continuous driving experience;

- Grid-scale energy storage systems: future research should explore the possibility of using electric cars as temporary energy storage resources for power grids, where electric vehicles can be used to improve peak management and help stabilize renewable energy networks;

In conclusion, future research in wireless transfer and battery management systems for electric cars has the potential to completely transform the mobility paradigm. By making charging more efficient, optimizing battery performance and integrating artificial intelligence, the automotive industry can significantly contribute to achieving sustainability goals and creating a greener and more energy efficient future.

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APPENDIX

The source code of the Arduino Uno platform in C language used to implement the control for the SimulIDE simulated version of the BMS was developed incrementally in 9 versions.

```
/* BMS simulator developed by hash_ro
  * v.1 - initial version
  * v.2 - added the output that signals if the battery is charged
  * v.3 - added LCD1602 display
  * v.4 - added resistive divider
  * v.5 - added NTC temperature sensor
  * v.6 - dividing the battery into 3 cells (3x)
  * v.6.1 - displaying the voltage on each cell
  * v.7 - addition of charging/charged electric cell status LEDs
  * v.8 - adding LEDs to signal the charging of each cell
  * v.9 - addition of UART+Rx+Tx bidirectional communication
*/
```

The source code of the Arduino Nano 3.0 development board in the C programming language used to implement the control for the hardware version of the BMS has been developed incrementally in 12 versions.

```
/* BMS simulator by hash_ro
   * v.1 - initial version
   * v.2 - added output if battery is charged
   * v.3 - added LCD1602 display
   * v.4 - added resistive divider
   * v.5 - added NTC
   * v.6 - dividing the battery into 3 electric cells (3x)
   * v.6.1 - voltage display on each cell
   * v.7 - Added status LEDs for charged/charged cells
   * v.8 - added a led for each fully charged cell
   * v.9 - added bidirectional serial communication (bluetooth) + Rx & Tx LEDs
   * v.9.1 - added Rx & Tx led indicator (force to light)
   * v.10 - added i2c LCD1602 + modified resistors in divider and NTC (100k)
   * v.10.a - inverted logic for relay control
   * v.10.b - charger reconnection if the voltage is at the limit value
   * v.11 - small optimizations
   * v.12 - led + bluetooth pinout change
   */
```