MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE400 – SUMMER PRACTICE REPORT

Student

Name: Göksenin Hande Bayazıt

ID Number: 2093441

Summer Practice

Company: AVL Research and Engineering

Department: Software & Electronics

Date: 19/06/2017 – 22/09/2017

Supervisor

Name: Elif Pınar Kesik

E-Mail: pinar.kesik@avl.com

Phone: +90 216 498 7950

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I.   INTRODUCTION

I have performed my third year summer practice (EE400) at AVL Research and Engineering, which is the office in Turkey of AVL List GmbH, one of the world's leading companies in the automotive industry that produces engineering solutions, design and consultancy. I had a 13-week-long internship which started on June 19, 2017 and ended on September 22, 2017. My supervisor during the summer practice was Elif Pınar Kesik, a senior electronic hardware design engineer in the Electronic Hardware Design Team of the Software & Electronics Department.

Software & Electronics Department consists of mainly six teams: Engine Controls, Transmission Controls, Hybrid Electric Vehicle (HEV) Controls, Vehicle Controls, Electronic Hardware Design and Basic Software. I was in Electronic Hardware Design Team but as of august, I also supported the projects of HEV Controls Team.

During my summer practice, I learnt lots of things (both technical and non-technical). Topics I have dealt with and work I have done includes designing DC-DC converters (one buck-boost and one boost), PCB design, efficiency simulation and data analysis, electronic circuit simulations and tests. Besides those, I was also given several little duties such as developing parts of algorithms, doing some calculations of electrical circuits.

In this report, most of the things that I have done and learnt during my summer practice are included. Some are not included as they are confidential information in the company. The report starts with a brief description of the company with necessary information. In the main part of the report, the designs that I have made, their procedures and simulation results, some of the algorithms that I have developed are included. Finally it is concluded with a summary of the explanations and also an appendix with a reference list is present.

II.   DESCRIPTION OF THE COMPANY

1. COMPANY NAME

Global: AVL List GmbH

Local: AVL Research and Engineering Ltd.

   (Turkish: AVL Araştırma ve Mühendislik San. Tic. Ltd. Şti)

2. COMPANY LOCATION

AVL is a global company originated in Graz, Austria.

AVL has two facilities in İstanbul: AGM-2, where I have performed my summer practice, and AGM-1.

- <u>AGM-1:</u> AVL Research and Engineering Turkey HQ

Akpınar Mahallesi Tuna Caddesi Ballıca Sokak No: 1 34885 Sancaktepe, İSTANBUL
Phone: +90 216 498 7950
Fax: +90 216 498 7956

- <u>AGM-2:</u>

Abdurrahman Gazi Mah. Atatürk Cad. ByOffice No: 22 Kat: 6 34920 Sultanbeyli, İSTANBUL

Tel: +90 312 210 18 57-58
Fax: +90 312 210 18 57-58

3. GENERAL DESCRIPTION OF THE COMPANY

a. ORGANIZATIONAL STRUCTURE

The company consists of three main departments: Mechanical Design, Software – Electronics and Calibration. The organizational structure of the company is indicated in Figure 1.
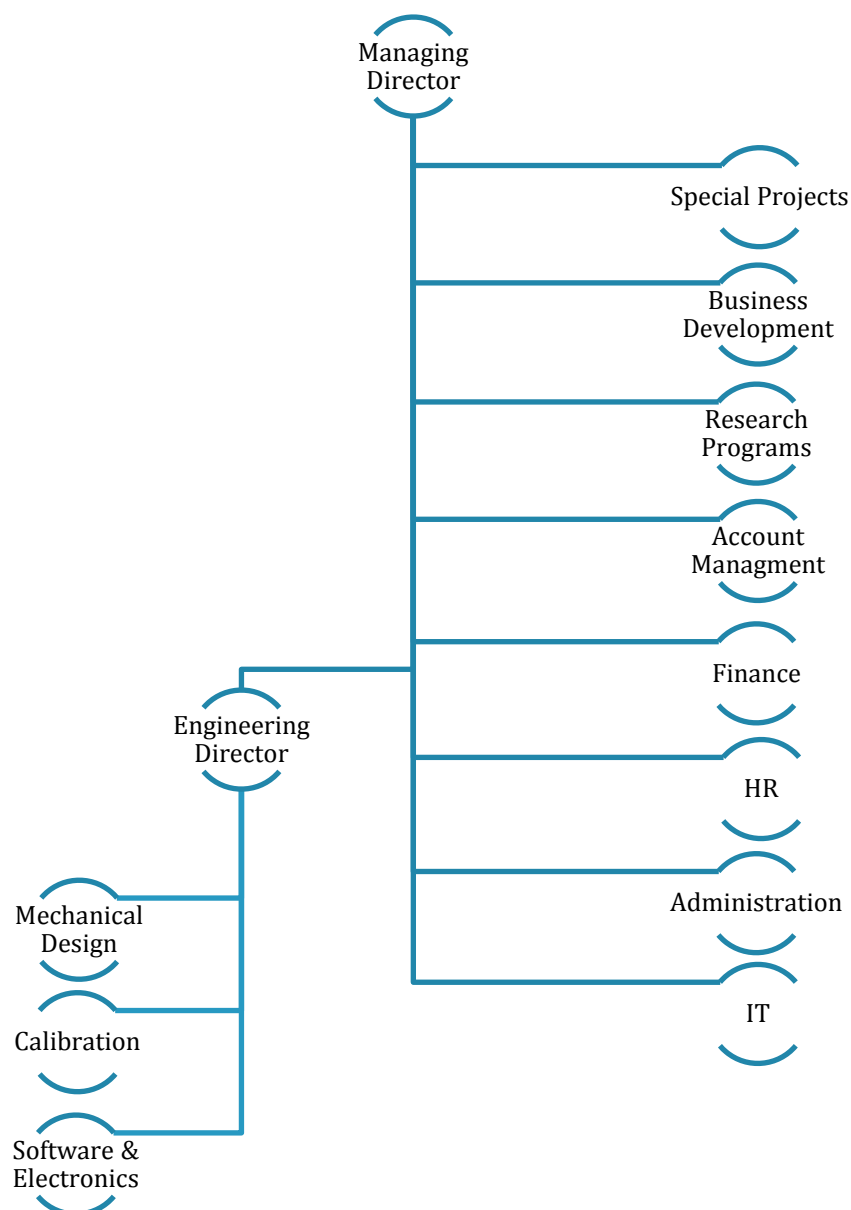

Figure 1: Organizational Structure of the Company

b. NUMBER OF EMPLOYEES

By the end of August 2017, there are more than 140 employees, where more than 100 of them are engineers (mostly electrical, electronics, mechanical, computer, control systems engineers).

c. MAIN AREA OF BUSINESS

i. AVL Global

AVL is the world's largest independent company for the development of powertrain systems with internal combustion engines as well as instrumentation and test systems.

AVL is active in the following areas of business:

- **Powertrain Engineering**

AVL Powertrain Engineering is an expert partner to the global automotive and mobility industry for the development of innovative powertrain systems. From diesel engines to electric drives, from alternative fuels to control software, from transmissions to batteries, we have been working in partnership with companies all over the world for more than 60 years. Unique synergies with AVL Instrumentation and Test Systems and AVL Advanced Simulation Technologies enable the development of highly creative, mature and application-specific solutions for our customers in order that they meet their future market challenges.

- **Instrumentation and Test Systems**

The need for CO_2 reduction, the increasing complexity of new powertrain systems, and a requirement to achieve the highest possible level of process efficiency - along with

the need to quickly launch new models - are some of the key challenges facing the automotive industry now and for the foreseeable future.

- **Simulation**

Powerful multi-dimensional simulation platforms developed on the basis of AVL's engineering knowledge guide you to practical, application oriented solutions.

AVL is providing a set of comprehensive simulation tools in a flexible and open environment enabling multi-disciplinary solutions as integral part of your powertrain development process. Fully validated state-of-the-art physical simulation models embedded in application specific simulation methods enable virtual prototyping on component and system level for most efficient combination of simulation, design and testing.

ii. AVL Turkey

AVL Turkey was established in 2008 to provide advanced technology engineering solutions for domestic and international companies in the automotive, defense industry and transportation sectors. AVL Turkey team, consisting of more than 100 engineers more than half of whom have been trained at master and doctorate level and has international experience, has extensive experience in field experience with many domestic and international projects for serial production. They are working on the development of various intelligent control system algorithms, such as internal combustion engine (ICE) design, ICE calibration, control of exhaust gas processing systems, automatic transmission control, electric vehicle control, battery management systems, hardware and software of electric motors and drives.

iii. Departments of AVL Turkey

- **Software & Electronics**

AVL's globally recognized department of software and electronics with its expertise, is developing control systems for internal combustion engines, gearboxes,

electric motors, batteries and control systems for hybrid and electric vehicles. The department has a wide range of knowledge and experience on system level analysis, simulation, identification of requirements, algorithm and software development, design of electrical and electronic hardware equipment, testing of real-time simulators (HiL) for approval of designs. An important part of the dynamic and flexible team consisting of more than 70 experts has international training and work experience.

- **Mechanical Design**

Design Department of AVL Turkey, offers advanced engineering solutions with expert staff working on the design and analysis of internal combustion engines, gearboxes and power transmission systems. With AVL's 70 years of experience, it is able to combine the best designs with the latest technologies for the different needs of the customers. Design teams work on a wide range of products ranging from automobiles to trains, tractors to ships, provide local support to producers around the world, and compete in competitive projects. In today's conditions where emission regulations are tightened and fuel consumption becomes more and more challenging day by day, using AVL's product development know-how and methodologies, it can produce faster and clearer solutions.

- **Calibration**

Calibration Department of AVL Turkey is Turkey's pioneer in diesel engine calibration, working in partnership with the world's leading engine control unit providers, working in a wide range of projects ranging from light and heavy duty trucks to road and ground vehicles. With its extensive portfolio of local and global producers and international training and experience, Calibration Department provides solutions for emissions and fuel economy, performance and driving development, and integrated

diagnostic enhancement. The team is also increasing its quality of the work with a facility where the motor, power line, chassis tests and virtual tests can be conducted.

4. BRIEF HISTORY OF THE COMPANY

1946   Prof. Dr. Hans List started up as an independent engineer.

1948   A team of diesel engine construction experts headed by Prof. Dr. Hans List got together to set up IBL ("Ingenieurbüro List" or List Engineering).

1951   IBL became AVL - "Anstalt für Verbrennungskraftmaschinen", Prof. Dr. Hans List (or Institute for Internal Combustion Engines).

1960   AVL initially became involved in engine instrumentation for its own purposes, manufacturing such instruments as quartz pressure transducers, monitoring and control units, instruments for engine indicating etc. So it was that the group's second division - AVL Engine Instrumentation - was born.

2007   AVL introduces the i60 series of Emission measurement systems. Setting a new industry standard in usability, accuracy and reliability.

AVL expands electronics portfolio: With the newly tailored „Powertrain Software Strategy" AVL is looking to increase their focus on the area of calibration software for powertrain control units which includes for example engine, transmission, hybrid and exhaust gas after-treatment control.

AVL takes over Le Moteur Moderne. As a local contact for the French automobile industry, LMM will represent the global AVL engineering network and will also integrate services from the global tech centers of AVL.

2008   AVL amplifies its activities in the fields of application and software development in Germany and founds the wholly owned subsidiary "AVL Software and Functions GmbH" in Regensburg.

AVL presents its new image: kaleidoscope pictures which are intended to symbolize the unique business of AVL and a new logo guarantee a new strong brand image of the globally present company.

60 Years of Innovation: Providing an essential and continuous contribution to the developments in the automotive industry on the basis of technical innovations, that characterizes the high-tech company AVL for the previous 60 years.

III. WORK CONDUCTED AT AVL

1. DESIGN OF A DC/DC CONVERTER

Automotive manufacturers increase the electrification in vehicle powertrains in the form of hybrid electric vehicles and electric vehicles. As the vehicles with these type of architectures are based on high voltage battery systems, the number and need of switched mode power supplies have also increased further, compared to the vehicles with conventional powertrains.

One of the projects that I was involved in was the design and manufacturing of a device that can be connected between the Engine Control Unit (ECU) and the battery of a vehicle which can simulate the possible failures of the battery (e.g. short circuit and open circuit cases between different channels of the ECU).

As the device is between two buses with different voltage and current levels (and also, as the different subsystems of the device operate with the different voltage and current levels), numerous switched mode power supplies (SMPS) are needed to be used. One of those necessary SMPS's is the one with the following specifications:

- 9-36 VDC input voltage range
- 24 VDC output voltage
- 5 ADC output current
- 120 W output power
- High efficiency
- Compatibility with automotive standards

Because of the limited time due to the schedule of the project, a DC-DC converter module which can be seen on Figure 2 and whose datasheet is accessible by the link given

in References is bought. However, as buying these modules is costly, I was given the task of designing a DC-DC converter which has the same specifications.

Figure 2: DC-DC Converter, RSD-60G-24

To satisfy the given requirements, a buck-boost converter topology had to be used obviously, as the input voltage range is wide that it can be both below and above of the output voltage. For an SMPS design, heating and cooling is an important issue and as the voltage and current ratings of the buck-boost converter that I had to design should be quite high, efficiency also had to be as high as possible. For that reason, I decided to use a four-switch buck-boost converter topology. [1]

Four-switch buck boost converter is a synchronous converter. In this topology, two additional MOSFETs are used instead of freewheeling diodes. The lower voltage drop of the power MOSFET compared to the power diode enhances the efficiency as it decreases the power dissipation, which makes this topology more preferable compared to a conventional one unless the cost of the design is an issue.

a. Operation

For the sake of completeness, basic operation principles of a buck-boost converter can be explained as below [2].

In power converters, conservation of the energy principle is used and the electrical energy is stored on the inductor of the circuit. When the switch is open, the inductor stores energy from in the form of magnetic energy and discharges it when switch is closed. The positions of the switches and their duty cycles define their characteristics (whether it is a buck or boost converter and the output voltage).

Basic topology of a buck-boost converter and its voltage and current waveforms in buck and boost regions are provided on the Figures 3, 4 and 5 below.
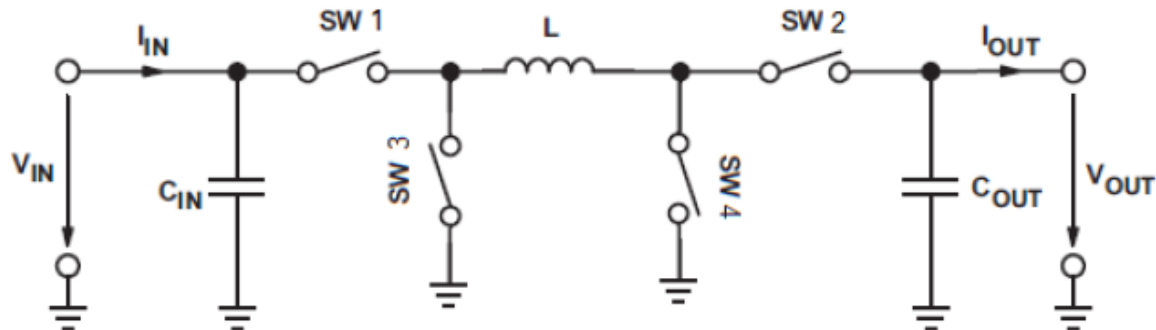
Figure 3: Buck Boost Converter Circuit Topology

In conventional topologies, SW1 and SW4 are MOSFETs where SW2 and SW3 are diodes. However in the design that will be explained later on, all four of them are MOSFETs.
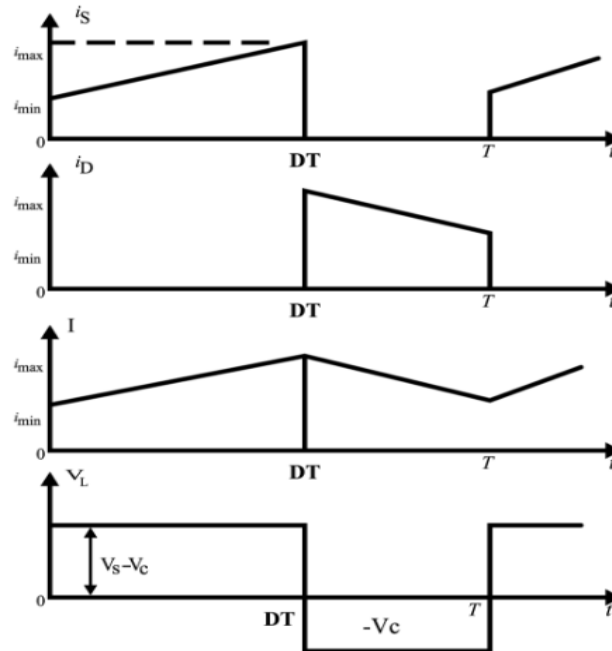
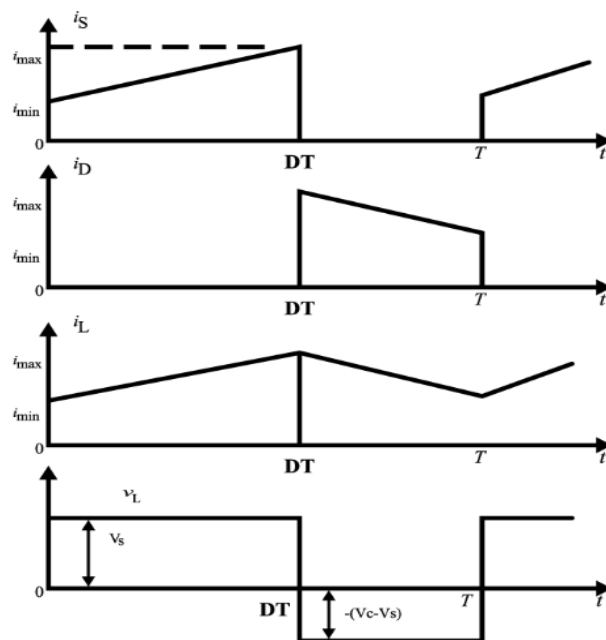*Figure 4: Voltage and Current Waveforms of Buck Operation*

Figure 5: Voltage and Current Waveforms of Boost Operation

b. Design Specifications

The converter that I had to going to design would be used in real life applications and it would be printed on a PCB. Therefore, calculating the inductance, capacitance and the values of the other primary elements in the main topology would not be sufficient for the design. For that reason, I started my design by choosing an appropriate microcontroller. LT8390 [3] was quite convenient due to its compatibility with four-switch buck boost converter topology, its high efficiency, wide input voltage range and high output current capability. Unfortunately, a solution with that chip would be costly (since the products of Linear Technology are more expensive and four MOSFETs are needed). However as LT's controllers are included in the library of LTspice, one can get more accurate simulation results, which improves the reliability of the design.

In order to make an accurate and reliable design, the following specifications had to be determined:

- Switching frequency selection
- Inductor selection
- R_{sense} selection
- MOSFET selection
- C_{in} and C_{out} selection
- Input & output current limit and UVLO limit
- Feedback
- Power dissipation and efficiency calculations

i. Switching Frequency Selection

The switching frequency of the circuit is adjusted by the internal oscillator of the controller. With a resistance connected to the RT pin of the LT8390, the oscillation frequency of the circuit can be set. This resistance can be determined by the values given on the Table 1 given below which is retrieved from the datasheet of the controller.

Table 1: Switching Frequency vs. Resistance

f_{OSC} (kHz)	R (kΩ)
150	309
200	226
300	140
400	100
500	75
600	59
650	51.1

Selecting the switch frequency has a trade-off: Switching frequency determines the inductance value and also it affects the switching losses. High switching frequency results in low inductance and capacitance values (hence smaller inductors and capacitors) however it causes a significant increase in the switching losses. For a lower frequency, this case is vice versa.

As high efficiency is an important requirement of my design and dimensions of the overall circuit is not an important issue, a lower switching frequency is more preferable.

I chose the switching frequency as 150 kHz and the resistance connected to RT around 300 kΩ (with 1% tolerance).

ii. Inductor and R_{sense} Selection

As the inductor is the main element that stores the energy, its value is directly determined by the current and voltage characteristics of the converter. Inductance value can be calculated for buck and boost operation modes differently by the given equations Eqn. 1 and 2 below.

$$L_{buck} > \frac{V_{out} * (V_{in,max} - V_{out})}{I_{ripple\%} * f_{sw} * V_{in,max} * I_{out}} \qquad Eqn.\,1$$

$$L_{boost} > \frac{V_{in,min}^2 * (V_{out} - V_{in,min})}{f_{sw} * I_{ripple\%} * I_{out} * V_{out}^2} \qquad Eqn.\,2$$

$$L_{buck} > \frac{24 * (36 - 24)}{0.8 * 150000 * 36 * 5} = 13\ \mu H$$

$$L_{boost} > \frac{9^2 * (24 - 9)}{150000 * 0.8 * 5 * 24^2} = 3.5\ \mu H$$

A 15 µH inductor is suitable for this design.

R_{sense} is the resistance between inductor current sense pins (LSP and LSN) and its largest possible value can be determined using Eqn. 3:

$$R_{sense} < \frac{2 * 50 \, mV * V_{in,min}}{2 * I_{out} * V_{out} + \Delta I_L * V_{in,min}} \qquad Eqn.\,3$$

Where ΔI_L denotes the ripple current flowing through the inductor. It can be calculated as in Eqn. 4:

$$\Delta I_L = \frac{V_{in,min} * (V_{out} - V_{in,min})}{f_{sw} * L * V_{out}} \qquad Eqn.\,4$$

For this case, L=15μH and switching frequency is 150 kHz. Hence the maximum R_{sense} is:

$$\Delta I_L = \frac{9 * (24 - 9)}{150k * 15\mu * 24} = 2.5 \, A$$

$$R_{sense} < \frac{2 * 50 \, mV * 9}{2 * 5 * 24 + 2.5 * 9} = 3.4 \, m\Omega$$

A 1 mΩ resistor is suitable for this design.

iii. MOSFET Selection

Power MOSFETs of the converter should be chosen considering the convenience of their parameters with the circuit operation and topology. In this circuit, MOSFETs with low R_{DS}, high breakdown voltage, high maximum I_{DS} and low threshold voltage (V_{GS}) are needed. Also the temperature variation of the R_{DS} should not be in a wide range and the thermal resistance of the packages should be as high as possible in order to prevent the increase in the temperature with heat dissipation. Additionally, rise and fall time values should also be as low as possible in order to minimize the switching losses.

For this circuit, BSC014N04LSI [4] and BSC009NE2LS5I [5] are convenient with their

- V_{DS}= 40 and 24 V

- R_{DS} =1.45 and 0.95 mΩ

- Max. I_{DS}= 100 A

- Appx. 1.5 V threshold voltage

- Rise and fall times in ns scale

- High thermal resistance

values respectively.

iv. C_{in} and C_{out} Selection

In a converter, capacitors are used in order to eliminate the ripples to obtain more stable output and have a more stable input [6][7]. Voltage deviations across the capacitor and equivalent series resistance (ESR) of the capacitor are the main concerns while choosing them. As the aim would be obtaining high capacitance and low ESR, o combination of them may be connected in parallel.

1. Output Capacitor

The minimum impedance of the capacitor (including ESR) should be larger than the ratio of the output voltage ripple and current ripple in order to be able to filter the current. Necessary output capacitance value can be calculated with the following formula (Eqn. 5):

$$C_{out} = \frac{I_{rip} * \frac{1}{f_{sw}}}{V_{rip} - (I_{rip} * ESR)} \qquad Eqn.\, 5$$

For I_{rip}= 2.5 A, 150 kHz switching frequency and V_{rip} = 100 mV:

$$C_{out} = \frac{2.5 * 6.67\mu}{0.1 - (2.5 * ESR)}$$

470 μF capacitors with approximately 50 mΩ ESR connected in parallel satisfy this condition.

2. Input Capacitor

For a similar condition with the previous case, 220 μF capacitors with approximately 50 mΩ ESR connected in parallel are convenient for the design.

v. Input & Output Current Limit and UVLO Limit

To stop the operation of the converter when the input voltage is too low, under voltage lockout (UVLO) function is used. A voltage divider is connected between the input voltage and UVLO pins. UVLO is programmed with the formula given in Eqn. 6:

$$V_{threshold} = 1.233\ V * \frac{R_1 + R_2}{R_2} + 2.5\mu A * R_1 \qquad Eqn.\ 6$$

Considering that the input voltage may drop up to 6 V (even if the minimum desired operation voltage of the converter is 9 V), 220 kΩ and 65 kΩ resistors are suitable for the circuit.

For the limitation of the output current, the resistor of the current sensor should be adjusted as in Eqn. 7:

$$R_{Sense} = \frac{100mV}{I_{out}} = \frac{100m}{5} = 20\ m\Omega \qquad Eqn.\ 7$$

vi. Feedback

As the controller has a voltage feedback pin (FB) the desired output voltage can be set. In order to achieve this, a voltage divider topology is needed.

The relation between the resistors of the divider should be as given in Eqn. 8:

$$V_{out} = 1\,V * \frac{R_{up} + R_{down}}{R_{down}} \qquad Eqn.\,8$$

Having a requirement of 24 V output voltage, the ratio $\frac{R_{up}}{R_{down}}$ should be 23.

41.2 kΩ and 1.8 kΩ satisfy this condition.

vii.   Power Dissipation Calculations

One of the most important parts of this design is the calculation of the power dissipation since the heat dissipated may cause a significant rise in the temperature of the system depending on the specification of the components. This is an unwanted case because the characteristics semiconductors, with which the microcontroller and MOSFETs are made, may change and hence affect the operation of the circuit.

The main source of heat dissipation (that will be considered) in this circuit are MOSFETs and resistors. Losses caused by capacitors can be ignored.

Losses due to MOSFETs are conduction and switching losses. The main reason of conduction loss is the resistance between drain and source of the MOSFET. Therefore a MOSFET in ON state can simply be modelled as a resistor R_{DS} and voltage drop across its drain and source terminals $V_{DS,on}$. As a result, conduction loss is simply power dissipation on a resistor as in Eqn. 9:

$$P_{cond} = R_{DS} * I_{DS}^2 \qquad Eqn.\,9$$

Switching loss [8] is caused by the change in the charge of the gate capacitance during transitions from H to L and L to H. It can be calculated with the formula given in Eqn. 10:

$$P_{sw} = \frac{V_{in} * I_{load} * f_{sw} * (t_r + t_f)}{2} \qquad Eqn.\,10$$

As the R_{DS} values of the MOSFETs are around 1 mΩ, resulting conduction loss will be in miliwatts, therefore it will not cause a significant change in the temperature.

When calculating the switching loss per MOSFET, V_{in} can be considered as 12 V (because it is an approximate value) and I_{load} as 7.5 A ($I_{load,max} = I_{load} + I_{ripple}$)

$$P_{sw,1} = \frac{12 * 7.5 * 150k * 61n}{2} = 0.41\,W$$

$$P_{sw,2} = \frac{12 * 7.5 * 150k * 9n}{2} = 0.06\,W$$

Seeing the switching loss calculations, it can be concluded that switching loss also will not cause a significant temperature rise.

c. Simulation Results

The schematic of the circuit is given on Figure 6. The simulation results (input and output voltage values, output current, inductor current, voltage and current ripples for both buck and boost operation regions) are provided on Figures 7-16. Also the Altium schematic, PCB layout and 3D view of the PCB are presented in Appendices A, B and C respectively. The results are mostly convenient with the calculations.
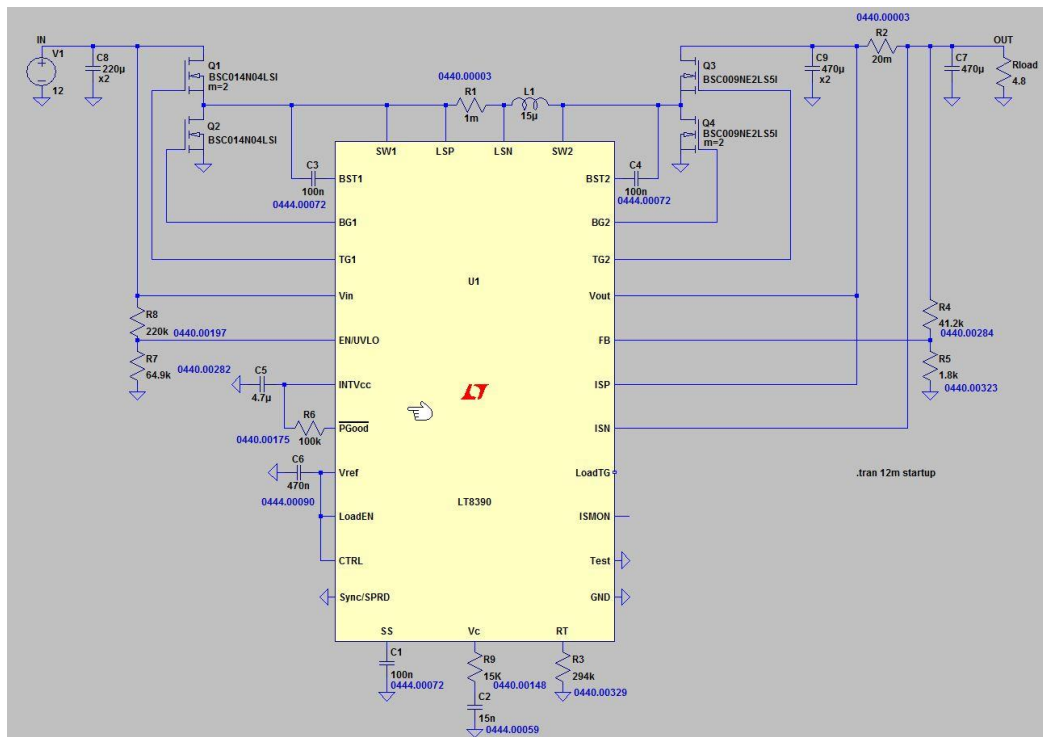
Figure 6: Schematic of the Circuit
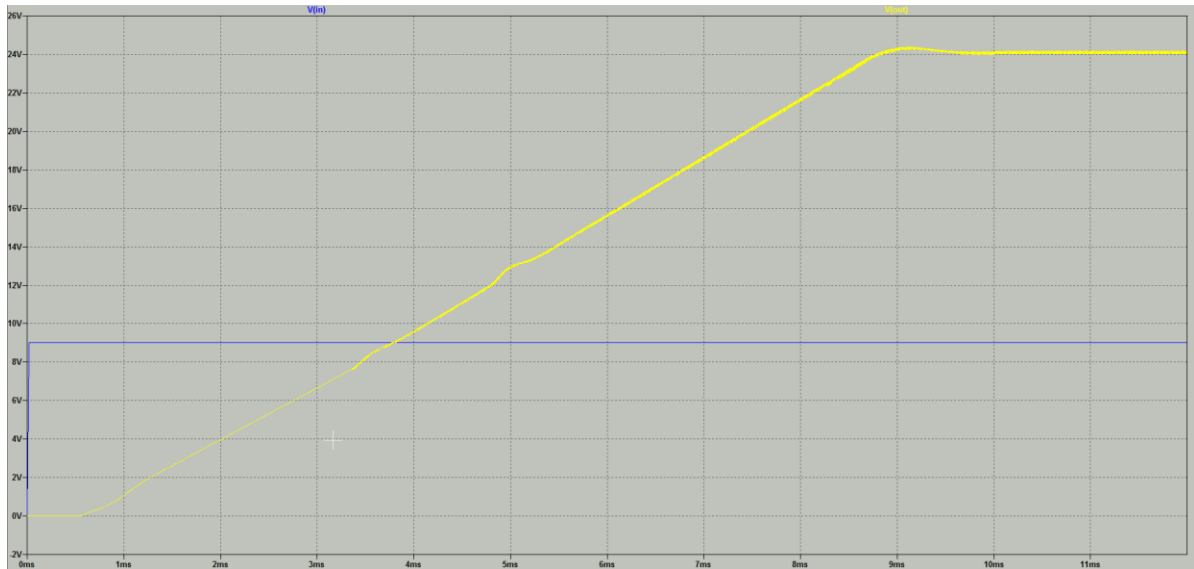
Figure 7: Input and Output Voltages (Boost)

Figure 8: Output and Inductor Current (Boost)
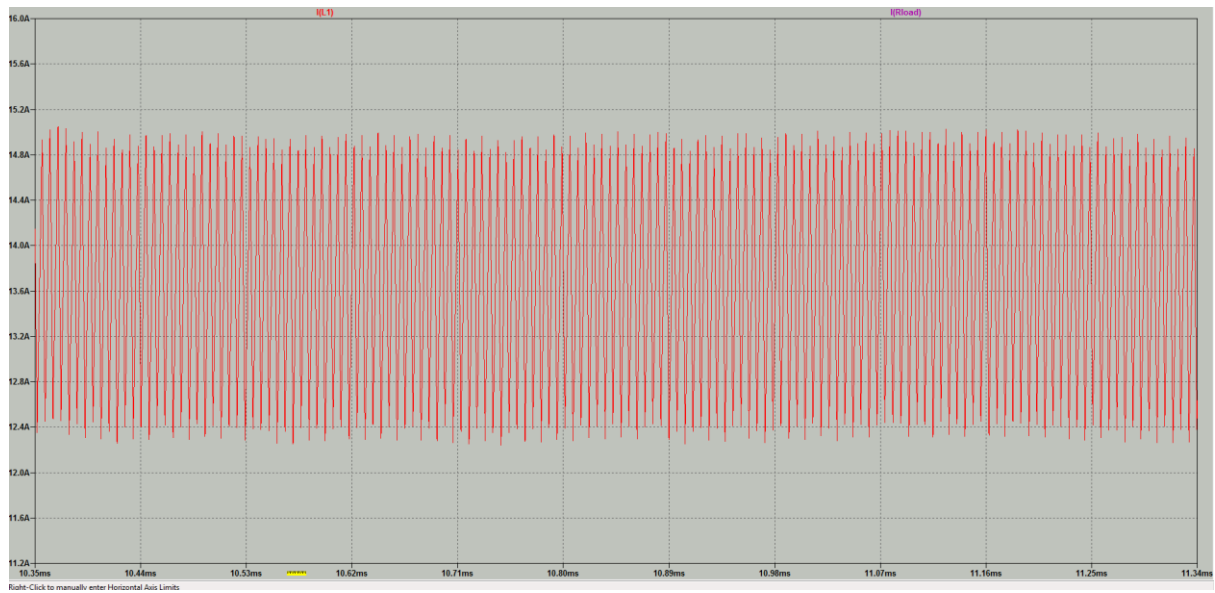
Figure 9: Inductor Ripple (Boost)
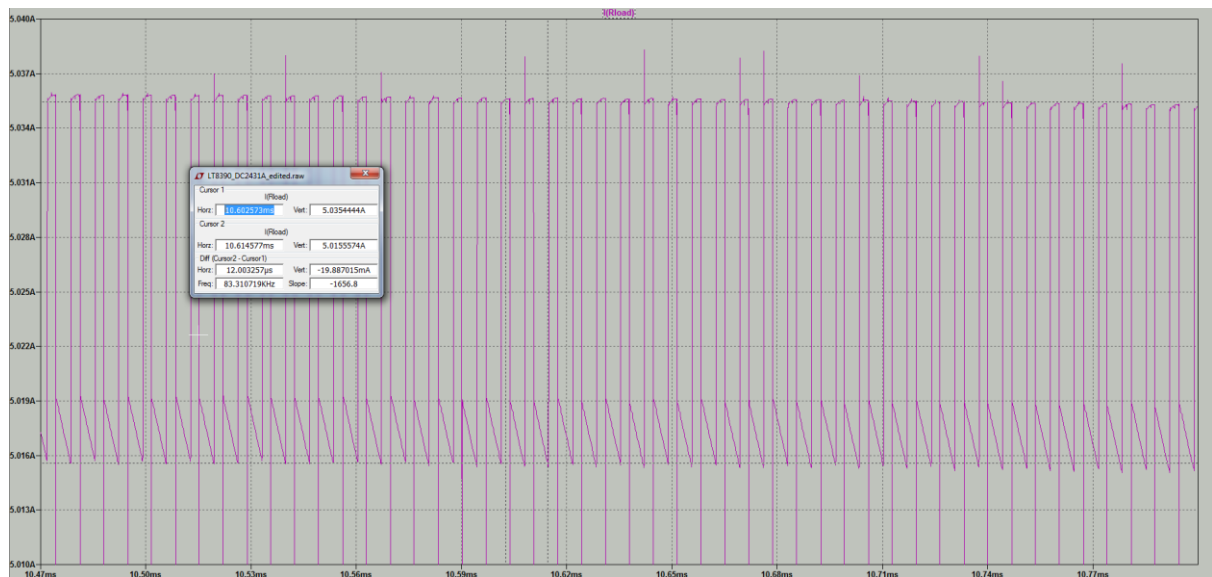
Figure 10: Output Current Ripple (Boost)
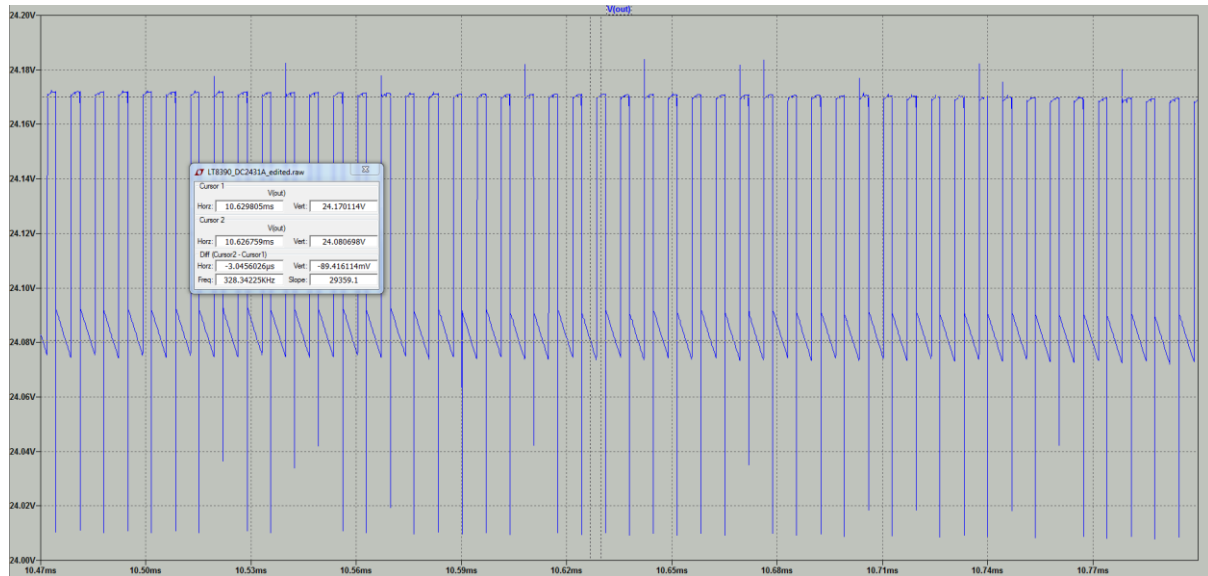
Figure 11: Output Voltage Ripple (Boost)

Figure 12: Input and Output Voltages (Buck)
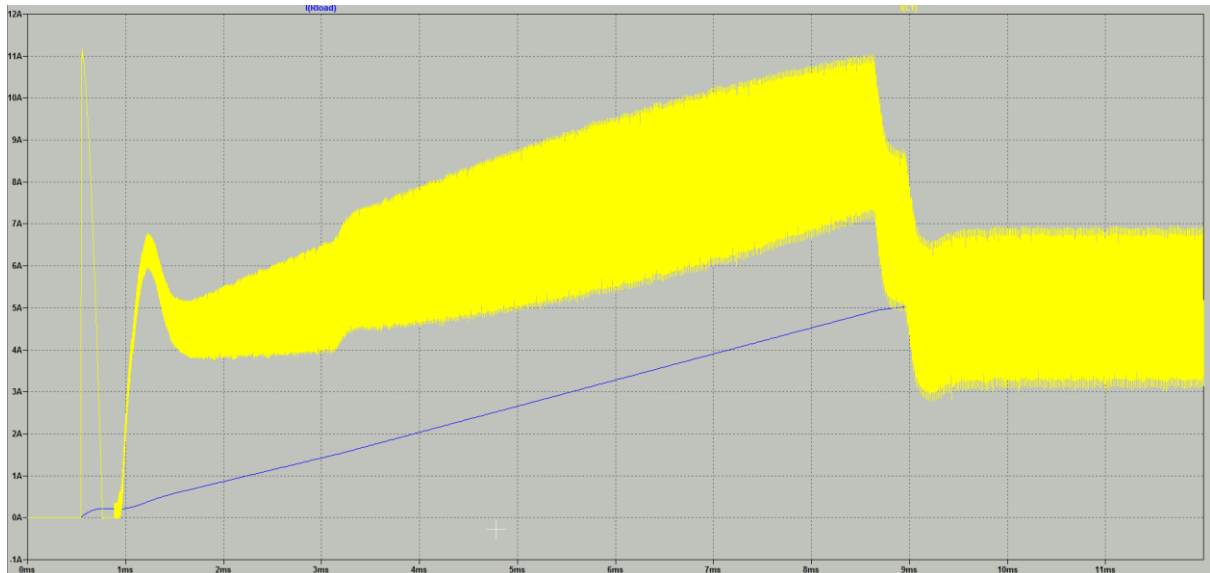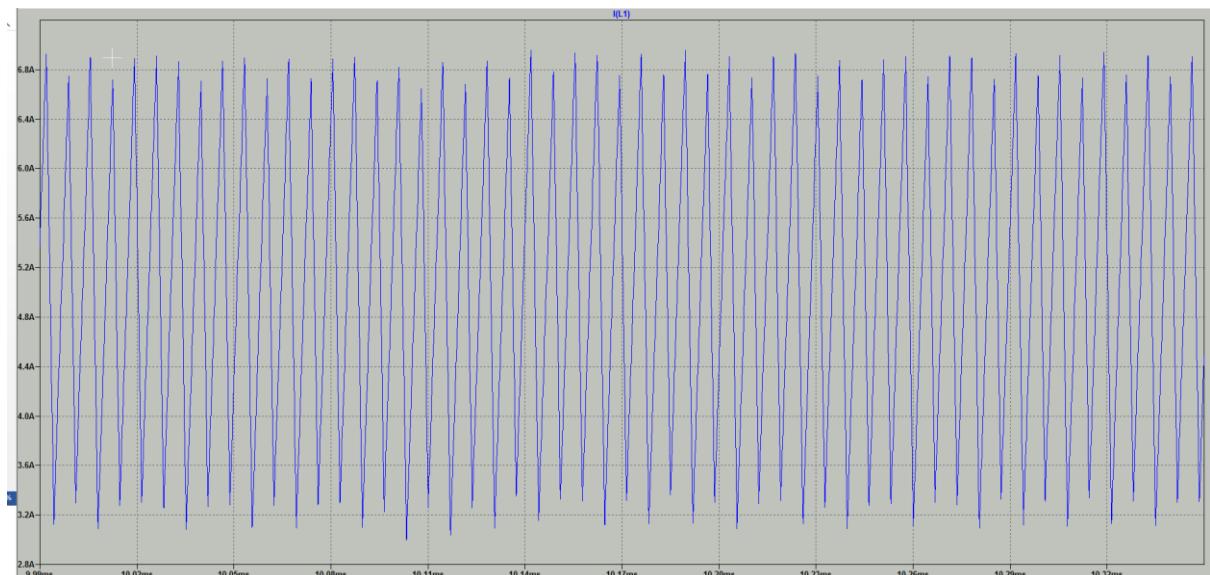
Figure 13: Output and Inductor Current (Buck)
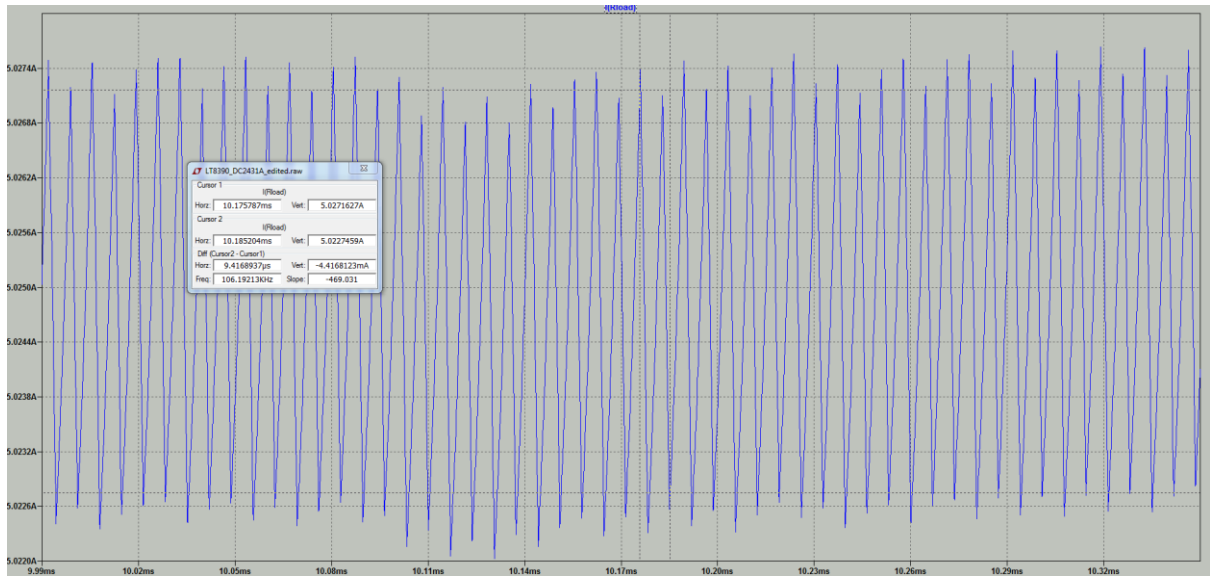

Figure 14: Inductor Current Ripple (Buck)
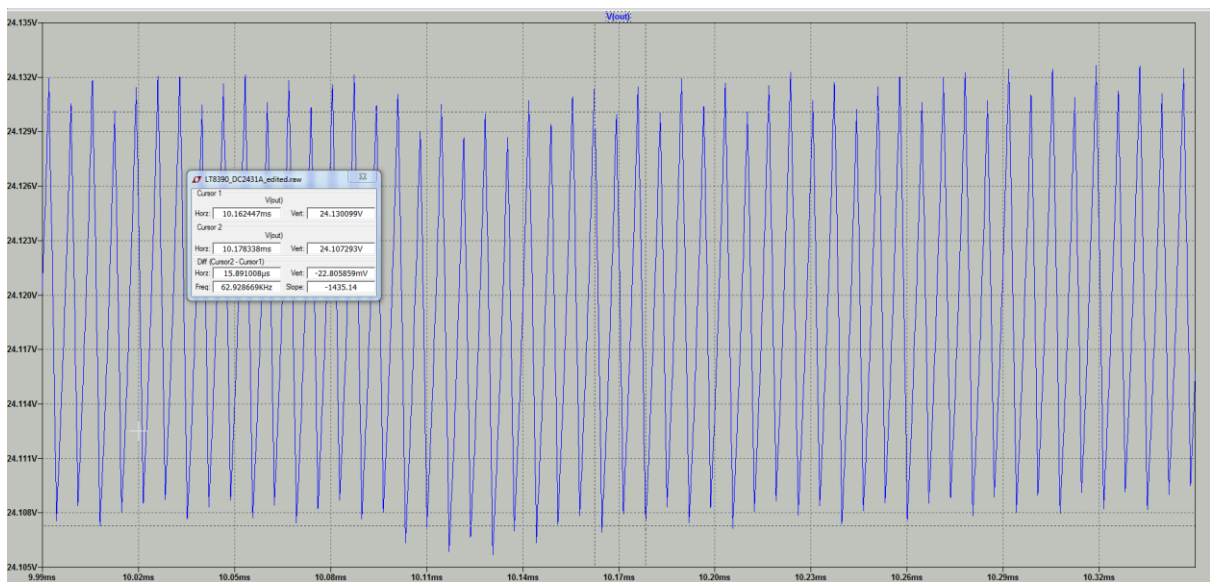
Figure 15: Output Current Ripple (Buck)

Figure 16: Output Voltage Ripple (Buck)

2. EFFICIENCY ANALYSIS OF AN E-DRIVE SYSTEM

One of the projects that I was involved in during a month of my summer practice was the analysis and calculation process of the efficiency of an e-drive system of a hybrid electric vehicle. In this project, we built a model of the motor drive in PSIM and as we were already given the measured data (stator inductance, resistance, rated torque and rated power, current) with respect to varying torque and speed of the electrical machine by the customer, we were able to simulate each data point corresponding to each different torque and speed value using PSIM, MATLAB and Simulink. Having the simulation results, we created the maps of efficiency and losses of the electrical machine on MATLAB.

However as this whole process is a part of an ongoing project, further information and the detailed work we have done here is considered as confidential information. As a result, unfortunately, I am not able to provide my detailed work in this report. Nevertheless, the algorithm that I have developed in order to plot the maps using the data set of the simulation results is present in Appendix D.

3. ISO16750-2 STANDARDIZED VOLTAGE WAVEFORMS

In automotive industry, specifications of the equipments used in vehicles have been defined with some standards. The producers must ensure that their products have the defined qualifications in order to be able to sell them. ISO16750-2 is one of the automotive standards: International standard for the environmental conditions and testing for electrical and electronic equipment of road vehicles [9]. In ISO16750-2, characteristics of the electrical loads of a road vehicle are defined. Some failure conditions and states of the battery because of which the electronic parts of the vehicle must not fail are also included. Three of these states are presented on Figures 17-19.
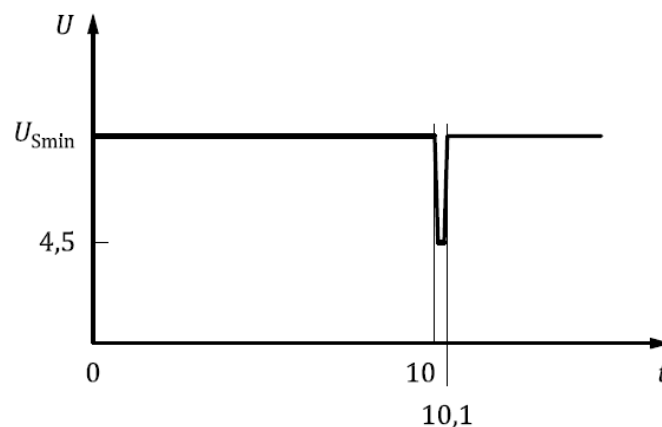

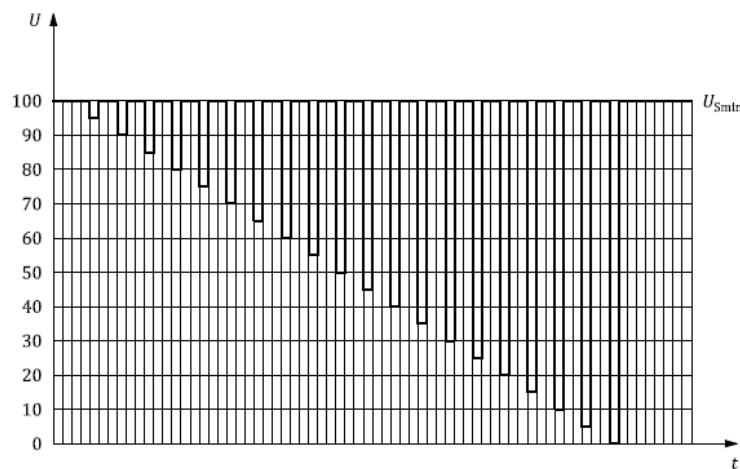*Figure 17: Short Voltage Drop for Systems with 12 V Nominal Voltage*

Figure 18: Supply Voltage Profile for the Reset Test
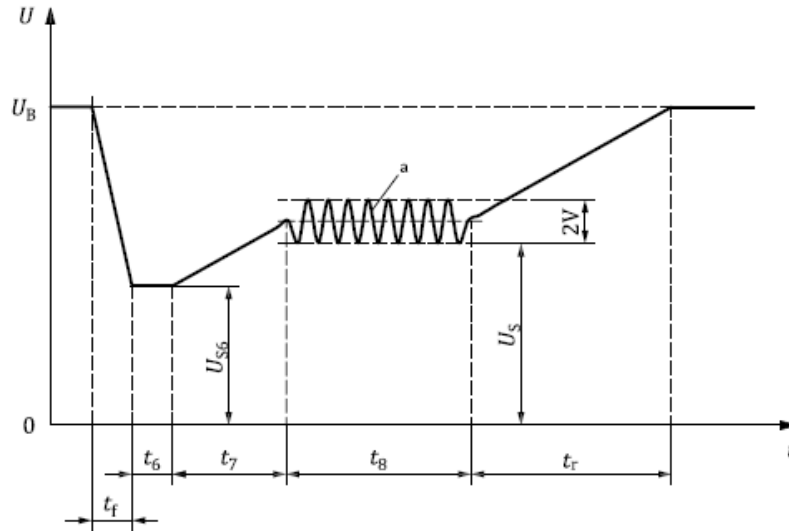
Figure 19: Starting Profile

As the electronic systems that are designed must not fail under these input voltage conditions, they need to be tested and simulated in order to observe the response of the system to the input voltage. For that reason, I have created piecewise linear (PWL) voltage waveforms that can be used in LTspice simulations, with MATLAB. The starting profile PWL voltage waveform is presented on the Figure 20 as an example. Also the MATLAB algorithms are provided in Appendix E.
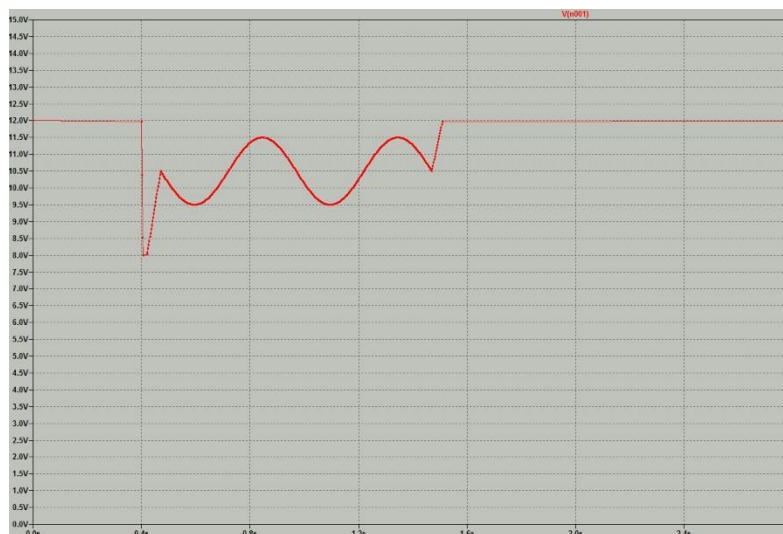

Figure 20: Starting Profile PWL Voltage Waveform

4. TESTS

As I stated before, one of the projects that I was involved in was the design and manufacturing of a device that can be connected between the Engine Control Unit (ECU) and the battery of a vehicle which can simulate the possible failures of the battery (e.g. short circuit and open circuit cases between different channels of the ECU). The devices achieves this using numerous of relays that can turn on and off the necessary channels. Having the PCB's of the device printed, they were to be tested by checking the voltage levels of each of the relays (using a MATLAB routine), possible mechanical problems, voltage levels and waveforms of the CAN communication channels.

As an example, two of the oscilloscope screenshots of the tested communication channels are provided below on Figures 21 and 22 below. The test is made by observing the waveform of the channel having sent a HIGH input to the controller. The results were commonly as expected.
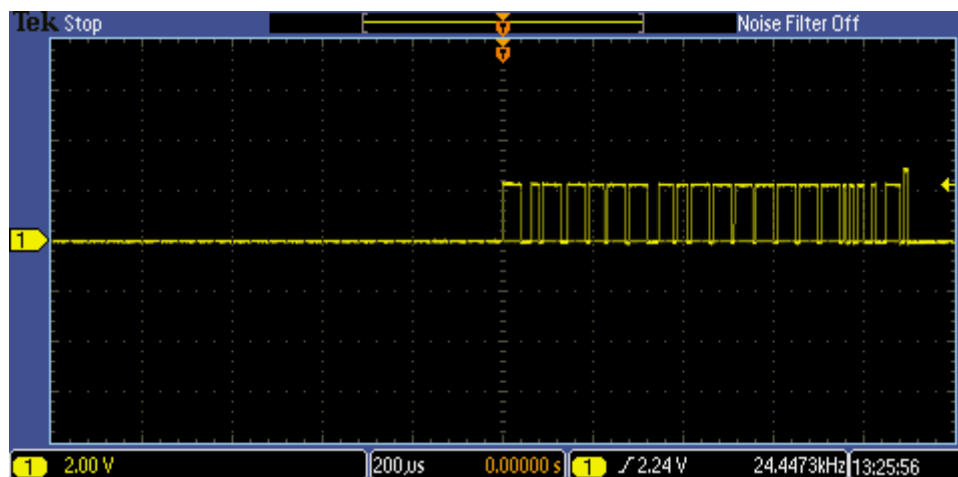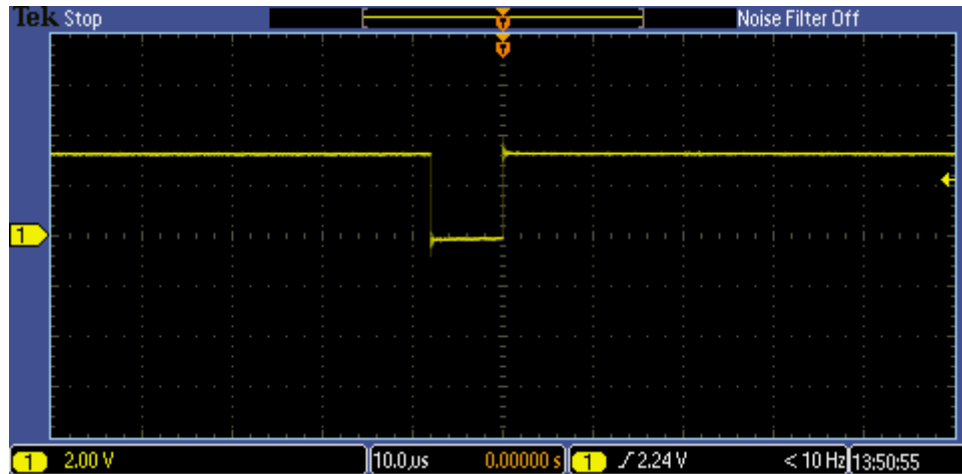

Figure 21: Test Results-1

Figure 22: Test Results - 2

IV.   CONCLUSION

I have always been interested in vehicles and automotive and I was planning to work in automotive industry. For that reason, I thought that AVL Turkey would be the best choice in Turkey to spend my summer practice period in as I knew that they worked with well-known automotive manufacturers by providing them engineering solutions.

Fortunately, I was not disappointed as I spent an excellent three-month-long internship period in AVL. In fact, my summer practice period was that long in order to be able to have a full knowledge of work done in the company and be a part of an ongoing project. Throughout the time I spent in AVL, as I stated previously in my report, I had the chance of working with two teams: Electronic Hardware Design and Hybrid Electric Vehicle Controls. As a result of this, I had to study not only the electronic components (i.e. electronic control unit –ECU-) of a vehicle but also the hybrid drivetrain topology, electrical machines and their drives, which is actually my main area of interest.

What makes me think that this internship has been quite instructive for me is I believe I learnt things that I may not learn in school. To be more specific, understanding the design process of a system (not only the standard calculations and knowledge of the topologies but also the points to consider such as protection, durability, manufacturability, cost and efficiency) is the main accomplishment of my internship. Besides, being involved in professional life and being a part of a team of engineers was a great opportunity to observe and plan my future. Also, living in İstanbul by myself and earning a living for three months was an important and wonderful experience as I have lived in Ankara since I was born.

Last but not least, I feel lucky and grateful for working with my colleagues and with my supervisor Elif Pınar Kesik in particular, since they all have been encouraging, supportive and helpful to me. Considering my inexperience, they answered my questions and helped me out with patience even if they were quite busy all the time.
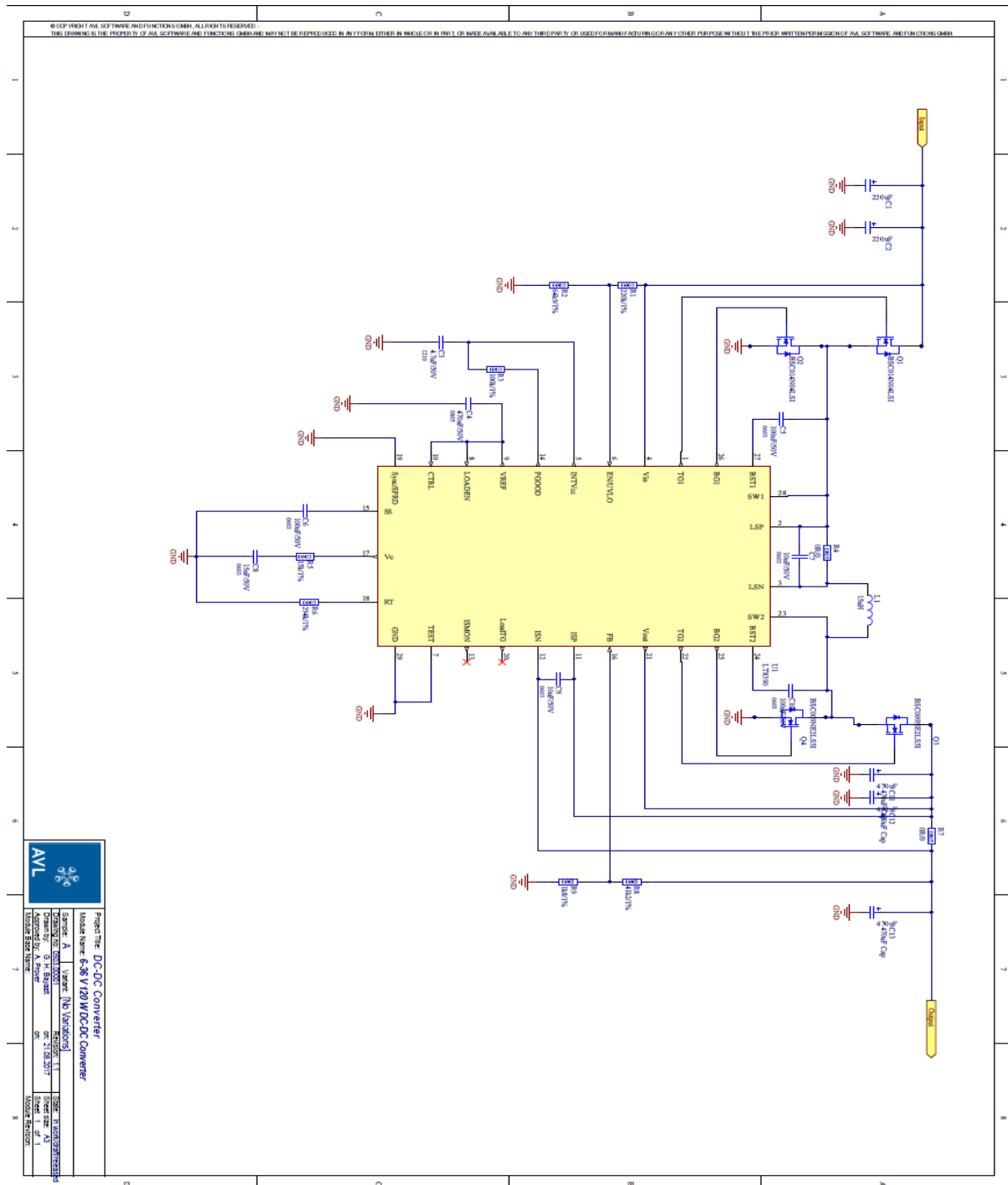
To conclude, I think I spent an instructive and enjoyable internship period and hence, I would recommend AVL as a summer practice location to other EEE students.
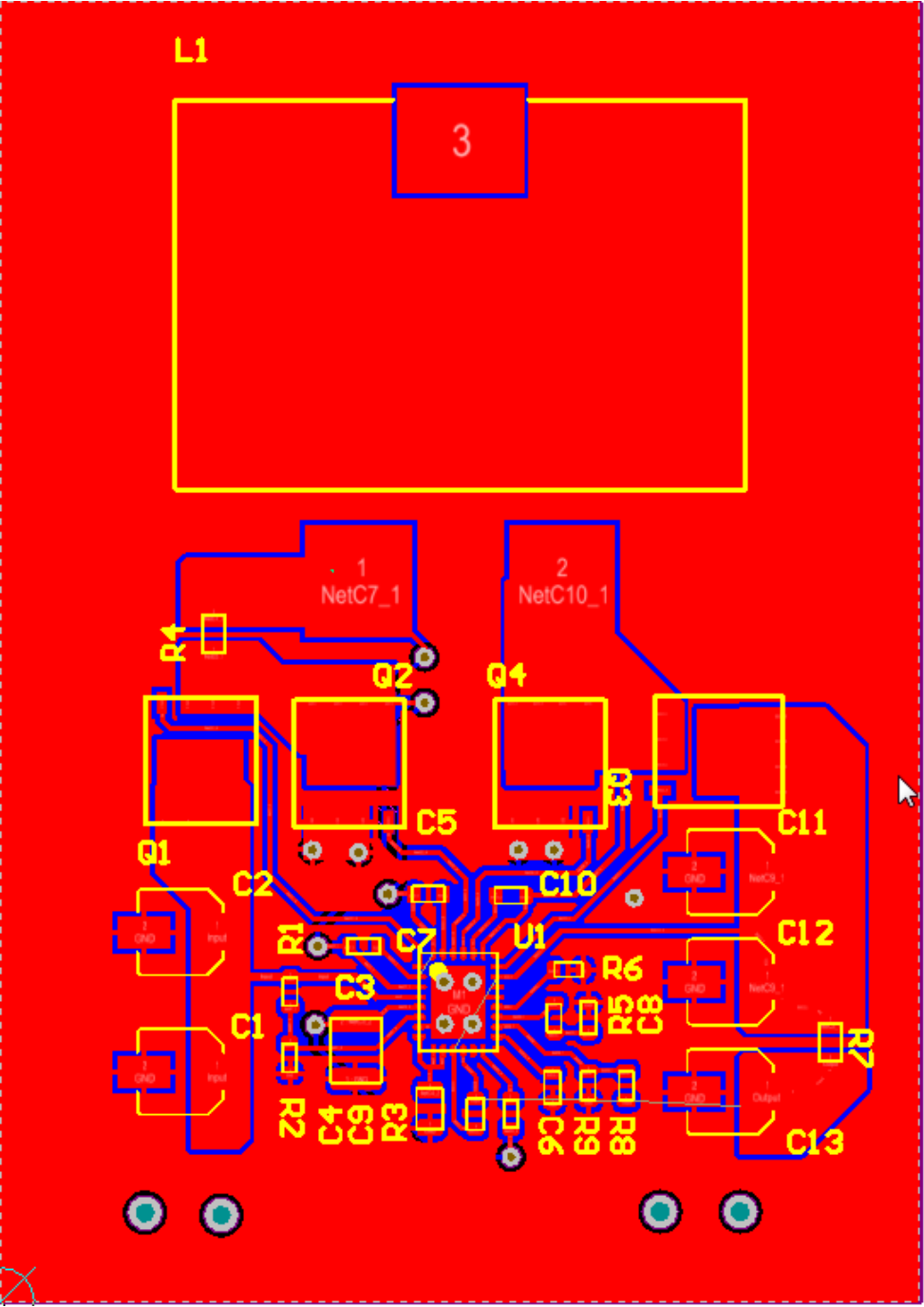
V.   REFERENCES

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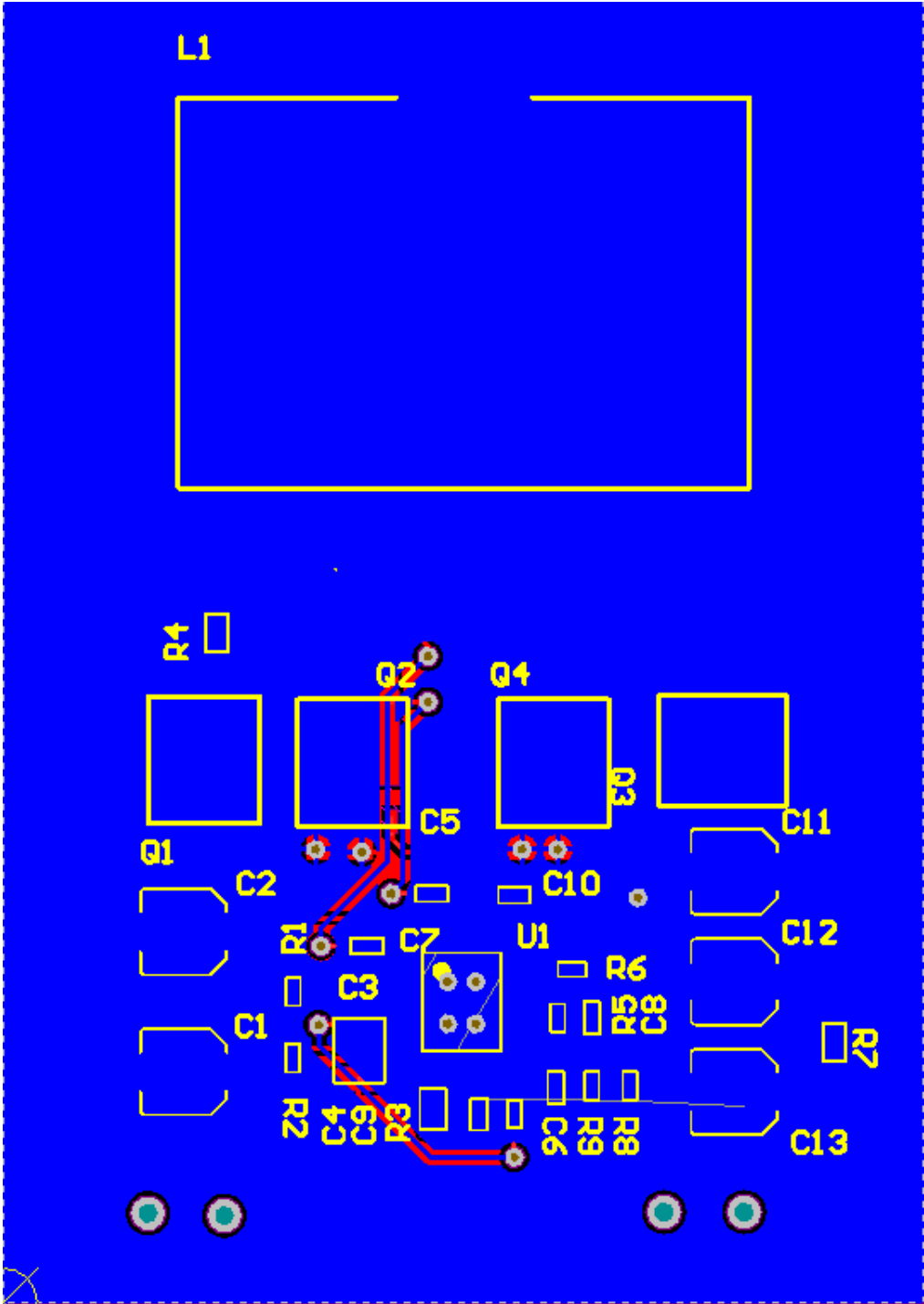[9] "ISO16750-2" https://www.iso.org/standard/61280.html

VI.   APPENDICES

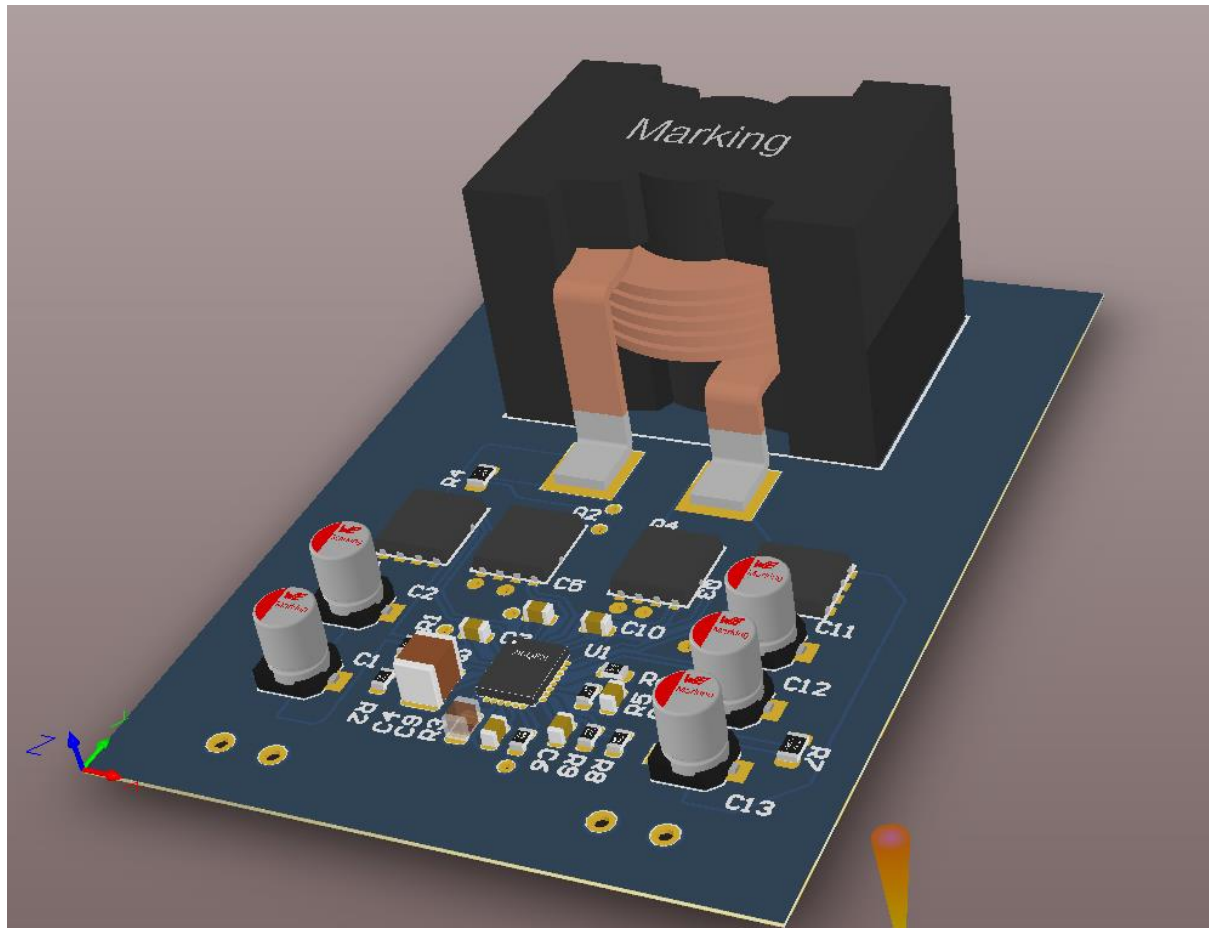## A. SCHEMATIC OF THE BUCK-BOOST CONVERTER

B. PCB LAYOUT

C. 3D VIEW OF THE PCB

D. MATLAB CODE FOR PLOTTING THE EFFICIENCY MAPS

Interpolation of the Efficiency Map

Run the sections separately.

Step1: Load data

```
clc;
close all;
clear all;

load NewSim.mat;
TqRef_tbl=TqRef_tbl*9.68;
NRef_vec=NRef_vec/9.68;
save('reference','NRef_vec','TqRef_tbl','PLoss_tbl');
clear all;
load lookupdata.mat;
load reference.mat;
Fsw=8000;

TqV=reshape(TqRef_tbl,[33*84,1]);
SpeedV=reshape(NRef_vec,[33*84,1]);
LossV=reshape(PLoss_tbl,[33*84,1]);
```

Step 2: Curve fitting

```
cftool;

% Adjustments:
% set x axis: SpeedV
% set y axis: TqV
% set z: LossV
% set method: Linear
% Interpolant
% save fitted curve to workspace as "fittedmodel" (Toolbar>Fit>Save to
% workspace)
```

Step 3: Plot the map

```matlab
    PlotPosition=[624   0.13*474   1.75*672   1.75*504];
    mkdir ZF_400V
    path = 'ZF_400V\';

    for i=1:length(SpPlot)

        for j=1:length(TqPlot)
    LossTable(i,j)=fittedmodel(SpPlot(i),TqPlot(j));

        end
    end
    LossTable=LossTable'

    figure
    [C,h]=contourf(SpPlot,TqPlot,LossTable,15);
    clabel(C,h);
    title(strcat('Total Inverter Loss [W]','  f_s=',num2str(Fsw),' Hz')); ylabel('Torque
[Nm]'); xlabel('Speed [rpm]'); colorbar; set(gcf,'Position',PlotPosition); grid on;
    saveas(gcf, [path,'Total Inverter Loss','.jpg'],'jpg');

    time=(1:length(SpeedV))';

    Valid_SpeedV=timeseries(SpeedV,time);
    Valid_TqV=timeseries(TqV,time);
    Valid_LossV=timeseries(LossV,time);

    sim('interpolated_map');

%   The discrepancy between the original and interpolated data can be
%   observed on the scope.
```

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E. PWL VOLTAGE WAVEFORMS

1. Starting Profile

```
clc
close all
clear all

% level 1 severity

t1=0:0.00001:2.500;
t1=transpose(t1);
tf1=0.00001:0.00001:0.00500;
tf1=transpose(tf1);
tf2=0.00001:0.00001:0.01000;
tf2=transpose(tf2);
tr1=0.00001:0.00001:0.05000;
tr1=transpose(tr1);
tr2=0.00001:0.00001:0.04000;
tr2=transpose(tr2);

sample=numel(t1);

cr12=zeros(sample,2);
cr24=zeros(sample,2);

x=ones(40001,1) ;%for both
x1=12*x;
x2=24*x;

y1=12-(12-8)/0.005.*tf1; %for 12v
y2=24-(24-10)/0.01.*tf2; %for 24

z1=8*ones(1500,1); %for 12v
z2=10*ones(5000,1); %for 24v

u=1/0.05.*tr1; %for both
u1=8+(10.5-8)*u ;%12
u2=10+(21-10)*u; %24

w=2*pi*2;
tsin=0.00001:0.00001:1;
tsin=transpose(tsin);
v1=10.5-sin(w*tsin) ;%12
v2=21-sin(w*tsin) ;%24

m=1/0.04.*tr2; %for both
m1=10.5+(-10.5+12)*m; %12
```

```
m2=21+(-21+24)*m; %24

n1=12*ones(99000,1);
n2=24*ones(95000,1);

cr12(:,1)=t1;
cr12(:,2)=cat(1,x1,y1,z1,u1,v1,m1,n1);

cr24(:,1)=t1;
cr24(:,2)=cat(1,x2,y2,z2,u2,v2,m2,n2);
```

2. Reset

```
clc
close all
clear all

t=0:0.000000001:0.00350;
t=transpose(t);

waveform=zeros(numel(t),2)
waveform(:,1)=t

tt=1:1:50000;
tt=transpose(tt);

tfall=0.000000001:0.000000001:0.0000001
tfall=transpose(tfall)

volt=zeros(3*numel(tt),20);


V=12; %supply voltage


a=ones(50000,1)
c=ones(49800,1)
d=1/(-0.000100000+0.000100100).*tfall

for i=1:20


v1=V*a
v2=V-V/20*i*d
v3=(V-V/20*i)*c
v4=(V-V/20*i)+V/20*i*d

volt(:,i)=cat(1,v1,v2,v3,v4,v1)

end
```

```
init=V*ones(150001,1)
fin=V*ones(350000,1)
middle=cat(1,volt(:,1),volt(:,2),volt(:,3),volt(:,4),volt(:,5),volt(:,6),volt(:,7),
volt(:,8),volt(:,9),volt(:,10),volt(:,11),volt(:,12),volt(:,13),volt(:,14),volt(:,1
5),volt(:,16),volt(:,17),volt(:,18),volt(:,19),volt(:,20))
clear volt
waveform(:,2)=cat(1,init,middle,fin)

% waveform(:,2)=2*waveform(:,2)
% plot(t,waveform(:,2))
```

3. Momentarily Drop

```
clc
close all
clear all

t=0:0.00001:12
t=transpose(t)
tfall=0.00001:0.00001:0.01
tfall=transpose(tfall)

sample=numel(t)

v12=zeros(sample,2)
v24=zeros(sample,2)

a=ones(1000001,1)
c=ones(8000,1)
d=1/(-10+0+10.01).*tfall
e=ones(190000,1)

v12_1=12*a
v12_2=12-(12-4.5)*d
v12_3=4.5*c
v12_4=4.5+(12-4.5)*d
v12_5=12*e

v12(:,1)=t
v12(:,2)=cat(1,v12_1,v12_2,v12_3,v12_4,v12_5)


v24_1=24*a
v24_2=24-(24-9)*d
v24_3=9*c
v24_4=9+(24-9)*d
v24_5=24*e

v24(:,1)=t
v24(:,2)=cat(1,v24_1,v24_2,v24_3,v24_4,v24_5)
val=v24(:,2)
```