UNIVERSITATEA „POLITEHNICA” din BUCUREŞTI

ŞCOALA DOCTORALĂ ETTI-B

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TEZĂ DE DOCTORAT

Electric Heated Catalyst Controller Design for Automotive Emission Control
- Summary -

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COMISIA DE DOCTORAT

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BUCUREŞTI 2021

Foreword for summary

The following is a summary of my PhD Thesis. The summary follows the structure and the chapters of the thesis. For better readability, only the Chapter and Subchapters are shown in this summary. The acronyms used in the text are not explained. A full list of acronyms is available at the beginning of the Thesis. Numbering of the figures is following the figures numbering used in the Thesis. Only a part of the bibliographic references is shown in this document. Full list is available in the Thesis.

Chapter 1 Introduction

1.1 Introduction

The growth of the automotive industry around the world has transformed the automobiles in being one of the important pollutants around the world.

Exhaust gasses contain several types of pollutants, which have a wide environmental impact. The CO2 composition is a greenhouse gas. It is estimated that around 20% of the CO2 emissions in European Union are coming from motor vehicles [1.1]. Carbon monoxide is a highly toxic gas. It was estimated that 52% of CO emissions were generated by motor vehicles [1.2]. NOx are nitrogen oxides which are both toxic to humans, and can create acid rain. In US, most of the NOx emissions are being generated by motor vehicles [1.3]. Particulate matter products are having adverse effects on human health. Around 1 to 2 percent of all the particulate matters in US are generated from motor vehicles, mostly Diesel engines [1.4].

Given the impact of the automotive industry as a pollutant, governments have started to define emission standards for vehicles.

The emissions standards are legal requirements defined by governments around the world to govern the air pollutants released in the atmosphere. Automotive emission standards set limits on the pollutants released by automobiles.

1.2 Emissions control

Government bodies around the world are defining the emission limits to be fulfilled by the new vehicles, but are also defining the testing procedures to be followed for emission measurements. In Europe this is the regulated by the EEC directives. In US, they are regulated by the Environmental Protection Agency.

Especially for Diesel engines, the exhaust systems have reached a high complexity, where the emission system is regulated in some cases by a separate control unit.

Selective Catalyst Reduction, together with a specialized catalyst is used to reduce the emissions. To assure the catalyst operation, a light-off temperature needs to be reached by the catalyst. This temperature can be achieved by heating the catalyst by the exhaust gasses. To heat-up the catalyst quicker, an electrical heater can be used.

1.3 Research Area

The research scope for the thesis is the control of the electrical heated catalyst in automotive environment (mostly electrical).

The operation of the electrically heated catalyst is described, together with power levels. These operation modes and power levels are requirements coming from system level. The load is analyzed in terms of construction and electrical parameters.

Different environments in terms of voltage boardnet are analyzed and discussed: 12V legacy systems, 48V systems for mild-hybrid and high voltage systems. The research is mostly focused on legacy 12V and 48V mild hybrid systems.

Current state of the art solutions are presented. Several problems are identified for the existing solutions.

Following, new implementation proposals are shown for both 12V and 48V systems. For each solution presented, results are presented in terms of design / calculation, simulation (electrical / thermal), implementation (Layout, PCB, housing) and finally measurement results.

The different implementation problems are analyzed: thermal environment and operation, impact on the boardnet, conducted emissions, PCB design and electronic packaging.

Chapter 2
Automotive emission legislation

2.1 Emission legislation history

The first emission norms were created in California in 1963, as a response to the smog problems which appeared in Los Angeles due to the heavy traffic. Quickly after, other nations followed. In the thesis, the focus will be mostly on the European norms, with a slight incursion through the norms in US. [2.1]

Although each region and country might have a slightly different emission legislation, a manufacturer which would like to sell their cars all across the globe needs to fulfill each country emission regulation. There are several vehicle class definitions – passenger vehicles, light commercial vehicles and trucks and busses. The following discussion will focus on the limits for the passenger vehicles.

In Europe, the set of EURO norms was introduced starting with EURO 1 in 1992. Currently, EURO6 – rev B is approved, and it regulates the amount of CO, NOx, THC and particle matter a vehicle can emit. A set of technologies, like multiple point injection, Particle filter, Selective Catalyst Reduction and regenerative braking on 48V battery are used to fulfill the emission norms. It is foreseen that Electric Heated Catalyst will be necessary for fulfilling EURO – 7 Norm.

Figure 1 Euro 1- 3 emission control technologies

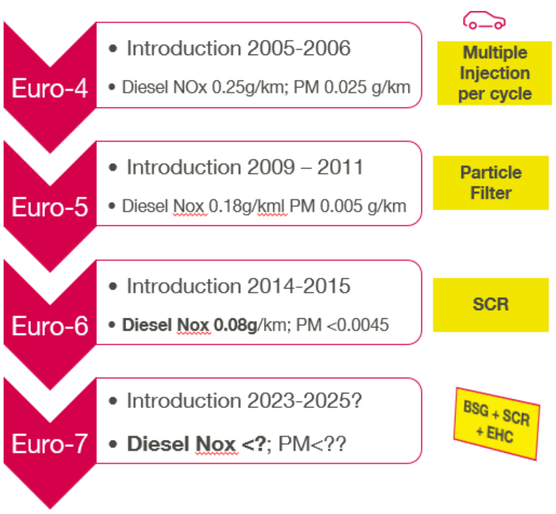

Figure 2 Euro 4- 7 emission control technologies

2.2 Solutions for meeting emission legislation – SCR

For Diesel engines, Selective Catalyst Reduction systems use a reactive agent to convert the Nitrogen Oxides into harmless Nitrogen N_2 and water H_2O, with the help of a catalyst. This system is used for reducing the NO_x emissions in Diesel engines.

The system overview is presented in the figure below.

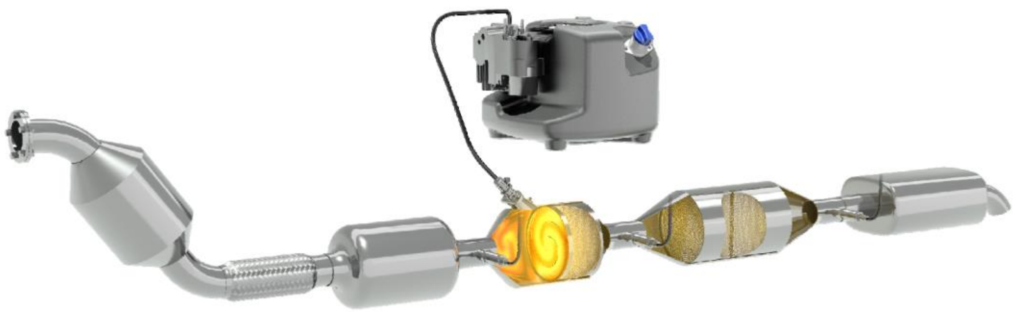

Figure 3 Selective Catalyst reduction system

The reducing agent used is Urea, with the commercial name of AdBlue. This is stored in an on-board tank, which needs to be periodically refilled. A pump is getting the liquid from the tank, and is creating pressure in the tubing. An AdBlue injector is placed right before the catalyst.

Several sensors are placed across the complete system, such that the reaction can be controlled. There are temperature sensors before and after each catalyst, NOx sensors before and after the catalysator, and pressure sensors to detect that the DPF is clogged.

2.3 Solutions for meeting emission legislation - EHC

As the catalysts operates at temperature above 200°C, the emission control system is not fully functional during transient periods after engine turn-on. The start-stop system, which turns off the engine during a halt at a semaphore light is diminishing the efficiency of the emission control system. This is due to the frequent engine stops, which will allow the catalyst to cool. The same problem is present for the mild hybrid vehicles, where for the internal combustion engine could be operated intermittently.

To compensate for these points, an electric heater is placed just in front of the catalyst, that can heat-up the exhaust gasses, which in turn will heat up the body of the catalyst.

Figure 4 Continental Electrically Heated Catalyst (left) and implementation in a gasoline engine(right)

2.4 Solutions for meeting emission legislation – BSG

The 48V system is presented in more detail in Chapter 4 – "Boardnet voltage levels in Automotive", subchapter 4.2.

In this section it is mostly presented as a complementary system for the EHC, necessary to further reduce emissions.

A vehicle which contains a 48V systems is called mild-hybrid. The main scope of introducing the 48V technology was to reduce the CO_2 emissions, by recuperating the energy during braking, and using it for engine start-up, acceleration and cruising. On the 48V battery, additional high-power loads can be connected which need more power than the legacy 12V system can deliver.

A good example of such a load is the EHC. The picture below is an example of EHC implementation inside a Diesel engine. The EHC is supplied through a controller from the 48V boardnet.

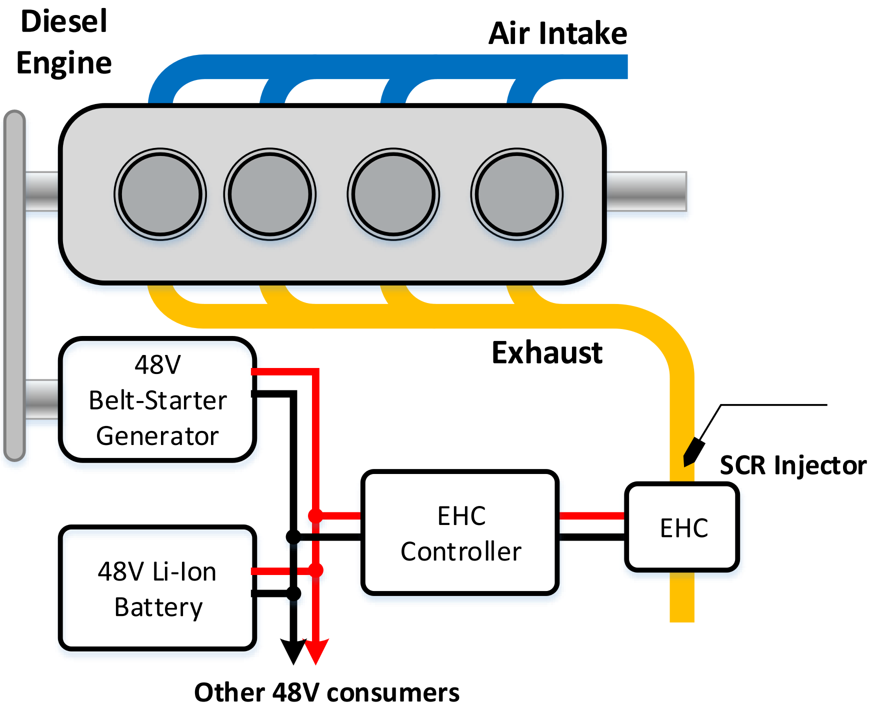

Figure 5 48V system used with EHC to reduce emissions

For gasoline engines, the same system is used, of course without the SCR injection. Operation mode for Gasoline Engines is different from Diesel engines. This is discussed in more detail in Chapter 3 – „Electrically Heated Catalyst Load Definition and Operation”, Subchapter 3.2 – “EHC Operating modes”

Chapter 3
Electrically Heated Catalyst Load Definition and Operation

There are several producers of catalyst for automotive, but only some of them are offering the possibility to have an electrically heated unit. Out of these, only a couple of them are offering a unit which is prepared for high-volume production.

3.1 Electrical Heated Catalyst load

The catalyst heater from Emitec is constructed from a metal foil similar to a corrugated cardboard, which is then coiled around itself in a spiral shape. Ceramic insulator pins hold the grid on the catalyst, while also offering insulation between the housing and the resistive heater.

Figure 6 Emitec EHC build cross-section [3.2] and cut-out [3.1]

The position of the pins is optimized such that the heating grid will dampen natural frequency vibration thus improving vibration durability, and enhance the thermal cycle durability.

In the 12V systems, it was common to have only one connector to the 12V supply, and the return path would have been connected through exhaust manifold thorough engine, chasis and back to the battery.

For 48V system this is no longer acceptable, mainly due to two factors. First one is that the 48V return current that will have to pass through the exhaust – engine – chassis – battery chain will create a voltage drop which can impact the sensors and ECU’s connected to engine Ground. The second factor is that, in case of a failure of the GND link between the engine and the chassis, all the ECU’s referenced to engine ground would be supplied to the 48V battery, which might lead to a catastrophic failure. In this case, the EHC supplied from 48V usually have two connector pins, one for the + supply and the other for the – supply.

The electric heater is a resistive load, with little to no thermal coefficient. This is due to the material used for the heater manufacturing. The tolerance of the resistance is mainly attributed to the mechanical parameters of the build: thickness variation of the foil and variation in foil width.

The operation of the catalyst must ensure that the temperature of the heater does not exceed 1000°C.

3.2 EHC Operating modes

Main purpose of the electrically heated catalyst is to maintain the catalyst above the light-off temperature. Its operation is different between gasoline and diesel engines. It is also depending on the system environment: temperature of the exhaust gases, exhaust gas flow, external temperature, vehicle speed (external wind).

In gasoline engines, the exhaust temperature is much higher, and once the catalyst has reached the light-off temperature, it will remain above the temperature given that the engine is not stopped.

For diesel engines, the exhaust temperature is lower, and it can happen that during cruising the temperature can drop significantly, so a steady power is necessary to maintain the catalyst temperature.

In some cases, for diesel engines the power requested can be as high as 4kW for a period of 100s, after which it will drop. To maintain the temperature of the catalyst in worst-case conditions, a power level of 1kW can be requested for an undefined amount of time.

Hybrid vehicles and start-stop systems are having an important role in the operation of the EHC. The EHC has to compensate the cooling of the catalyst when the ICE is off. This mode necessary to operate irrespective for both diesel and gasoline engines.

Chapter 4
Boardnet Voltage Levels in Automotive

The de-facto standard voltage in a vehicle is 12V. The automotive 12V system is well understood, and there are several ISO standards [4.1] specifying the electrical 12V environment.

In the last years, a second boardnet voltage in the automotive world is appearing - the 48V boardnet. Specific standards are describing the electrical environment for 48V systems.

The high-voltage hybrid electric vehicles have batteries with voltages higher than 60V, and can reach up to 800V. Additional to electrical environment, electrical safety of the complete system needs to be considered.

This chapter makes an overview of the 12V and 48V automotive systems, and shortly touches the operation of higher voltage automotive systems.

4.1 12V Automotive

The legacy energy supply for automotive is the 12V lead-acid battery. This is a rechargeable battery that supplies the electric current for the vehicle. The main purpose of this battery is to start the ICE. Once the ICE is running, the energy for the vehicle is supplied by the alternator. Typically, an engine start discharges less than 3 percent of the battery capacity. For this reason, the automotive batteries are designed to supply a high current for a short time (during engine start).

Although the battery offers a steady supply voltage, due to the wiring harness and the different loads being turned on and off, a control unit connected to the battery supply line cannot be assured of a steady voltage. For example, the supply voltage might range from 2V to 28V. A reverse polarity condition might occur. Pulses of up to + / - 200V can appear on the supply line.

The legacy 12V electrical system is shown in figure below. The ignition key controls the distribution of power to the entire vehicle.

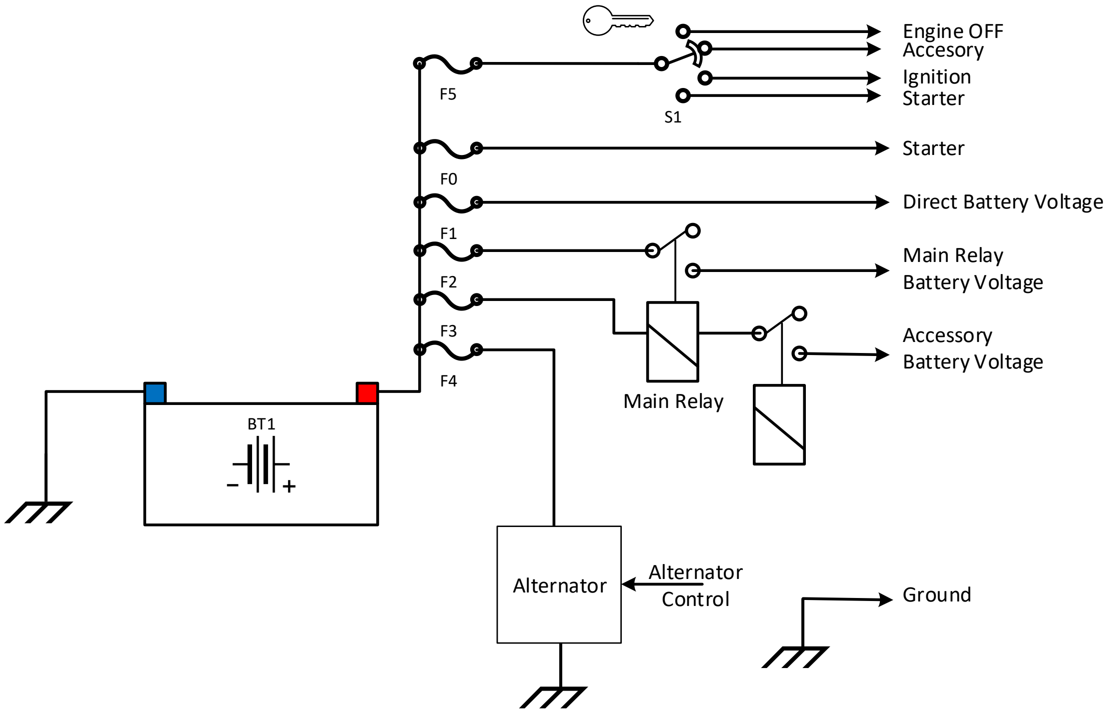

Figure 7 Legacy automotive 12V supply system

While the ICE is running, the alternator re-charges the battery and supplies most of the energy needed for the car to run. The alternator is an electric machine which converts the mechanical energy into electrical energy.

Most of the electrical subsystems are supplied through the main relay contact, such that they will only be supplied when the engine is running. Some subsystems need to be always-on (e.g., security alarm, accessibility sub-systems, and other advanced functionalities). The general requirements for the ECUs connected directly at the battery line is to have a sleep current less than 100µA.

Start-stop systems stop the engine when idling at a traffic light. When the clutch is pressed, the engine starts running again. The battery for they start-stop systems needs to support both the capability to have frequent cranking cycles, and to supply the operation of the vehicle electrical system while the ICE is off.

On the 12V environment, there are several ISO Pulses defined for testing the electronic control units connected to them, for e.g., ISO16750, ISO7637-2. Additionally, each OEM have customized and improved these standards with their own experience (LV124 for German OEMs – VW, Mercedes, BMW, Renault, Ford FMC1278). An electronic control unit needs to qualify according to a test plan following these standards. A detailed description of the pulses and tests is presented in the Thesis.

4.2 48V mild hybrid

Newer hybrid vehicles are using a secondary Lithium 48V battery, having the advantage that CO_2 emissions reduction is possible by using recuperation of energy during braking.

The 48V boardnet is shown in the figure below.

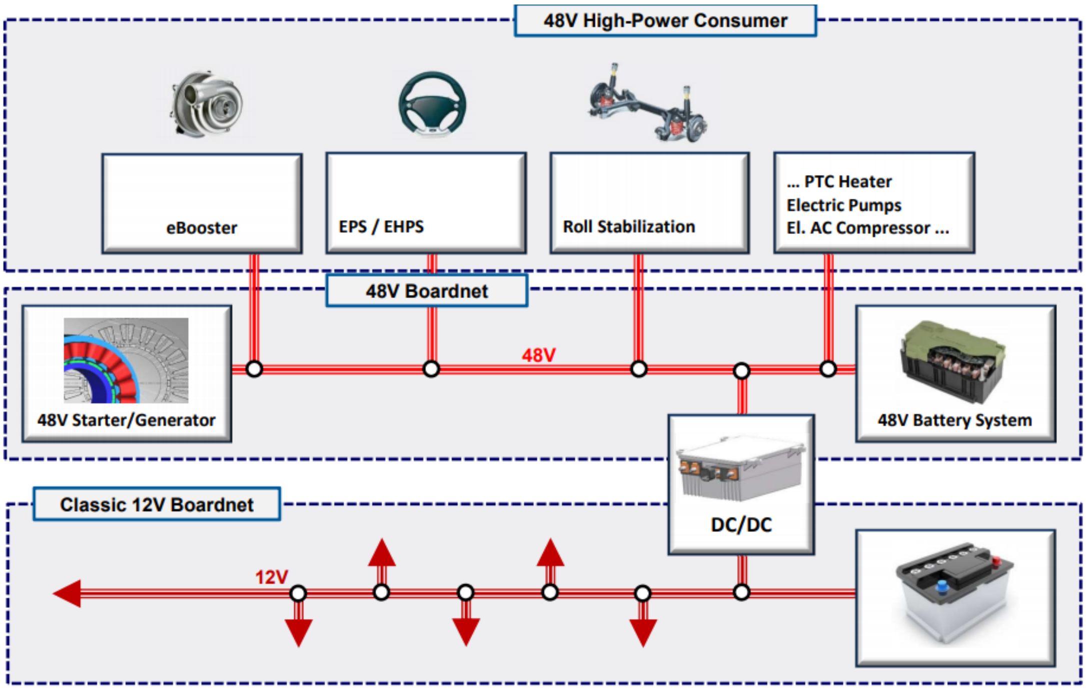

Figure 8 vehicle power architecture for 48V systems [4.7]

The system is centered around a 48V Lithium battery. An energy link is provided between the 12V and 48V by the means of a bi-directional DC-DC converter. The system allows the recuperation of the vehicle energy during braking, by the means of an electrical machine.

The belt driven starter generator is one example of electrical machine used for 48V. The 48V BSG is the easiest and most cost efficient type of electrical machine to implement in an existing vehicle. This is done by replacing the alternator with the

BSG unit, and a decoupling tensioner or clutch might be used to control the mechanical coupling / de-coupling of the BSG shaft.

A 48V - 12V Bi-directional DC/DC converter is the link between the 12V and 48V boardnet. The DC/DC converter is used to transfer energy between the two subsystems.

On the 48V boardnet environment, there are defined a set of possible pulses and voltage ranges that one might expect. The VDA320 [4.13] norm defines the requirements, test conditions and tests to be performed on the electronic components used in a vehicle which are supplied from 48V boardnet. A detailed description of the pulses and tests is presented in the Thesis.

4.3 HV electronics (Voltage class B)

The plug-in hybrid vehicles with battery levels higher than 60V DC have both the advantages of an extended range given by the ICE, as well as pollution-free operation from electric motor.

HV hybrid vehicles Internal combustion engine still require a catalyst for meeting future emission norms. An isolated DC-DC converter is required to supply this heated catalyst. The catalyst control from high voltage electronics is not covered in the thesis.

4.4 Electro-magnetic interference requirements

Electromagnetic compatibility is a very important aspect that has to be taken into account when designing an electronic product. Both EMC emissions and EMC interferences are regulated by international standards, like CISPR25.

EMC interference spectrum ranges from low frequency (e.g., noise from power supplies, low-voltage network, audio amplifiers) up to high frequencies (e.g., radio interferences, communication signals) and ultra-high frequencies (e.g., GSM telephony, Radar signals)

Electro-magnetic compatibility needs to be analyzed on both component level and vehicle level. A detailed description of the emission tests procedure on component level is presented in the Thesis.

Chapter 5

Electric Heated Catalyst Controller Designs

In this chapter, several solutions for EHC controllers are presented, both for 12V and 48V systems. Prior art for the 12V system is presented. This chapter contains my individual contributions in the area of EHC controllers.

5.1 Legacy 12V EHC controllers

First reference documentation for the control of the electric heated catalyst is found in the patents from US and Japan manufacturers in the early 90s. The solutions proposed at that time for the EHC control were either by modifying the alternator circuit, or by using an on/off relay control. Current and power required for heating up the EHC is in the range of 100A, and several kW Power.

The early solutions do not consider circuit protection and heating capacity. A potential failure in the system (e.g., wiring harness short-circuit, controller short-circuit, etc.) might cause a fire in the vehicle. In best case, the circuit is protected by a fuse. However, at such high currents this might not be sufficient (harness and battery are over-stressed, impossibility of linear heating control, no diagnostic function, no diagnostic for contactor welding failure).

Another implementation is presented, in which the power switch is made by using semiconductors switches, with a higher control possibility. The main disadvantage of this implementation is that in case of a short-circuit to ground, the fault detection is limited.

A new solution for the EHC control for 12V system is presented, which will overcome the previous design disadvantages. The system overview is shown in the following figure. The control algorithm, implemented in the Engine Control Unit, controls the EHC temperature, keeps track of the power balance, energy supply – battery vs alternator. The E-CAT controller has only the function to actuate the load, and to perform basic On-Board Diagnostic.

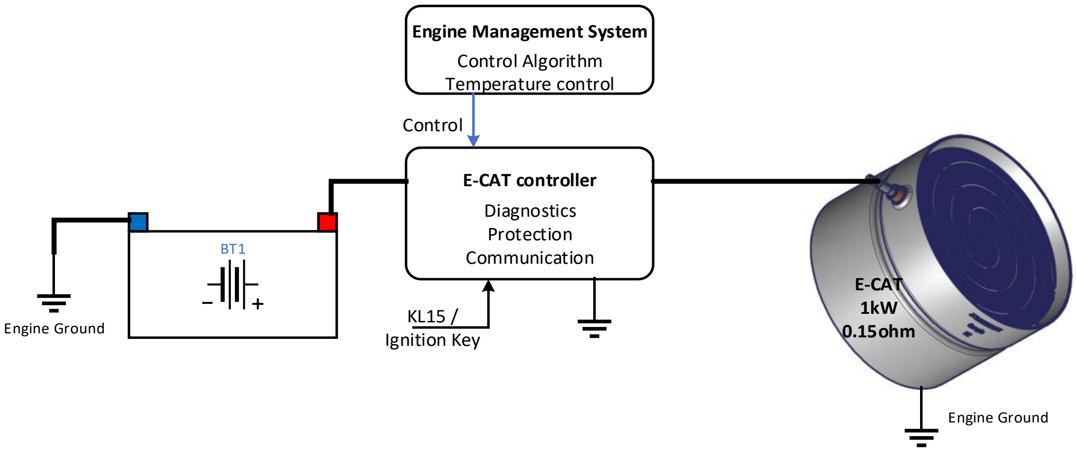

Figure 9 E-CAT system overview

First, the requirements for the circuit are clearly defined. These are composed of electrical parameters, control circuits, fault protection and diagnostic, self-diagnostic, operation modes and operation environment (electrical and mechanical).

The block diagram for the E-CAT heater control is shown in the figure below.

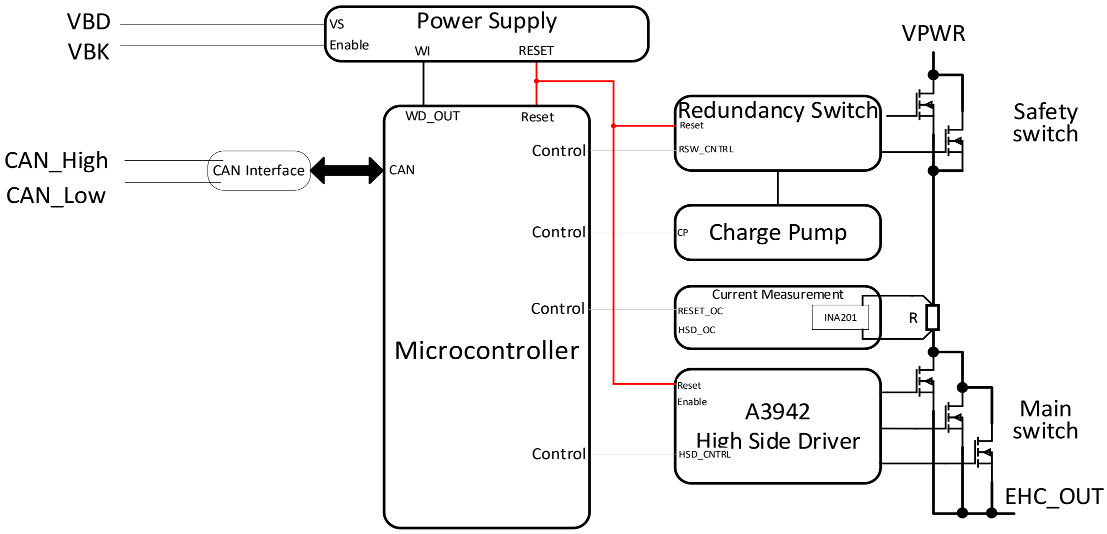

Figure 10 E-CAT controller

The circuit is built around a microcontroller, which controls two sets of switches – safety switch and main switch. It measured the output voltage and current for diagnostic. The safety switch offers a redundancy path to turn-off in case of a main switch failure. The safety switch is usually turned on all the time, while the main switch is used for PWM control.

For evaluating the viability of the design, a power dissipation estimation is made, followed by a thermal simulation. Two scenarios are considered, and the power dissipation for the main components is calculated based on the operation conditions and component specifications. Total power dissipation for the unit was calculated at 13.9W.

The mechanical design used is made of a plastic housing, PCB and a sheet metal cooling plate. The picture of the model is shown in the figure below.

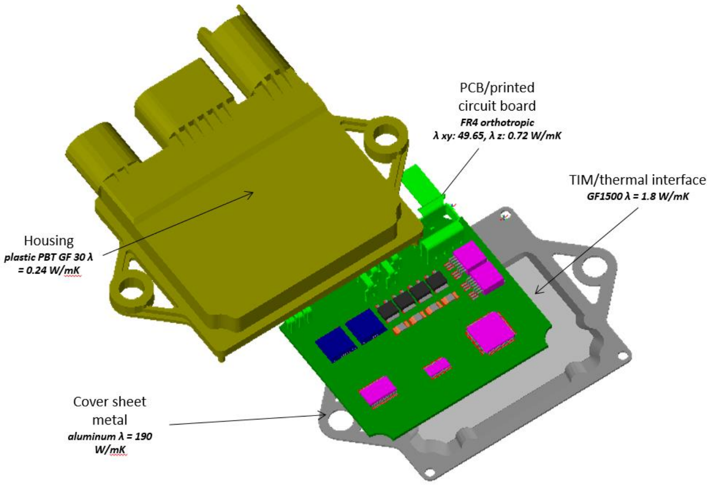

Figure 11 Thermal simulation model

To run the thermal simulation, the operating conditions, mechanical model and power dissipation are necessary. The simulation is run using Ansys, and the results prove the feasibility of the design.

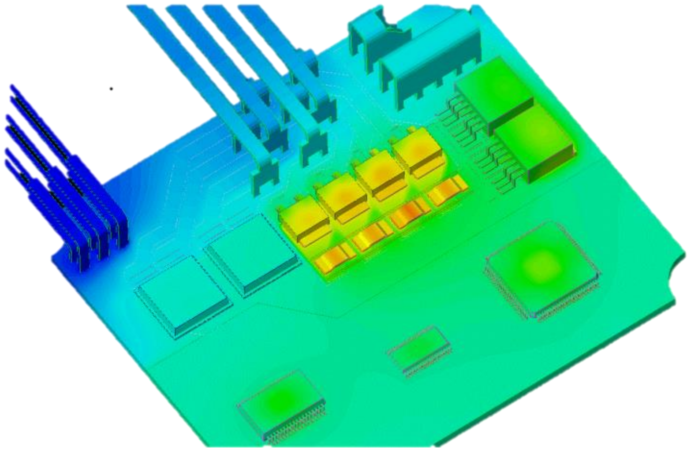

Figure 12 Thermal simulation for E-CAT1 controller, scenario 1

Once the feasibility has been proven, the design of each subcircuit is presented.

Safety switch control circuit was design based on a set of 2 AUIRF1324S-7P MOS transistors. These transistors are driven by a push-pull circuit supplied from a charge-pump. In case the charge-pump voltage drops below a specified voltage, the transistors are turned off.

The current Measurement & protection circuit detects an overcurrent flowing through a shunt resistor. INA201 is used for current measurement. The design for the shunt resistor is made in such a way that power dissipation has to be limited, and it should offer enough voltage drop for the operational amplifier to sense. The final resistor is made out of 3 resistors of 1mΩ. A special PCB layout is made to minimize measurements error. The total current measurement error is calculated to +6.08% -6.04% at 100A.

The main PWM switch uses 3 transistors, as these transistors will also get the switching power dissipation. A3942 circuit is used to drive the transistors.

In case of a short-circuit presented on the output, an analysis is made to assure that all the components on the line can withstand the short-circuit pulse. The duration of the short-circuit pulse is calculated based on a worst-case short-circuit load (equivalent of 1meter 50mm^2 copper wire), and the reaction time of the protection circuit. The current will rise up to 176.2A until the protection circuit will interrupt the current. It is shown that all the components can withstand the short-circuit pulse.

Further, the layout of the complete unit is described. Special care was taken to assure a smooth path for the high current. The layout is integrated with the unit housing.

Once the unit is built, a set of tests are made to prove its function. Electronic tests show that the performance of the circuit is in line with the initial design requirements. More details are available in the thesis, including oscilloscope plots with normal operation, turn-on and turn-off characteristics. Thermal measurements are made to verify the heating-up of the product. These confirm the thermal simulation, and prove the capability of the design.

At the end of this subchapter, two additional improvements are presented. The first improvement is to use powerline communication for the EHC [5.20]. In doing this, the number of connectors can be reduced, thus decreasing the cost of the product. Second improvement is related to cooling SMD components [5.18]. The proposed idea is to extend the heatsink through the PCB, such that the thermal contact from the component heatsink case is made directly through the thermal interface material. Using this solution, the SMD component can be better cooled.

The subchapter ends with an overview of my own contributions.

5.2 For 48V systems / mild hybrid – Switch

As of today (2021), no solutions in serial production for EHC control are available for 48V system. One of the big advantages of the 48V system is that higher heating powers can be achieved, shorting the time to reach the catalyst light-off. This in turn reduces the cold start emissions.

The operation of the switch circuit is analyzed. Due to the wide voltage range possible on the 48V system (ranging from 36V to 54V for operation as per VDA320), the power of the unit varies widely, from 3.2kW to 7.29kW, while the instantaneous current will vary between 90A and 135A.

Further, the problems associated with this solution are analyzed. Activation and de-activation of the switching element produces transient pulses on the supply linewhich can be outside of the voltage range specified in the VDA320 norm. A lean turn-on and turn-off can be implemented in the switching element, but in this case the energy dissipated on the switching element is extremely high (calculated up to 100Joules). Another problem associated with this solution appears if the battery level is low, in which case the BSG is charging the battery. Any connection / disconnection of a high-power load on the 48V line will have a direct impact on the torque delivered by the internal combustion engine. This will have an impact on the speed and acceleration of the vehicle, which is not desirable. By using PWM to connect and disconnect the EHC, the life-time of the 48V battery is diminished.

The conclusion of this part is that a device needs to slowly turn-on and turn-off of the EHC.

The first idea presented is to use a control which contains a DC/DC converter to control the EHC. The block diagram of the proposed solution is shown in the figure below.

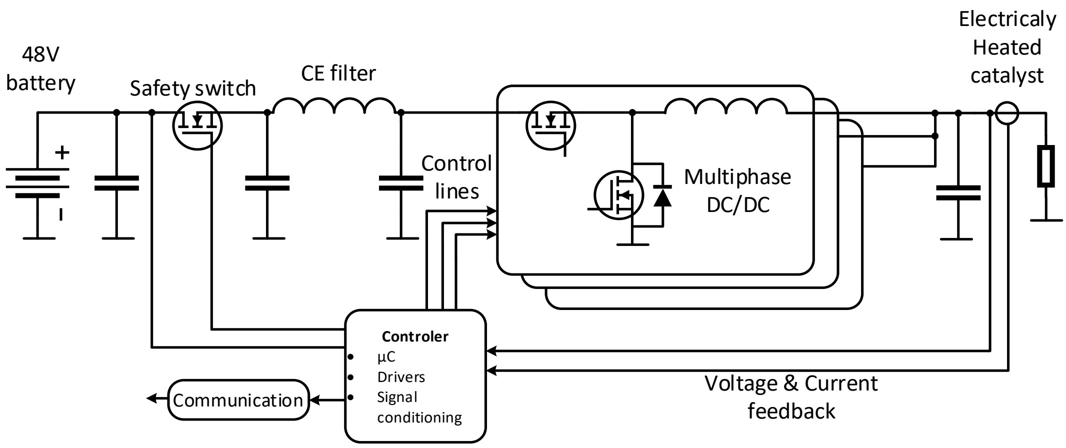

Figure 13 Controlling the EHC through a multi-phase DC/DC converter

The system contains a safety switch, with similar functionalities as the above presented 12V system. A conducted emission filter is necessary to reduce the noise created by the DC/DC switching. The multi-phase DC/DC controller will modulate the power necessary for the EHC, allowing for smooth turn-on and turn-off transitions.

For this system, a potential disadvantage is that even with a high efficiency DC/DC converter, during on time the power loss can be substantial – up to 160W.

To compensate for this, a second idea is presented, where a parallel switch is present parallel to the DC/DC converter. The block diagram for this circuit is shown below.

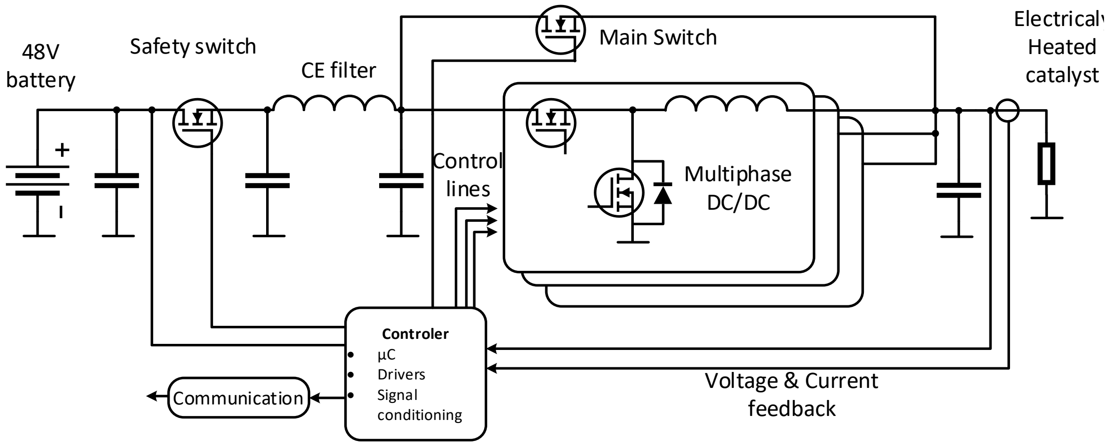

Figure 14 Multi-phase DC/DC converter in parallel with a switch

In this topology the DC-to-DC converter is used only during ramp-up and ramp-down, and the main switch is used to flow the current during maximum operation of the DC/DC.

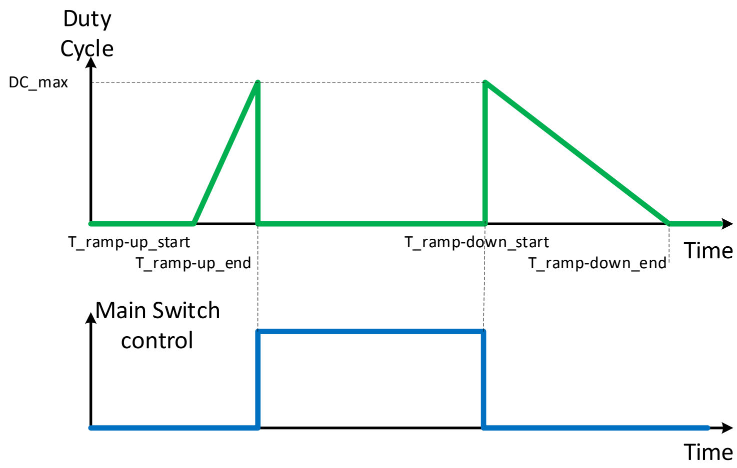

Figure 15 Using a DC/DC controller to ramp-up and ramp-down, and a main switch for the continuous operation of EHC

By using this concept, the DC/DC converter can be minimized by designing it to withstand only the transient turn-on and turn-on cycles.

This concept is further analyzed. First, a proof-of-concept simulation is made to better understand the circuit. A 2-phase DC-to-DC converter is used. As the simulation result is looking promising, the next step is to define the requirements for circuit design. Once these are fixed, the following step is to design each sub-circuit.

For the multi-phase DC-DC converter, the inductor value is analyzed based on the inductor current and operation frequency. Three inductor values are analyzed on different currents and switching frequencies. An inductor with a value of 1µH is chosen that will operate at 260kHz. Furthermore, an analysis of how the coil inductance is changing with the current is made, as this can impact the operation of the converter. A method is presented to calculate the DC/DC inductance current out of the datasheet graph plotting inductance vs current. The method is applied for the selected inductor – Wuerth 7443640100B coil – showing that it can be used for this design.

The switching transistors used are GS61008P from GaN systems. This new type of transistors offers possibility for a very fast turn-on and turn-off.

As in the previous design, the power dissipation of the main components is calculated. Altough the operation of the DC/DC is transient, the maximum power operation point is used for calculation of the power loss of the D/DC. The losses in the coil are calculated to 1.45W. For the switching transistors, each phase of the switching cycle is analyzed, resulting in a switching loss of 21.11W for the high-side transistor, and 17.44W on the low-side transistor. This means that the theoretical efficiency of the converter can reach 98%.

For the Main switch and Safety Switch design, a set of two IASU300N08S5 transistors from Infineon are used. The current flows through these transistors during steady-on operation of the circuit. The power losses in this case are 8.47W per transistor.

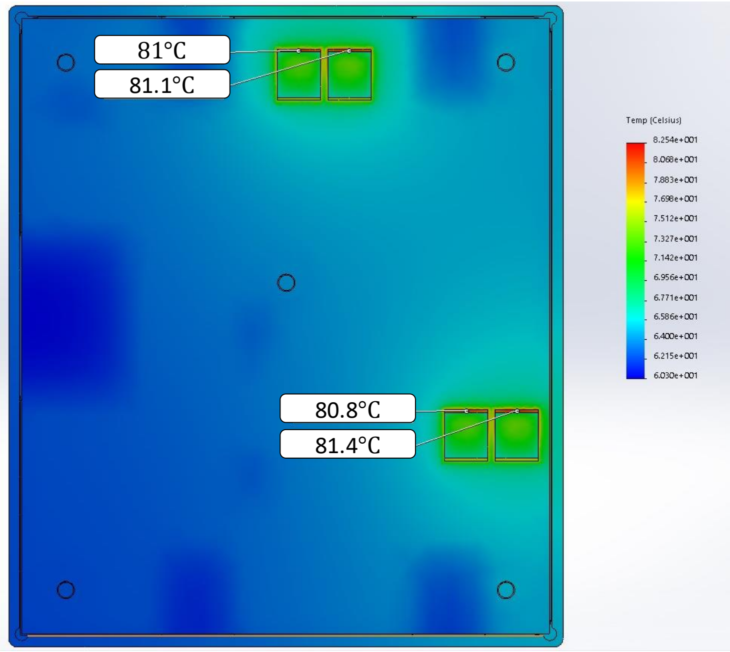

Figure 16 Operation mode 2, Steady-state operation, MOS transistor die temperatures

Having the power losses calculated, a thermal simulation is made. Both transient (DC/DC operation) and steady-state (main switch operation) are analyzed. The thermal simulation is showing that the components are well within their specified temperature. In the figure above it can be seen the simulation result for the steady-state operation.

The design of the conducted emissions filter for the DC/DC EHC controller is further presented. The requirements for the filter design are described, specifying that the circuit would need to pass CISPR-25 Class 2 emission standard. A filter design procedure is presented, in which the initial current shape and the measurement circuit are defined. Circuit simulation has to prove the filter characteristics. A number of iterations are made until the filter meets the design targets.

Following the proposed design procedure, the first step is to define the signal which requires filtering. As the DC-DC converter operates in a transient mode, in which the duty cycle is changing, the current that has to be filtered is also changing. In the performance of the filter is analyzed based on the current shape in six time points. The shape of the current in these six points is shown.

Next step in the design procedure is to create a simulation model. The transfer function of the measurement circuit is calculated, taking into account the influence of the measurement setup and that of the LISN (Line Impedance Stabilization Network). Two topologies are analyzed - 3rd order and 5th order filters. Their equivalent transfer functions are determined, and used for the simulation. A simulation is run to understand how the conductive emissions will look without a filter. Results of the simulation are shown in the figure below.

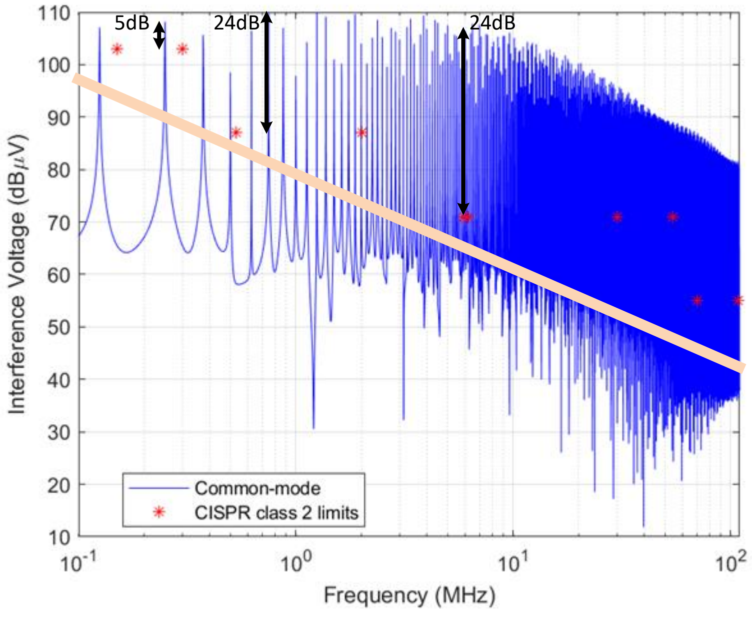

Figure 17 CE Emissions without filtering for current at 25ms, and with how much they are over-passing the limits.

This shows that a filter with an attenuation of 20dB/decade, with the cut-off frequency lower than 100kHz can reach the design targets.

The implementation of the filter uses shielded power inductors and ceramic capacitors. Simulations are run with both the 3rd order and 5th order filter, using nominal values for the components. This shows that the performance of the filter is nominal.

However, it is shown that the real components chosen – capacitor TDK CKG57NX7S2A226M500JJ [5.35] and coil 7443082015 from Würth – have different parameters in usage. The capacitor value is strongly dependent on the DC bias voltage and temperature, while it's ESR is depending of the measured frequency. As previously shown, the coil inductance depends on both the temperature and current passing through it.

Factoring into the simulation the real components values, the performance of the filter changes significantly, and it is not fulfilling initial design targets. An iteration is made with updated component values, and the implementation of the final filter design is shown. The final filter implementation takes into account real component parameters.

The implementation of the 48V EHCC controller is made around an FPGA module using the Lattice ICE40LP9K. The block diagram of the unit is presented in the figure below.

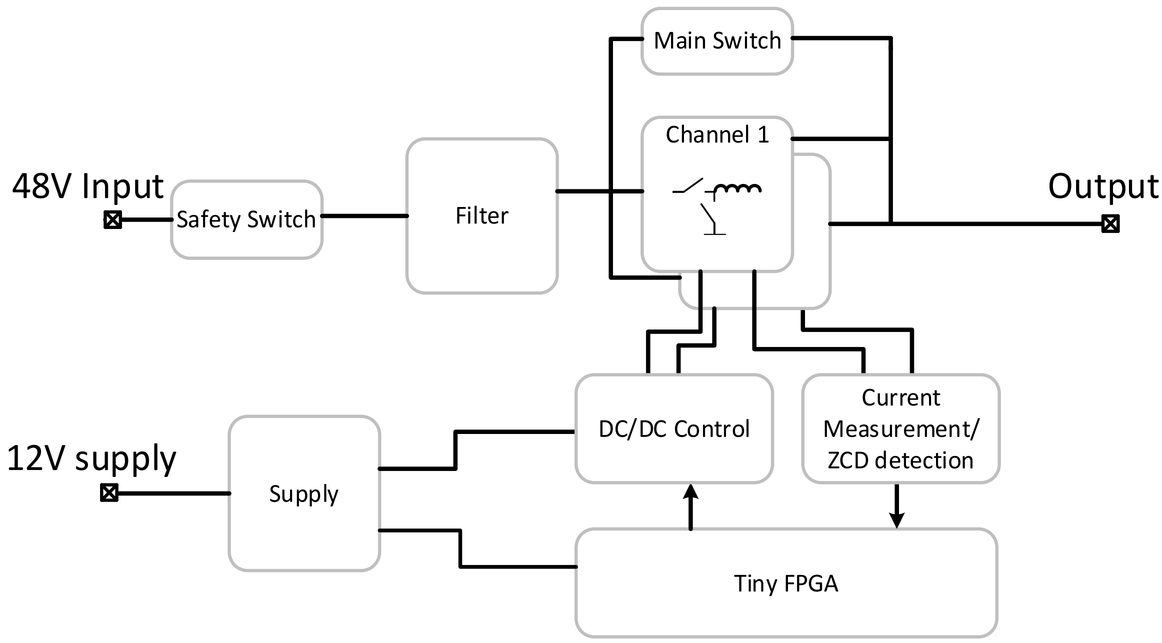

Figure 18 Circuit Block Diagram

The supply circuit generates a 6V supply for the GaN transistor drivers, a negative -2.495V for the analog comparators and preemptive ZCD circuit, and 5V and 3.3V for the logic supply. The current measurement circuit uses a lossless current measurement method, where the voltage drop over the coil is measured. The inductance of the coil is compensated by using an R-C circuit before the INA240A1 current measurement circuit.

During operation, it is expected that the current between the two phases of the DC/DC converter can become unbalanced. To prevent this, a balancing circuit is proposed. The RMS current value on each inductor is measured, and compared to each other. This is feed back to the FPGA circuit, such that it can compensate the imbalance by slightly modifying the duty cycle for one phase.

During Discontinuous Current Mode operation, the low side transistor operation could decrease the efficiency of the circuit by operating when the current decreases below 0A. To prevent this, a Preemptive Diode Emulation Detection circuit is designed. The Voltage drop over the low-side transistor is measured and compared with a negative voltage threshold of -100mV. This signals to the FPGA circuit that the low-side transistor needs to be turned off. Operation of the preemptive diode emulation circuit is shown in the figure below.

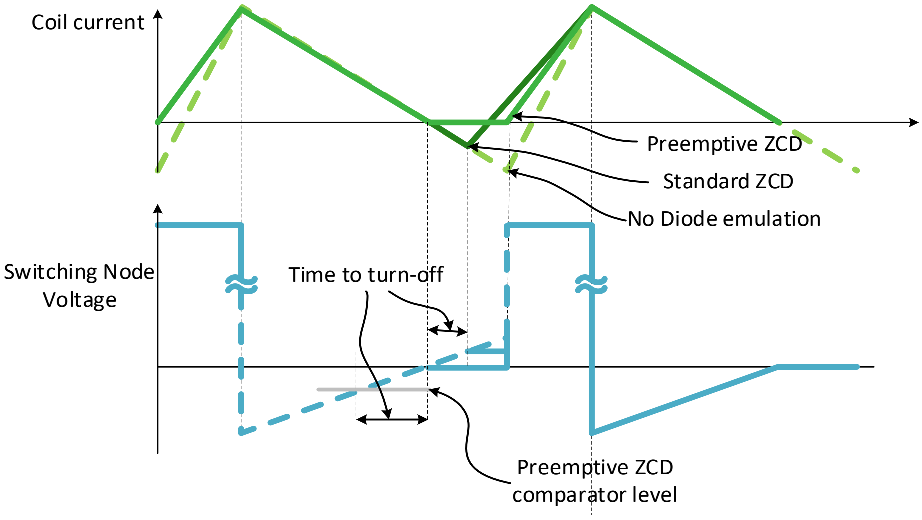

Figure 19 Preemptive diode emulation operation

A special driver circuit for GaN transistors is used – LMG1205. Special care needs to be taken on the layout design for this circuit, due to the high speeds used.

Several considerations are taken into account for the Layout design: Interconnection technology, Copper trace current capabilities, EMC considerations, Thermal constraints, Testability and Technology used. The high current connections are made through a set of Wuerth power elements. The placement of the components was made in such a way that the current path for every operation scenario is as short as possible. In this regard, both transient and Steady state operation are considered. Special care was taken to allow the copper traces to have sufficient width for such high currents. The thermal connections of the main switching transistors were already proven by thermal simulation.

The board was implemented into a 4-Layer design, on FR4 PCB of 1.6mm width technology with 70µm copper. Special care was taken for the high frequency signals for driving the GaN transistors, assuring low impedance path for both charging and discharging the gate capacitance. The current measurement signals were shielded by a GND guard ring, and both the layers above and below were GND.

The filter components were arranged in such a way that there would be no cross-talk between the different filter sections. A 3-D picture of the designed board can be seen in the figure below.

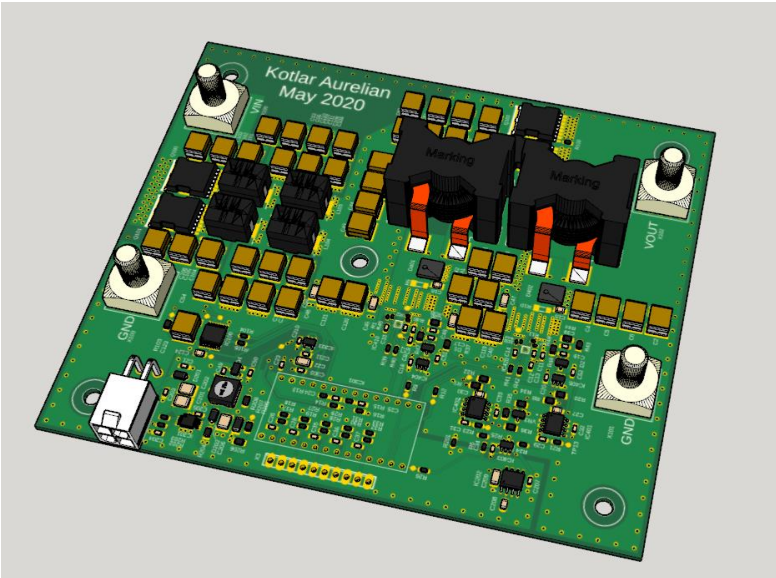

Figure 20 Implementation of the filter on the PCB

The mechanical Housing design was made such that it assured easy manufacturability. Pockets holes for cooling GaN transistors were provisioned, while the overall PCB was cooled by a gluing the board with a Thermal Interface Material to the housing. A cross-section through the housing can be seen below.

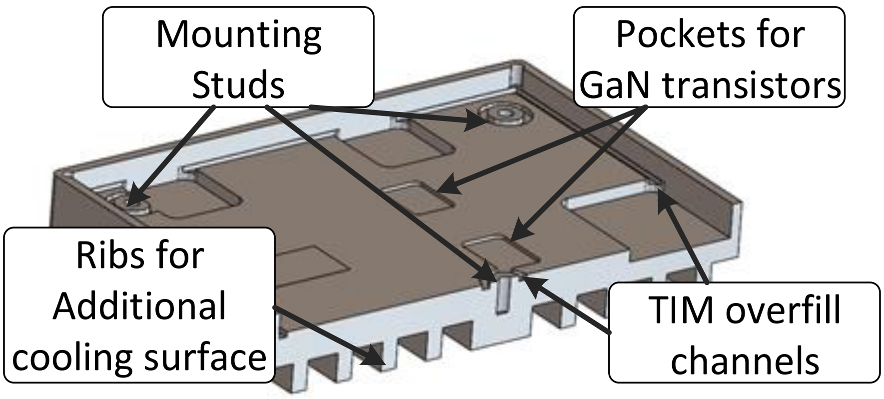

Figure 21 Housing features

Finaly, the picture of the final product is shown in the figure below.

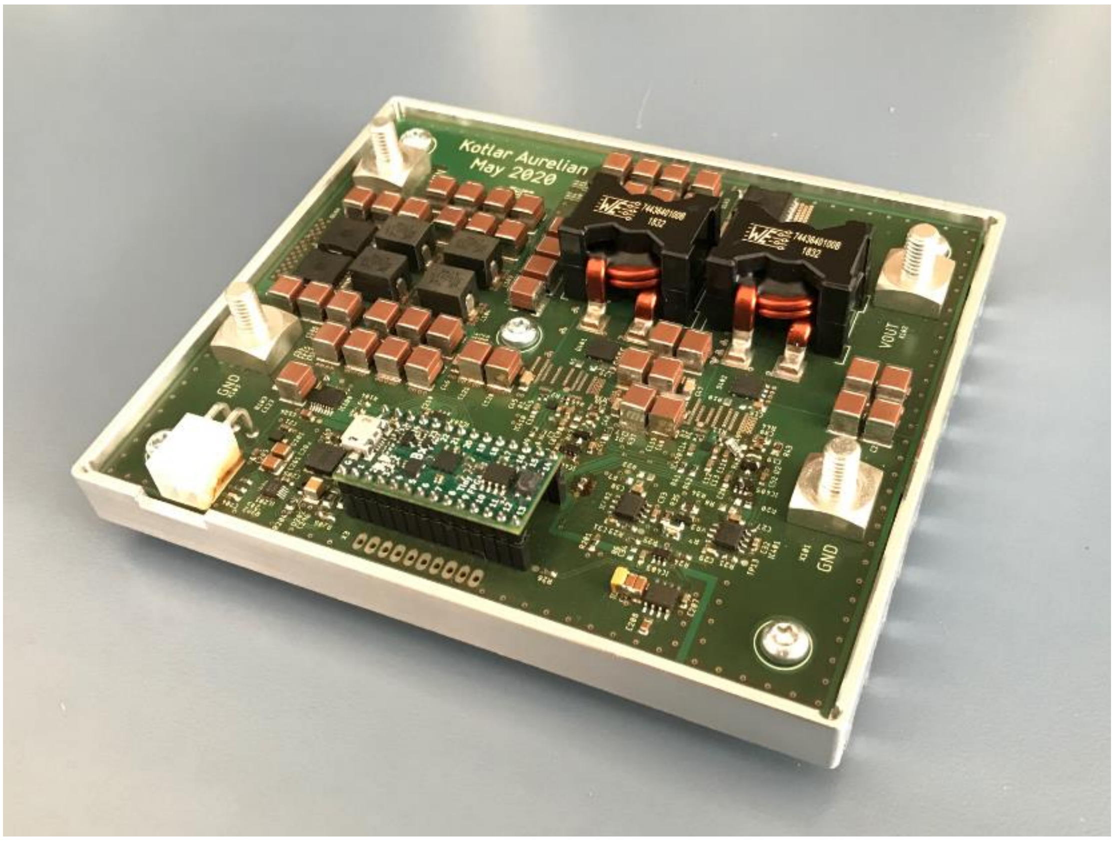

Figure 22 EHC for 48V with DC/DC converter and a parallel switch – product picture

Chapter 6
Conclusions

The technology of electric heating of the catalyst has a potential to reduce emissions in Automotive passenger vehicles. This is accentuated for the mild hybrid vehicles, with a 48V battery.

6.1 General conclusions

As the catalyst has to be heated with high power, the control of the EHC is a non-trivial task. The power ranges vary from 1kW for 12V systems to 7kW for 48V systems.
For the systems with EHC supplied from the 12V battery, a simpler controller can be used. For the control of the EHC supplied on the 48V boardnet, a special controller with a DC/DC converter is needed, especially for the turn-on and turn-off.
For high power electronics, calculation of power losses and initial thermal simulation is important to check the viability of the design.

Real component behavior needs to be taken into account during design phase. There are several examples: coil versus current in DC/DC design; DC Bias characteristics for MLCC. This was considered for both the DC/DC converter design and for the CE filter design.

PCB design has to be carefully made, especially for the parts carrying high current and high switching frequencies.

6.2 Obtained results

During my PhD I have built samples for both the 12V system and the 48V system EHC controller. I have authored and co-authored 5 articles related to the PhD, and I was a supervisor for one diploma Thesis. I have three international patents granted for the work presented in this thesis.

6.3 Further research

For the 48V systems, additional development would be necessary to further increase the efficiency of the overall system.

Another area of research is the supply of the EHCC from a voltage higher than 60V. Due to the isolation requirements, an insulated step-down converter is needed.

Chapter 7
Overview of own contributions

In this chapter, a final list of all the contributions that I had in this research area is presented. This is not further presented in this summary.

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