IOSUD - Universitatea Politehnica Timişoara
Şcoala Doctorală de Studii Inginereşti

Contributions to main circuits design used in transmission control unit in automotive domain

Ph.D. Thesis – Abstract

for achieving the scientific title of Ph.D. at
Politehnica University of Timisoara
in the doctoral field of Electrical Engineering

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Tabel of contents

Thesis domain

„ Automotive ” is the technological field of electronic devices used in the vechicles industry. At present, the degree of computerization of cars is very high, taking into account the very large number of electrical and electronic components belonging to electronic control units, also called ECUs (Electronic Control Unit). A modern vehicle contains even more than 100 such electronic control units (ECUs), so the performance and quality of a car are directly influenced by the reliability of each electronic component. A brief list of the most used ECUs would be: the electronic engine control unit (ECU - Engine Control Unit), **electronic transmission control unit (TCU - Transmission Control Unit**), electronic control unit for 4 wheels (XCU-4 wheel drive Control Unit / Transfer Case Control Unit), electronic stability system (ESP - Electronic Stability Program), electronic braking system (ABS - Anti-lock Braking System), traction control systems (TCS - Traction Control Systems), electronic control system (adaptive) of speed (CC - Cruise Control, ACC - Adaptive Cruise Control), etc.

The requirements of the automotive market require continuous innovations and implicitly the increase of complexity / performance at increasingly shorter intervals. All due to several factors, such as: increasing environmental protection requirements by reducing carbon dioxide emissions, strengthening functional safety and cyber security, increasing economic efficiency, decrease in delivery time, scalability of products that can be used as easily as possible, increased comfort. As all these requirements have become mandatory at present, it is all the more necessary to deliver functionally validated ECU electronic systems, but also from a safety point of view.

Electronic control units in the automotive industry are part of the category of devices with high reliability, because in the first place is the safety of passengers and the vehicle, throughout the operation. Thus, each ECU in the automotive industry is subject to a rigorous product development process, of which the most common are the “ V cycle ” model, cascade model (Waterfall) or agile model (Agile). Regardless of the product development model chosen, the actual design is performed on several levels, starting from the analysis of requirements, concept, architecture, modeling and simulation to testing, validation and integration. This development process, on the one hand, must comply with legislative rules imposed by European, American and Asian legislation, and on the other hand the international standard for safety in cars ISO26262. To these are added the specific requirements and standards of car manufacturers.

It should be noted that not only ECU producers must meet these standards, but every company producing electronic components for the automotive industry must follow the latest standards imposed on this industry. Deviating from these standards and norms can make a product unusable in the automotive industry, fines of non-compliance, legal deviations and last but not least the damage to the company's image. In order to be able to highlight and prove the safe operation of an ECU, from a qualitative point of view, the design process for ECUs must be structured on several levels, efficient and sufficiently reliable in all operating conditions.

In addition to the cumulation of rules and standards, there is another key factor for the development process of an ECU, namely the time of the design process. Due to the globalization and adaptation of vehicles to the new market concepts, the stages of the development of an ECU have a development cycle between 2 and 3 years, compared to 1990 when the development cycle reached even 5 years. Basically, at present, a half-life of allocated development is assisted, clearly resulting in a need to improve design procedures and a need to standardize concepts for reuse. The challenges posed by the development of an ECU in the shortest possible time are in fact the **main motivation of the doctoral thesis**. The importance of clearly defining the whole development process is also highlighted. In addition, based on the author's professional experience, the aim is to define design procedures for various electronic circuits intended for use in automotive applications, such as the electronic automated transmission control unit.

Research objectives

The main research direction of this thesis is the design and validation of the various electronic circuits constituting a TCU. The TCU electronic module may initially seem a very well defined module over the years, 2022 being an anniversary year in which 40 years have passed since the emergence of the first automated transmission system. Looking at the current situation, however, it can be said that it is particularly interesting and challenging to implement new solutions for TCU to pursue the new electrification trend. The automotive industry is currently facing new challenges in this direction of having only hybrid / electric vehicles on the market. Thus, changes or improvements are needed for each level of the entire system. In fact, the electronic control unit of the automated transmission is also subject to the trend of changes, so the related hardware part has a lot of features that can be improved.

The main purpose of this thesis is to analyze and provide various optimization solutions regarding the robust operation of a TCU safely, either imposed by international standards or legislative rules, or required by car manufacturers. The professional experience of the author, from the last ten years in the field of hardware development in the automotive industry, was a decisive factor in choosing the doctoral topic " Contributions regarding the design of circuits related to the electronic control unit of the automated transmission in the automotive field ".

However, there were **two challenges** that were always the basis of the content of this thesis, namely:

1) What would a design look like in which the notion of functional safety and thermal safety could be implemented from the design stage?

2) What improvements could be made to ensure that a circuit works properly throughout the life cycle?

In the context of current scientific developments in the automotive field, doctoral research is based on a structured approach. For the beginning, information on the current state of research in the automotive field is collected. Beyond the aspects related to the understanding of the theoretical and experimental notions targeted by the approached study, the main purpose is the research of electronic control units of automated transmission, by proposing new design procedures that focus on improving the hardware. The application and validation of the proposed models followed the observance of the stages:

Requirements→ Architecture/Concept → Design → Validation/Verification.

Both the design method and the interpretation of the results were carried out in a detailed and accessible way, in order to create a scalable product. That is, the aim was to create the possibility of using information by other potential control units, not necessarily only those related to automated transmission.

The objectives pursued in the research are the following:

- defining a design procedure that can be used successfully to perform a hardware design that meets the automotive safety requirements in terms of the power supply;
- defining generic thermal assessment procedures that meet the vehicles safety requirements, in terms of the safe and stable basic electronic components operation;
- standardizing the proposed procedures to strengthen the notion of generic, sustainable, reusable models;
- validation of the models proposed by the experiment.

Following the objectives set out above, the research focused on the analysis and selection of the main electronic components, such as: power supplies, microcontroller and power circuit components. The product obtained is intended to be robust both in terms of safety and in terms of functionality on an extensive temperature range. In this respect, not only the selection of components matters, but also the design procedure, which is why, based on their own experience, design procedures of an electronic control unit will be proposed. In order to achieve the objectives mentioned in this chapter, the whole sentence is organized in **three important research directions:**

- presentation of existing theoretical solutions
- synthesis of requirements and regulations related to the treated subject
- experience resulting from professional activity

Chapter 1. Introduction

The thesis is structured on seven chapters, each based on the three relevant research directions mentioned above. The first chapter is the introductory one in which the objectives, motivation and direction of research were presented, while achieving the classification of the research topic approached in the vast context of the automotive field.

Chapter 2. General description of the electronic automated transmission control system

From the perspective of the motivation of the topic chosen for research in the doctoral thesis, in chapter 2 a review of the current stage of automated transmission was presented. A summary of the main requirements to be taken into account in the development of the electronic automated transmission control unit was also presented. In addition, the main theoretical considerations, framed in the context of current development, regarding the stages of safe development of an electronic control unit and the main related components were outlined: microcontroller, power circuit, inverter control circuit and switching elements. The development phases for a TCU hardware architecture were presented in detail, their presentation being passed through the filter of professional experience.

The following aspects were analyzed:

- Synthetic presentation of a brief history of the evolution of automated transmission systems and electronic control units of automated transmission
- Classification of automated transmission systems and presentation of double-clutch transmission for vehicles
- Classification of current configurations of electronic control units according to their location in the vehicle and depending on the type of controlled drive system (electrohydraulic or electromechanical)
- Defining the TCU development process through the " V-cycle "model: concept – design - validation
- Detailed presentation, based on one's own experience, of each stage for the development of a TCU: definition and analysis of requirements, implementation of architecture and design itself, starting from modeling/simulation and at the end, project validation by experimental measurements
- Defining the TCU design concept, by clearly outlining the most significant requirements: TCU location, power range required for the BLDC actuator, actuator control algorithm, cyber safety and security requirements, vehicle manufacturer-specific functionality requirements, operating conditions, level of integration, and last but not least, total cost
- Brief mention of the design requirements of the electronic automated transmission control unit and highlighting opportunities for improvement in its performance
- Analytical and descriptive study of modern technologies, regarding the main electronic components related to TCU, the block diagram being highlighted in fig.1:

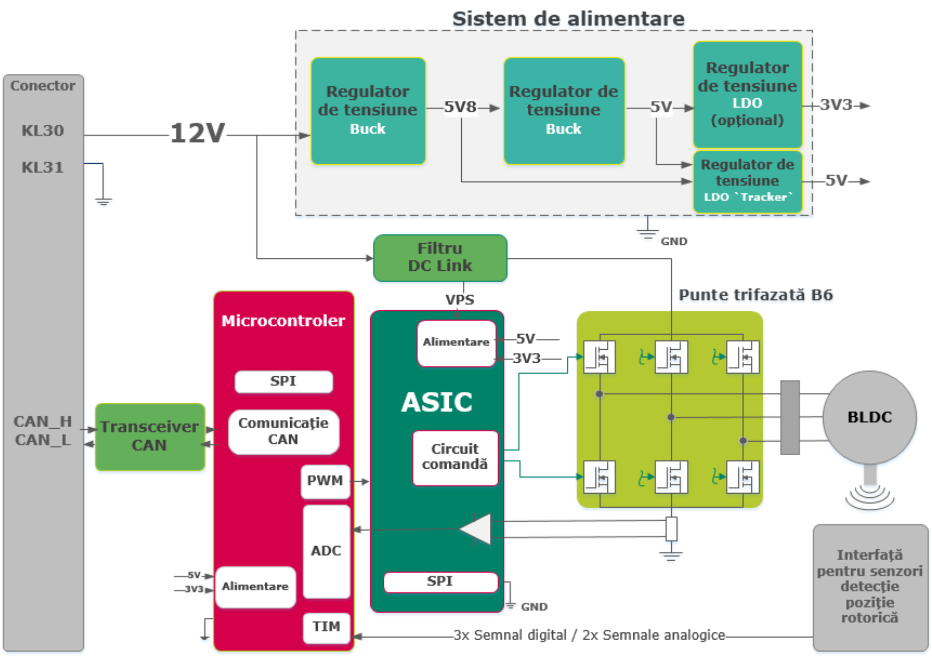


Fig.1. Block diagram for TCU

- Detailed study of the main circuits related to a TCU for the purpose of an appropriate selection that meets the requirements of the application. The study focused on the power system, microcontroller, the inverter control circuit and its constituent switching elements (MOSFETs).

Chapter 3. Contributions to the safe power supply system design of the electronic automated transmission control unit

At the beginning of chapter three, a comparative analysis was provided in terms of the most efficient and actual components. A wide range of top automotive manufacturers for microcontroller and integrated power circuit (system basis chip- SBC) have been considered. Because a hardware design is viewed on the one hand by the performance lens, but on the other side by that of safety in vehicles, a design procedure was also proposed in a manner based on the expertise gained from industrial activity. The proposed procedure consists in complying with several design stages, mentioning the requirements of each stage in order to finally obtain a robust and stable product. The procedure was applied in the design of the supply circuit and the microcontroller related to a TCU. For the complexity and innovation of the proposed concept, the concept of safety activation for high safety applications such as ASIL C (Automotive Safety Integrity Level) was also taken into account.

The following aspects were analyzed:

- Synthesis of the functional safety properties of the main components of a microcontroller unit (MCU) and system basic chip (SBC), in order to design a fault tolerant system, to ensure the desired stability and performance
- Presentation of the design procedure: the proposal, based on the experience and based on the theoretical V-cycle model, of a reference design procedure for the interconnection of top circuits (MCU - SBC), based on own tehnical paper [4]
- Description of each stage of the design procedure to give it the necessary portability/scalability in order to develop any new circuit: not only related to the TCU unit, but applicable to any electronic control unit
- Analytical and comparative study: investigation of “ market ” semiconductors in the present, in order to properly select the components: MCU - SBC
- Proposing a unique concept of a single power supply, considering only 5V between microcontroller and SBC, starting from requirements such as those related to supply voltages, cost, integration, time, possibilities for diagnosis and management of errors, operating conditions. The proposed block diagram is shown in fig.2.

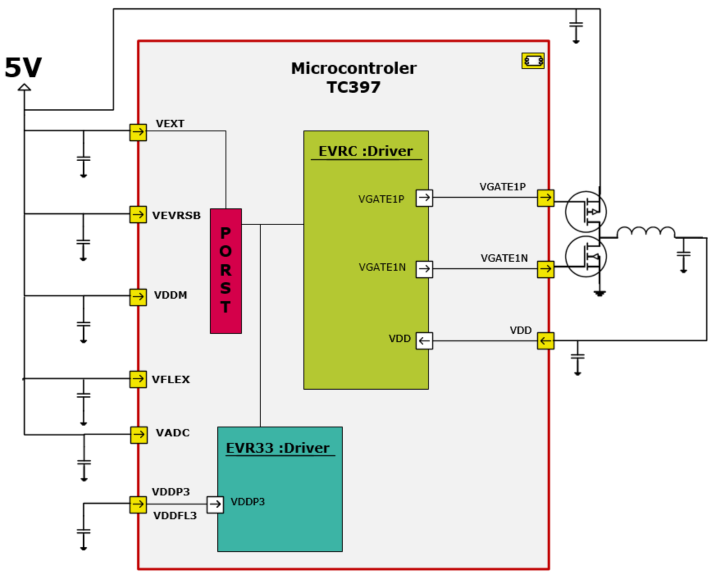


Fig.2. Proposed block diagram for single 5V power supply of the TC397 microcontroller

- Presentation of the criteria for a robust design by imposing analyzes / simulations that include scenarios in the most unfavorable cases (worst case scenarios). Typical values usually offered in the technical specifications of component manufacturers will not be taken into account
- Tracking the most restrictive functional safety regulations
- Propose a new concept of activating functional safety in case of error, including all cases of failure
- Presentation of the concept of activating the state of safety in a modular manner – scalable. The two attributes contribute to a slight integration of the proposed circuit in a rapid development cycle of an electronic control unit.
- Architecture called SWOP (Switch-off Path) has been proposed by the author to ensure functional safety for the detection, prevention and isolation of defects. The main benefit that this architecture (fig.3.) brings is that it is a generalized concept and can be applied to any MCU - SBC combination.

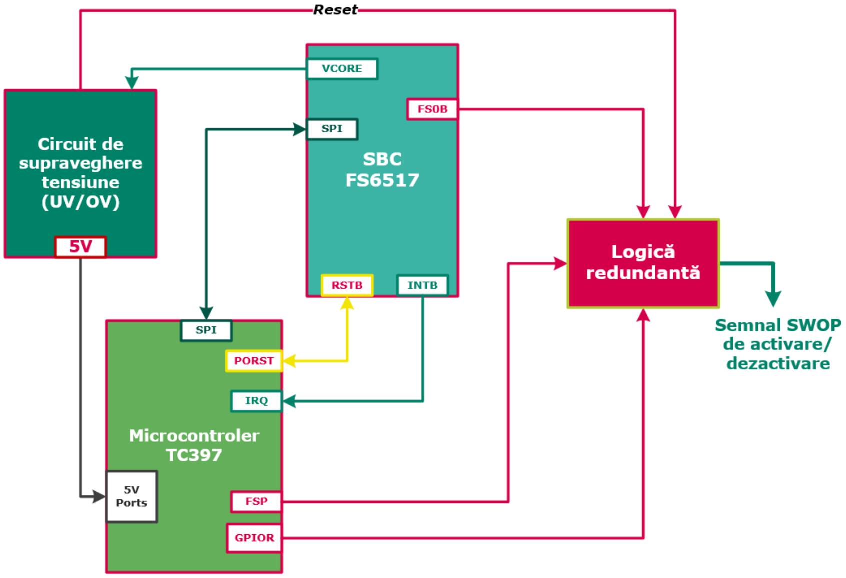


Fig.3. Proposed block diagram for TCU deactivation in case of error

Chapter 4. Contributions to the safe power supply system of the electronic control unit – 48V hybrid system

Chapter 4 presented the electrification trend in the automotive field, followed by a brief description of hybrid systems. Of great interest at present is the mild-hybridsystem whose main power supply has a level of 48V. Starting from the design of electronic control units related to mild-hybrid systems, the rules and requirements specific to product development were highlighted, with reference to the standards VDA320 and ISO26262. Due to the complexity of the mild-hybrid system and the new requirements imposed by safety and reliability, a new power architecture has been proposed for the 48V automated transmission control unit.

Because functional safety is mainly pursued, the unit's ability to monitor the levels of supply voltages was pursued, but also the reaction of the whole system in case of error. In this respect, the proposed concept was subjected to experimental validation by means of a prototype board. The test board was designed to cover a variety of errors (overvoltage, undervoltage), being usable for both manual and automated testing. The 48V power supply concept has been subject to experimental validation to obtain certification that it can be integrated at any time for hybrid type TCU series applications.

The following aspects were analyzed:

- Presentation of the electrification trend through a comprehensive description of 48V mild-hybrid systems and by highlighting the current state regarding the hardware design challenges
- Brief description of the milld-hybrid system whose main power supply has a level of 48V, a block diagram is ilustratted in fig.4.

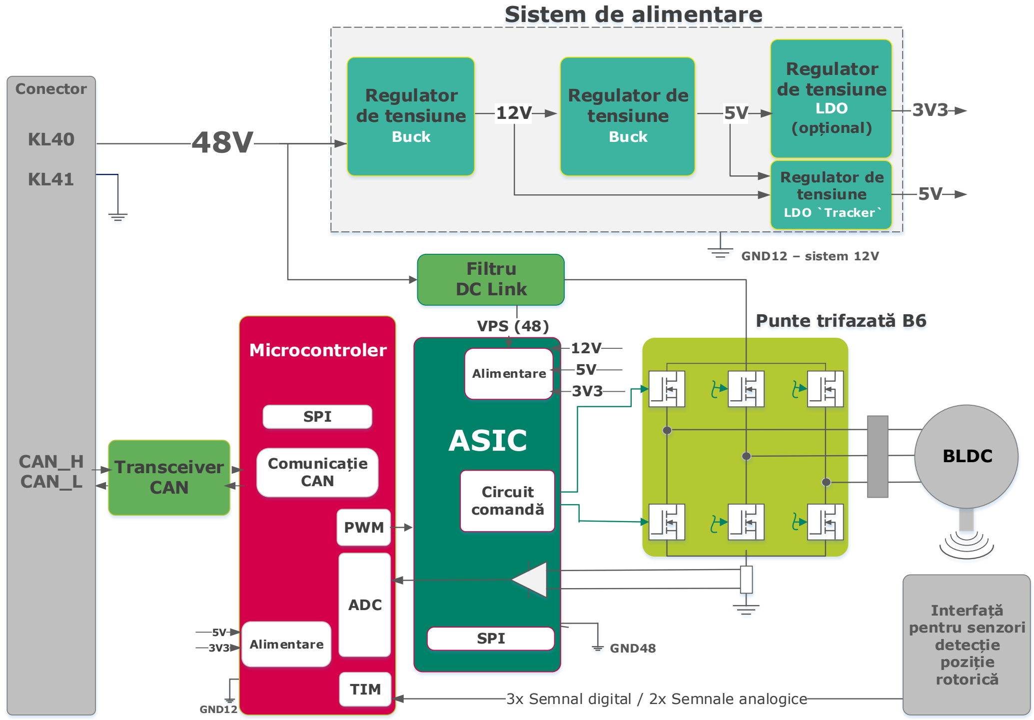


Fig.4. TCU block diagram –48V power supply system

- Synthesization of standards, regulations and requirements for the TCU development, with reference to VDA320 and ISO26262 standards
- Due to the complexity of the mild-hybrid system and the new requirements imposed by safety and reliability, a new power architecture has been proposed for the 48V automated transmission control unit
- Proposal of a new TCU architecture for a 48V mild-hybridsystem, based on its own tehnical paper [9]
- Presentation of a validation platform for the proposed architecture, having as interest the monitoring of supply voltages, but also the reaction of the whole system in case of voltage faults (overvoltage/undervoltage)
- Identifying and exposing all the advantages of having a concept validated since the development phase of a product (have a tested prototype)
- Design and implementation of a test platform to cover a variety of errors (overvoltage/undervoltage), being adapted for manual and automated testing
- Experimental validation of the maximum levels for the related voltages, the assembly of which is provided in fig.5. This is done by a fault injection error process described in detail. Last but not least, the importance of functional safety is also demonstrated by defining and validating FTTI (Fault Tolerant Time Interval).

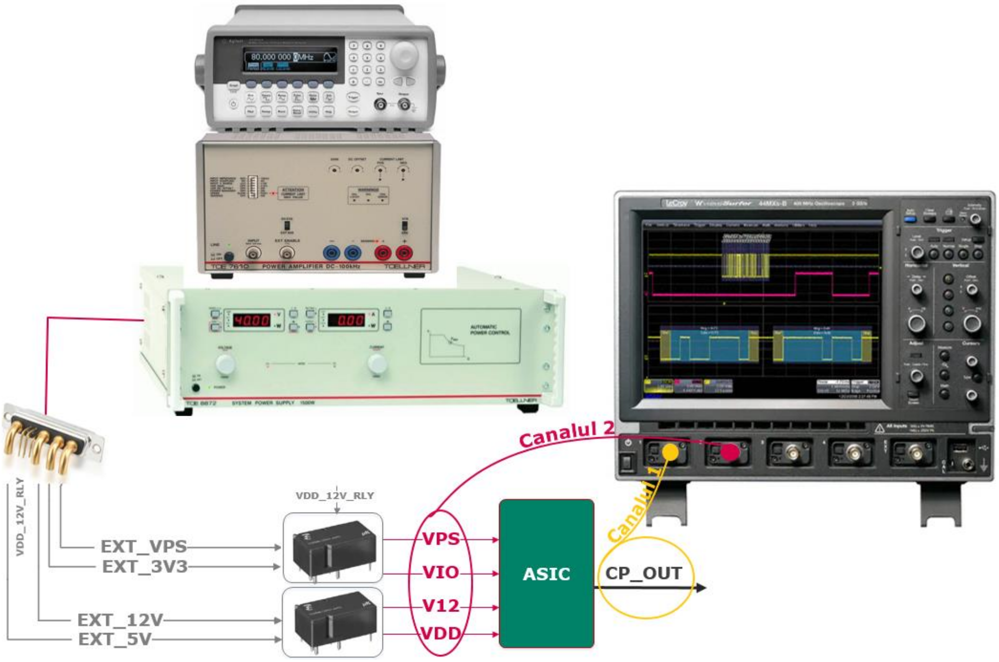


Fig.5. Experimental bench configuration for overvoltage and undervoltage detection

- Strengthening the validated power supply concept, which can be integrated at any time for hybrid type TCU series applications.

Chapter 5. Contributions on the thermal performance evaluation of the electronic transmission control unit– 48V hybrid system

Chapter 5 was based on therma-safety requirements. Special focus was considered to be on measuring temperature with maximum accuracy and on the importance of precise measurements for the products with high ASIL safety levels. In the first part of the chapter, the author listed the design possibilities that currently exist in terms of detecting the temperature of the components in the circuit. The appropriate solution for identifying the temperature measuring circuit was chosen using the Pugh method. In the second part, the experimental validation for the chosen components was followed. It was insisted that the failure or degradation of the power circuit caused by the operation at high temperatures can be anticipated if self-heating of the components is considered during the design phase. The switching elements were analyzed - MOSFET type transistors, as they are the main elements of the power circuit in the TCU mild-hybrid architecture. Their thermal performance was investigated and a method of investigating the temperature of the junction was proposed, taking into account the additional gradient of temperature due to self-heating.

The following aspects were analyzed:

- Presentation of the currently existing design possibilities for measuring ambiental temperature in an electronic control unit
- Review of existing possibilities for measuring or determing the component junction temperature
- Analytical study applying the Pugh method in order to identify the most suitable solution in accordance with the requirements of the application
- Detailed description about the failures of the power circuit caused by the operation at high temperatures can be anticipated if the self-heating of the components is taken into

account during the design phase.

- Propose, based on own tehnical paper [15], a method of complete investigation of the junction temperature, taking into account the temperature due to self-heating. The stages are illustrated in fig.6:

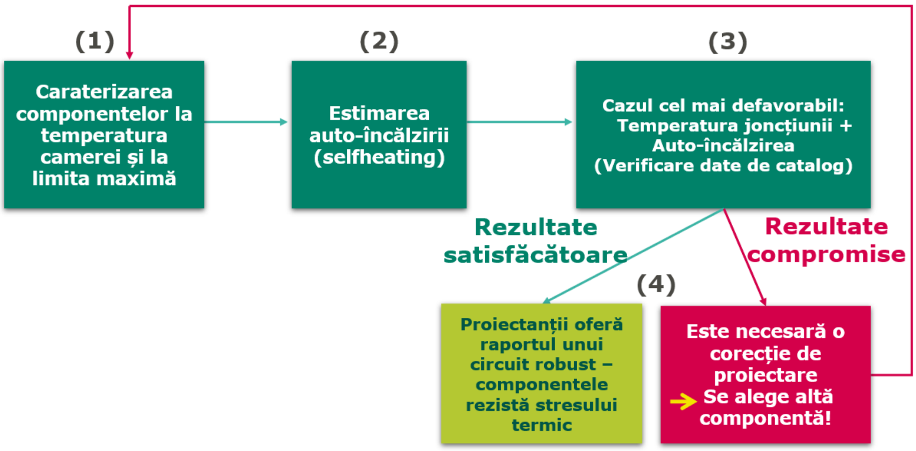


Fig.6. The flow of the proposed junction temperature estimation procedure of MOSFET transistor

- Highlighting the scalability of the method, as there is a possibility of reuse in other applications with a high level of safety that integrate switching power elements
- Experimental validation in order to investigate thermal behavior of the power components chosen in the design. Only by experimental verification (assembly is illustrated in fig.7) can be guaranteed that the design complies with the limits and requirements imposed by the application.

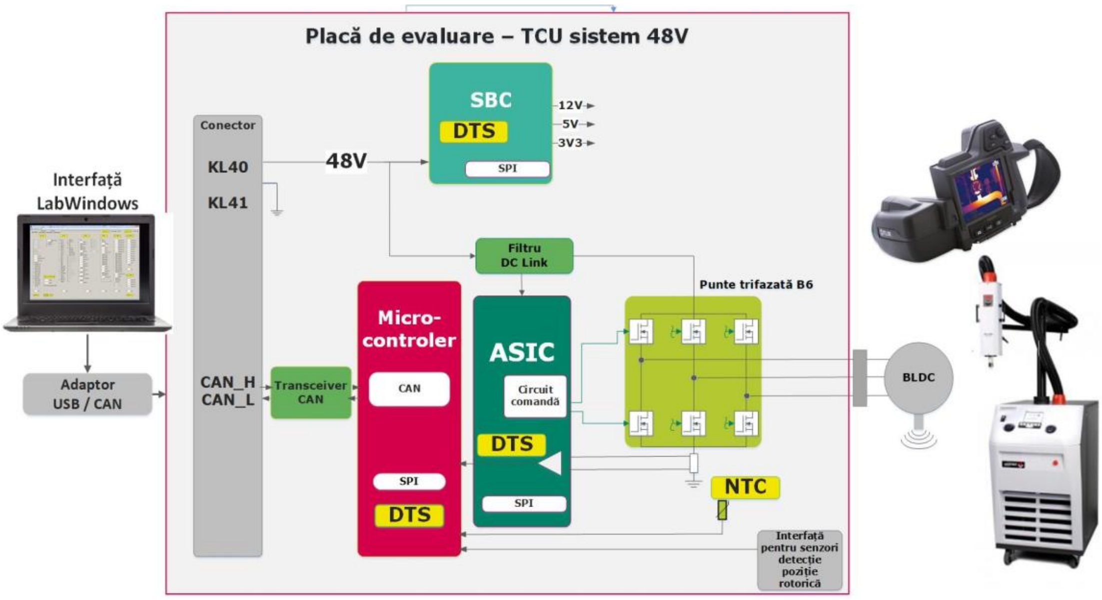


Fig.7. Experimental bench configuration for thermal measurements termice (MOSFET)

Chapter 6. Contributions on estimating the lifetime of multilayer ceramic capacitors in the electronic transmission control unit

Chapter 6 focused on the study of thermal functional safety by assessing the reliability and robustness of electronic components. Methods for estimating the lifetime of electronic components have been presented, especially for passive components, such as multilayer ceramic capacitors (MLCC-Multilayer Ceramic Capacitors). The research was dedicated to lifetime estimation and lifetime stress distribution for MLCC. Lifetime estimation is required to define MLCC behavior in operating conditions and to prove robustness, reliability and design safety. The worst case scenario was considered, when there are external temperature stimuli due to the powers dissipated from the circuit. Thus, the chapter included contributions in terms of a complete lifetime estimation due to influence of self-heating temperature.

The following aspects were analyzed:

- General introduction about reliability in general and detailed definition for the reliability of multilayer ceramic capacitors - MLCC
- Review of existing theoretical studies on the generic method of estimating the components lifetime
- Comprehensive documentation about realiability versus accelerations methods. The acceleration method of MLCC capacitors has been presented.
- Based on own tehnical paper [17], the proposal of a calculation algorithm that contributes to improving the accuracy of the MLCC lifetime estimation, considering a new parameter in the formula: the additional self-heating of components
- Propose a procedure for a complete estimation of its lifetime estimation formula and lifetime stress distribution. The procedure steps are illustrated in fig.8. The decision-making process regarding the usage/ changing the component according to the result of the calculated life distribution was highlighted.

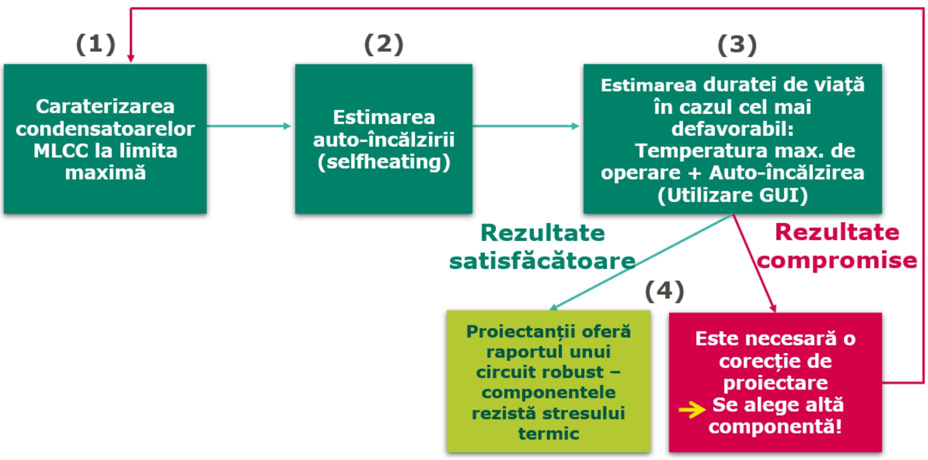
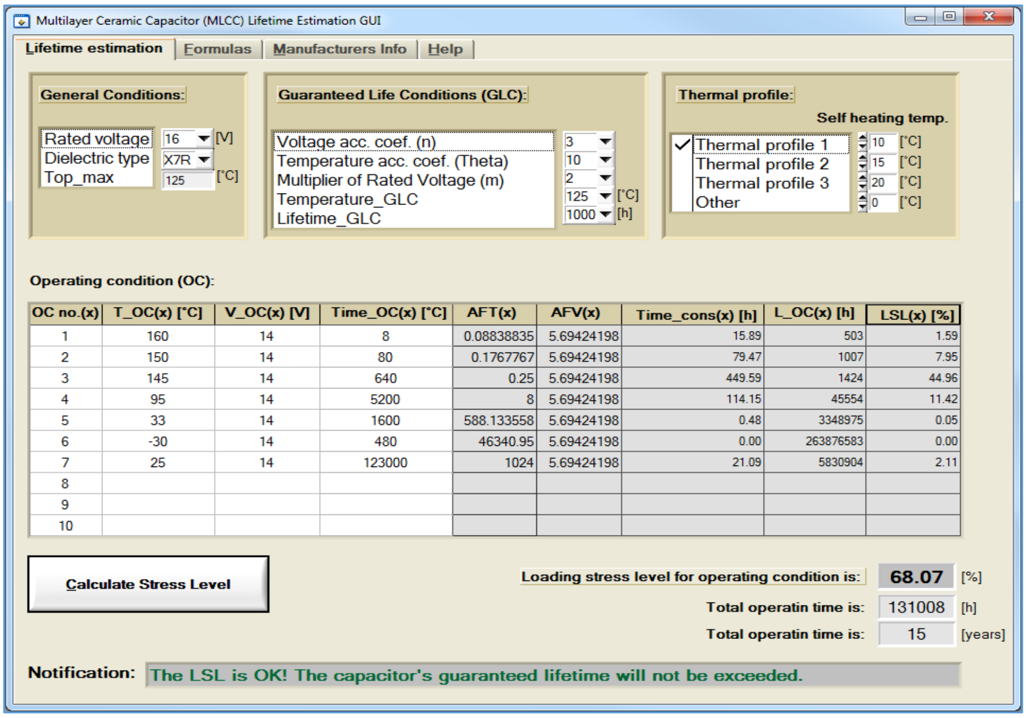


Fig.8. The flow of the proposed life estimation procedure of MLCC

- Development of a graphical interface (according to fig.9), with the possibility of reuse in other applications with a high level of safety, which integrates the automated lifetime distribution calculation for MLCC capacitors.
- Highlighting in this case the notion of scalability / modularity - the graphical interface is generalized, includes specific data of 6 different manufacturers of ceramic capacitors.


Multilayer Ceramic Capacitor (MLCC) Lifetime Estimation GUI

Lifetime estimation | Formulas | Manufacturers Info | Help

General Conditions:

Rated voltage 16 [V]
Dielectric type X7R
Top_max 125 [°C]

Guaranteed Life Conditions (GLC):

Voltage acc. coef. (n) 3
Temperature acc. coef. (Theta) 10
Multiplier of Rated Voltage (m) 2
Temperature_GLC 125 [°C]
Lifetime_GLC 1000 [h]

Thermal profile:

Self heating temp.

Thermal profile 1 10 [°C]
Thermal profile 2 15 [°C]
Thermal profile 3 20 [°C]
Other 0 [°C]

Operating condition (OC):

OC no.(x)	T_OC(x) [°C]	V_OC(x) [V]	Time_OC(x) [°C]	AFT(x)	AFV(x)	Time_cons(x) [h]	L_OC(x) [h]	LSL(x) [%]
1	160	14	8	0.08838835	5.69424198	15.89	503	1.59
2	150	14	80	0.1767767	5.69424198	79.47	1007	7.95
3	145	14	640	0.25	5.69424198	449.59	1424	44.96
4	95	14	5200	8	5.69424198	114.15	45554	11.42
5	33	14	1600	588.133558	5.69424198	0.48	3348975	0.05
6	-30	14	480	46340.95	5.69424198	0.00	263876583	0.00
7	25	14	123000	1024	5.69424198	21.09	5830904	2.11
8								
9								
10								

Calculate Stress Level

Loading stress level for operating condition is: 68.07 [%]
Total operatin time is: 131008 [h]
Total operatin time is: 15 [years]

Notification: The LSL is OK! The capacitor's guaranteed lifetime will not be exceeded.

Fig. 9. Fluxul procedurii de estimare propuse a duratei de viață a MLCC

- Experimental procedure by implementing the proposed algorithm for MLCC selection in the TCU application. The validation bench is illustrated in fig.10.

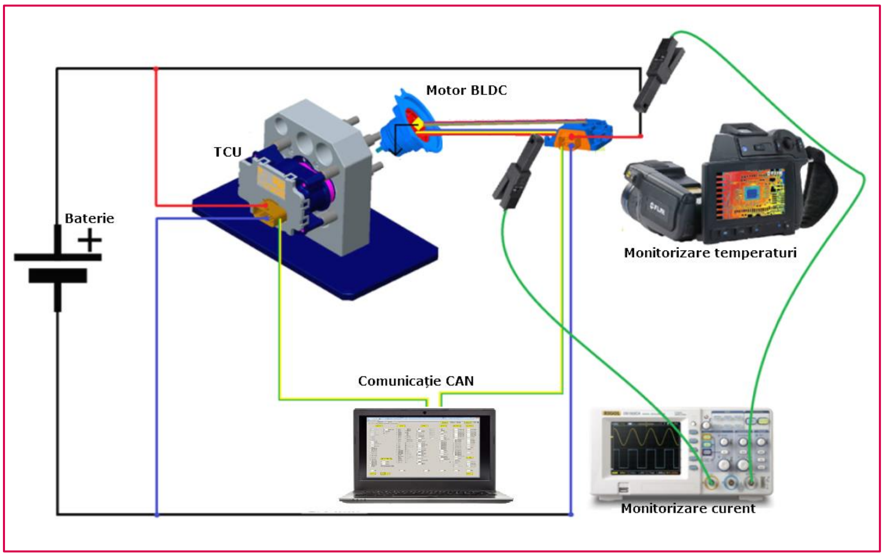


Fig. 10. Experimental bench configuration for thermal measurements (MLCC)

If the analyzed MLCC exceeds the maximum lifetime stress level limit, it can be replaced during the design phase, without any costs or effort. As demonstrated in the experimental section, the application of the proposed method for the purpose of determining the distribution of lifetime has a major importance in the decision-making process thus facilitating the interpretation of results. In this way, the hardware design engineer can be sure that MLCCs perform their function even in harsh conditions, such as operating at high temperatures.

Capitolul 7. General conclusions. Future development proposals

General conclusions

The doctoral thesis represents a synthesis of the author's activity carried out within an industrial concern. The design activity of circuits specific to the electronic control unit for autmated transmission (TCU) addressed actual tendencies, the automotive field towards electrification. Automated transmission always tends towards innovation and is constantly being improved, starting from the innovations of the industry producing components and electronic units, to the entire evolution of the automotive industry.

The research approach started from the study of automated transmission systems in the context of their scientific evolution. At the same time, the requirements, the standards and the vechicles operating specifications related to the development of a TCU were collected, both in a classic 12V system and in a 48V hybrid system. Research efforts have focused on analyzing and providing various design solutions and procedures that include the robust, safe, stable and efficient operation of a TCU in safe functioning conditions.

The thesis is structured on 7 chapters, each based on three relevant directions of analysis: presentation of existing theoretical knowledge related to the treated subject, synthesis of requirements and regulations, experience resulting from hardware professional activity. For each one, a structure with **three approaches** was followed: **theoretical** by framing the issue at the current stage, **methodical** by presenting design proposed procedures and **experimental** validations of the proposed theory. Both the proposed procedures and the interpretation of the results were carried out in an accessible way, in order to create a scalable product. The final scope was to create the possibility of re-use of information by other control units, not necessarily only those related to automated transmission.

The degree of novelty and scientific value are strengthened by meeting the objectives set at the beginning. The following results can be defined:

- a complete development procedure has been defined involving a product with high functional safety
- new architectures corresponding to the safety requirements of vehicles with specific features for the power suply circuit (12V and 48V) have been defined and validated
- generic thermal assessment procedures and components lifetime estimation in the context of increased safety requirements have been defined.

Future development proposals

The realization of all these improved architectures and design procedures proposed in this research is a solid argument for use in the future design of electronic automated transmission control units and beyond, whereas it only requires an adaptation to the specifics of the application. However, as the automotive field is in full development, so must hardware design follow the same trend. Thus, the importance of having concept architectures and well-defined procedures is emphasized once again. Starting from the design process presented in the thesis for TCU units powered classically (12V) and for hybrid TCU units (48V), research can be extended to new products in the automotive field. As a major trend today is the transition to products related to fully electric mobility due to the vehicles electrification.

The **electrification process** is a truly revolutionary for this industry comprising electronic components, electronic control units and vehicles. In all three areas there is a need for technological innovation, and the competitive market favors development as quickly as possible. Not only competition but also international regulations have forced producers to innovate. If in the period 2015-2020 the development was focused on classical and hybrid vehicle architectures, the period 2020 – 2025 focuses on electronic units related to completely electric vehicle architecture.

Following this trend, technological trends are expected that will completely influence the design, because now the batteries of the vehicles have supply voltages of the order of hundreds of volts: 400V, 800V. Stricter requirements and regulations for such power voltage values force the industry to explore completely new topologies, components and materials. Basically, power electronics will dominate this market, hence the need for the emergence of specific electronic components, such as **Wide Band Gap** semiconductor**.** The introduction of new components as well as the definition of new power supply concepts for control units will be sources of study for future research.

Starting from the design procedures presented in this thesis, but approaching the new technology for electrification products, further development perspectives can be created. I propose that the future process of developing an electronic control unit be subject to a slightly modified " V cycle " to emphasize development agility. If agile development is already implemented in software development, it is not used for hardware design and is an opportune starting point for completely new electrification products.

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