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Faculty of Electrical Engineering
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A KOMUNIKAČNÍCH TECHNOLOGIÍ

DEPARTMENT OF MICROELECTRONICS
ÚSTAV MIKROELEKTRONIKY

A DESIGN AND DEVELOPMENT OF A POWER SUPPLY FOR LAPTOPS IN ORDINARY MOTOR VEHICLES
NÁVRH A VÝVOJ NAPÁJECÍHO ZDROJE NOTEBOOKŮ DO BĚŽNÝCH MOTOROVÝCH VOZIDEL

MASTER'S THESIS
DIPLOMOVÁ PRÁCE

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Master's study program **Microelectronics**

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Student: Bc. Michal Urban   **ID:** 195256

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TITLE OF THESIS:

A Design and Development of a Power Supply for Laptops in Ordinary Motor Vehicles

INSTRUCTION:

Design and assemble a universal power supply for various laptops with the power of 60 to 120 W in various motor vehicles with the DC battery distribution network of the 6, 12, 24, and 36 V nominal voltages. The supply voltage for laptops (the output) is adjustable in the range from 16 V to 24 V, possibly a bit more.

RECOMMENDED LITERATURE:

Podle pokynů vedoucího práce

Date of project specification: 8.2.2021   **Deadline for submission:** 25.5.2021

Supervisor: Ing. Martin Šťáva, Ph.D.

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Chair of study program board

Abstract

The main goal of the thesis is to design and assemble a universal power supply for different laptops for use in cars, trucks, and motorcycles with output power up to 120W. The resulting power supply is equipped with USB-C connector for powering laptops and smart devices with Power Delivery support, USB-A connector with Quick Charge 3.0 and 12V automotive electrical outlet for powering other car accessories. The power supply includes input reverse polarity protection and overload protection for each output. The device also includes a LED display that allows the user to simply adjust the laptop voltage level and monitor the values of all outputs. The Arduino Nano microcontroller is used to control the output values, protection, and indication.

Keywords

Abstrakt

Cílem této práce je navrhnout a sestavit napájecí zdroj pro notebooky různých výrobců pro použití v osobních a nákladních automobilech a na motocyklech s výstupním výkonem až 120W. Výsledný zdroj obsahuje USB-C konektor pro podporu napájení notebooků a chytrých zařízení s podporou Power Delivery, dále USB-A konektor s podporou Quick Charge 3.0 a také 12V automobilovou zásuvku pro možnost připojení dalšího automobilového příslušenství. Napájecí zdroj dále disponuje ochranou proti přepětí a přepólování vstupního napětí a také ochranou proti přetížení jednotlivých výstupů. Součástí zařízení je také LED displej, který uživateli umožňuje pomocí vstupního rozhraní jednoduše nastavit výstupní napětí pro notebook a sledovat aktuální hodnoty všech výstupů. Pro nastavování výstupu, indikaci a ochrany je použit mikrokontroler Arduino Nano.

Klíčová slova

Napájecí zdroj, napájecí adaptér, notebook, vozidlo, automobil, Power Delivery, Quick Charge, Arduino

Rozšířený abstrakt

Tato práce se věnuje návrhu a sestavení napájecího zdroje pro notebooky pro použití v různých rozvodných sítích ve vozidlech. Vzhledem k postupné modernizaci a snaze o sjednocování napájecích standardů ve světě mobilních zařízení, je pozornost věnována také rychlonabíjení a univerzálním napájecím standardům s ním spojených. Většina moderních notebooků již podporuje nabíjení pomocí USB-C konektoru s podporou Power Delivery, ale je nutné brát v potaz zatím nemizející přítomnost standardních způsobů napájení. Výsledný napájecí zdroj tedy obsahuje jak výstup pro klasické notebookové napájecí konektory, tak i USB-C výstup s podporou zmíněného Power Delivery. Zdroj dále disponuje možností nabíjet chytré telefony a další zařízení, které podporují nabíjení pomocí Quick Charge, a to díky přítomnosti USB-A konektoru s podporou tohoto standardu. Mimo tyto výstupy je přítomna také klasická 12V automobilová zásuvka pro možnost napájení dalšího příslušenství a současně pro možnost připojit zařízení určené pro 12V výstup do vozidel, kde je hodnota napětí jiná. Cílem práce je tedy navrhnout univerzální řešení, které uživateli umožní napájet notebooky ve vozidlech nejen klasickým, ale také moderním způsobem, a dále efektivně nabít telefon a jiné zařízení pomocí rychlého nabíjení. To vše za podpory různých palubních napětí ve vozidlech od 6V do 36V a s maximálním možným výstupním výkonem 120W. Uživatelské rozhraní je zajištěno pomocí tlačítek a rotačního enkodéru, díky čemuž si uživatel může zvolit výstupní napětí pro notebook, vypínat jednotlivé vstupy a sledovat výstupní hodnoty. Napájecí zdroj disponuje i ochranou proti přepólování vstupního napětí a také ochranu proti přetížení jednotlivých výstupů. Řízení výstupů a realizace ochran proti přetížení je zajištěna pomocí mikrokontroleru Arduino Nano.

Bibliographic citation

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Author's Declaration

Author:	*Bc. Michal Urban*
Author's ID:	*195256*
Paper type:	*Master's Thesis*
Academic year:	*2020/21*
Topic:	*A Design and Development of a Power Supply for Laptops in Ordinary Motor Vehicles*

I declare that I have written this paper independently, under the guidance of the advisor and using exclusively the technical references and other sources of information cited in the project and listed in the comprehensive bibliography at the end of the project.

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Brno, May 25, 2021   --------------------------------------

author's signature

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INTRODUCTION

Switched-mode power supply is a basis of almost every consumer electronic device in most households nowadays. This type of power supply nearly pushed linear power supplies out of the consumer grade electronics thanks to its higher efficiency, lower cost, and smaller size. The power supply is needed to power electronic devices or to charge batteries inside the battery-powered devices. Aside from home electronics, the need for powering a device is in many cases emerging also outdoors, on the go or even in cars, trucks, and other vehicles. Therefore, the thesis is focused on power supplies for powering consumer electronic devices, such as laptops, smartphones or any other equipment that requires DC voltage in different types of vehicles.

None of existing available solutions comes without compromises. It is easy to find USB car charger for a reasonable price, but there is lack of one universal solution. Almost all modern smartphones support fast charging (in most cases it is Quick Charge or its derivatives) and laptops are slowly transitioning to it as well (in this case, there is practically only one available technology, which is power delivery). Due to the fact that there is still a need to keep older, hence current laptops in mind, the lack of a universal power adapters that combines old and new technologies is a gap in the market. Therefore, the purpose of this project is to bring a power adapter that supports Quick Charge, Power Delivery, but also can power older laptops - all in cars, trucks or even on motorcycles.

In the first place, the way of powering and charging small portable electronic devices in cars and existing possibilities and its drawbacks will be discussed. The thesis then deals with the theoretical background about power supplies, fast charging, laptops and other necessary information relevant to the topic of the thesis. The following chapter describes the design process of the final device from the general idea, over individual blocks of the design all the way to the circuit diagram and PCB layout realization. After the assembly and operation tests, the attention is paid to the user interface and the programming of the MCU along with ensuring the proper operation of all the components. The last chapter deals with the measurements of the parameters and output values of the finished device as well as to evaluate the desired requirements and specification and to what extent they are met.

1. RESEARCH

The socket used in cars, trucks, motorcycles boats and many other vehicles is called auxiliary power outlet (also known as automotive electrical outlet, automotive power socket, cigarette lighter receptacle etc.) and usually has 12V DC voltage. However, the voltage level in many trucks is 24V and in older motorcycles 6V. When the first vehicles with electrical systems arrived, these sockets along with radios were the first accessories that appeared in cars. But the original purpose of this socket, as one of the names implies, was not a power outlet, but a cigarette lighter [1]. Even if smoking is becoming less popular nowadays, these cigarette lighter sockets are unlikely to disappear from vehicles mainly because their primary usage is power outlet. There is a wide selection of available chargers to use in cars on the market. An adapter to vehicle's 12V or 14V cigar lighter socket with one or two USB ports to power devices requiring 5V charging (smartphones, GPS navigation unit, dash cameras etc.) is possible to buy at almost every gas station. Laptop car power adapters are equally accessible. These laptop power adapters are often universal (which means that they can be used with different laptops from various brands), but some laptop manufacturers even produce their own car power adapters for specific laptop model that are either sold separately or provided with the laptop itself. In some cases, laptop car power adapters can be equipped with USB port, which therefore adds support for smartphone or gadgets charging.

Another way to power or charge electronic devices in vehicles is a power inverter from 12V DC to 230V AC. This solution is needed to be mentioned, since it is a possible approach, but it is not ideal - cheaper inverters have insufficient real power and stability and the more expensive ones are not worth the investment for the purpose of charging a laptop and a smartphone. Besides the two facts mentioned in the previous sentence, this approach also means converting 12 V DC to 230V AC and then back to DC, which is not ideal and efficient by itself. The best possible option is therefore the DC-DC converter.

2. POWER SUPPLIES

Power supplies exist in a variety of types, but two types used in consumer-grade electronics are linear and switched-mode. Linear power supplies use considerably large transformer to drop the AC input voltage to a lower level, which is then regulated to desirable value with a linear regulator [2]. These regulators are not efficient and produce a large amount of heat, which leads to need of proper, often spacious heatsink. The presence of a large transformer and the requirement of appropriate cooling led to the gradual replacement of these power supplies by switched-mode power supplies [3]. Based on previously mentioned advantages of switched-power supplies over linear, it is clear, that the switched-power supplies are more appropriate to use in this project. Specifically, the DC-DC converters in buck-boost topology will be used, thanks to their ability to increase and decrease the voltage with relatively great efficiency.

2.1 Switched-mode power supplies

In general, switched-mode power supplies are more efficient, smaller, and lighter than linear power supplies. One of the disadvantages of switched-mode power supplies over linear is the complexity of the design. Thanks to the fact that they operate at higher frequencies, the components inside are often expensive [4]. The main blocks that switching power supply usually consists of include transient filtering, input rectifier (not always, when the input is DC, there is no need for rectifier), PFC, switcher, transformer, output rectifier, output filter, isolator and PWM controller (see figure below).
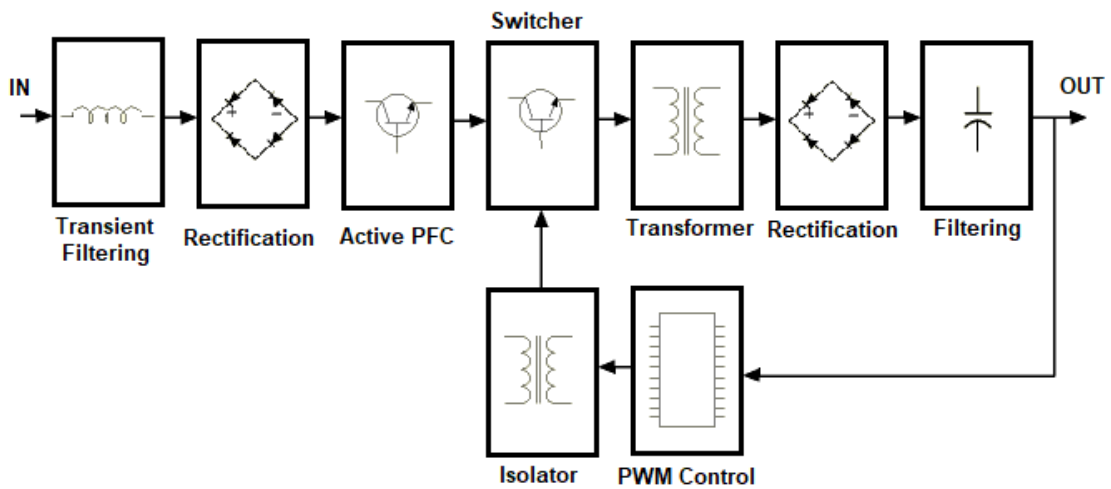
Fig. 2.1 Block diagram of switched-mode power supply with active PFC, taken from [5] and edited

Transient filtering, as the name implies, is used to filter undesirable voltage spikes that could occur on the input of the power supply from the power line. When a power supply designed for AC input is the case, then the input voltage is rectified. Another stage is PFC. According to the European Union standard IEC 61000-3-2 [6], every switched-power supply with power that exceeds 75 W must be equipped with PFC circuit. In the United States for example, there is no limitation or standard which regulates this, but there are other organizations that are trying to enforce this regulation. Among others it is a voluntary certification program 80 PLUS, that specifies a requirement of PFC 0.9% or greater at 100% load for a power supply to be certified with their trademark [7]. The input voltage must subsequently be converted to alternating shape so that it can be transformed. The converting process is accomplished using high-frequency switching transistors to create a square wave. After that, the voltage is finally transformed to the desired value by transformer. The output voltage is then rectified, and the alternating components are filtered out by the output filter. Based on the fact, that the output filter deals with relatively high frequencies, the qualitative requirements for the output filter are not as high as for the input filter. In every switched-mode power supply is a feedback circuit, which measures output voltage (or, in some cases even input and output current) and controls the switching of the transistors accordingly [8].

Based on whether they decrease or increase voltage, switched-mode power supplies exist in various topologies. The most common (with regard to this project), are buck, boost and buck-boost topology.

2.2 Buck topology

The buck topology simply converts voltage to a lower level, for example 24V from power source to a device that only requires 5V. In other words, the input voltage must not be lower than the output voltage. This conversion is often relatively efficient with only little power loss. The polarity of the output voltage is the same as the input [8].
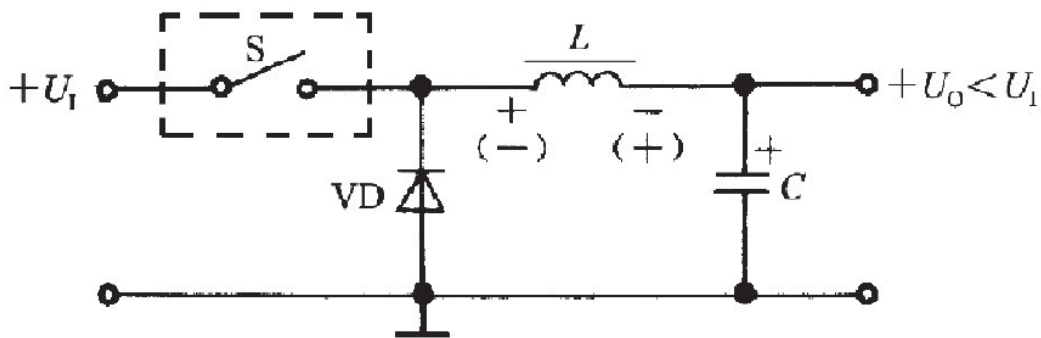
Fig.   2.2   Basic principle of buck converter, taken from [8]

According to the Figure 2.2, switching the switch S on leads to power being supplied to the load when a certain part is accumulated in inductor L and capacitor C. The left side of the inductor (U_L) voltage is positive, and the right side is negative. When the S is switched off, the U_L is reversed, which leads to the flow of electric energy through diode VD and thus to maintaining a constant output voltage.

2.3 Boost topology

This topology serves to the exactly opposite purpose than the previous. The boost converter converts the voltage to a higher level, which means the output voltage will always be greater than the input voltage. The polarity of the output voltage is the same as the input.
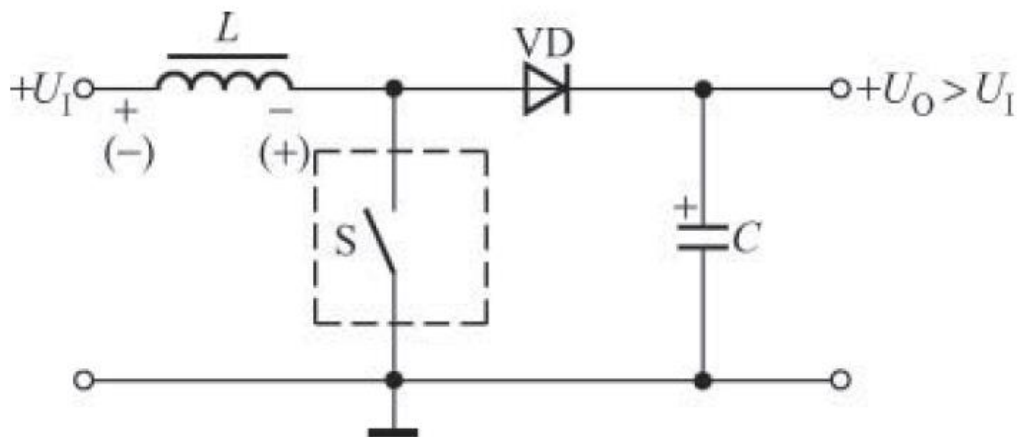
Fig. 2.3 Basic principle of boost converter, taken from [8]

Switching on the switch S allows current to flow through the inductor L with the right side being negative and the left side positive. This allows the capacitor C to supply output because the diode VD is bypassed. When the switch is switched off, the voltage polarity on the inductor is reversed resulting in the flow of the electric energy through the diode VD. Thanks to the high frequency of switching frequency, it is possible to maintain constant output voltage.

2.4 Buck-Boost topology

The buck-boost topology serves to increase, but also to decrease the input voltage. Strictly speaking, when the output voltage is lower than the input voltage, the converter works in

buck mode and when the output voltage is higher than the input voltage, the converter works in boost mode.
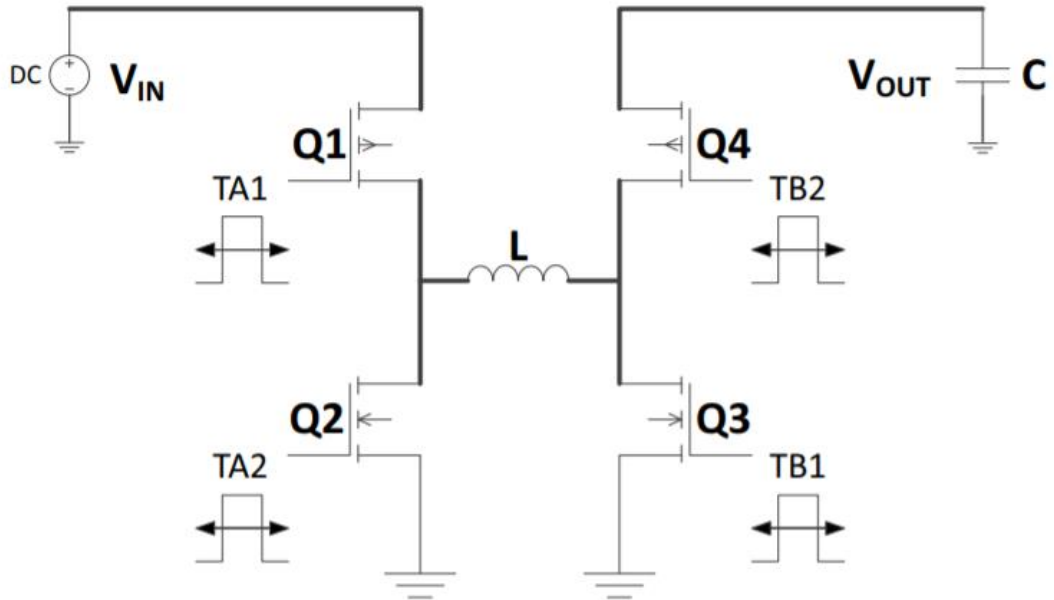
Fig.   2.4   Basic principle of buck-boost converter, adapted from [9]

In the buck mode, Q1 and Q2 are alternately closed and opened, Q4 remains closed and Q3 open. The closing of Q1 leads to current flow through the inductor and thus charging of the capacitor. The opening of Q1 then results in the discharge phase of the inductor. In the case of the boost mode operation, Q1 is closed, Q2 is opened the whole time and Q3 and Q4 are alternatively closed and opened. The opening of Q4 results in the inductor charge process and closing of Q4 causes the discharge process [9].

3. LAPTOP POWER ADAPTERS

3.1 AC adapters

The most common way of powering and charging laptops is using the power adapter provided from manufacturer of the laptop. Usually, this adapter consists of a so-called power brick, which is, generally speaking, switched-mode power supply with desired DC output appropriate for particular laptop. The voltage level of laptop adapters varies, but most laptops today require 19-20V. This voltage is well-balanced point, because higher voltage means lower current for the same power. 65W power adapter with 20 volts and 3.25 amperes is better than 13 volts and 5 amperes - lower current results in lower production cost, because manufacturers can use thinner, cheaper wires and lower-current components. On top of that, there is also a certification called Limited Power Source (LPS), specifically the LPS with non-inherent power delivery limits. This certification requires voltage equal or lower than 20 volts so if manufacturer adhere to this limit, the certification of such device becomes noticeably easier and less expensive [10]. Various connectors are used depending mainly on the manufacturer. The most common connector type is cylindrical connector, also known as barrel connector, sleeve connector etc. It is characterized by its cylindrical shape with or without a pin in the center. Another, slightly old type is snap and lock connector. Similarly, this connector has also a cylindrical shape, but with large diameter and usually four pins inside. Some manufacturers have also their own, specific types of connectors. In case of Apple laptops, for instance, it is rectangular-shape connector called MagSafe (currently, as well as many other connectors, replaced by USB-C) using five pins and, as its name implies, is characterized by magnet that holds the cable safely plugged, but it also simply disconnects if the cable is pulled (for example, someone stumble over it). Another manufacturer that uses different than cylindrical connector is Lenovo. Their connector is also, similar to Apple's, rectangular, but with only one signal pin inside it. Finally, yet importantly, the most modern connector is USB-C with Power Delivery [11].

Fig.　3.1　Left to right: Dell/HP cylindrical connector and Lenovo rectangular connector, taken from [12] and [13]

3.2　Fast charging

Fast charging is a term for charging smartphones, laptops, and other devices faster than is normally possible via common older methods. This charging method could be called smart charging since it relies on a communication between the power supply and the charged device. The reason why fast charging exist is that regular charging power is very limited. Originally, USB 2.0 was designed to 2.5 watts (5V, 0.5A), which is extremely low. In 2007, the specification called Battery Charing (the most recent version is BC1.2 from 2010) was introduced, which increased the power that could be delivered to USB charged device to 7.5W (5V, 1.5A) and brought charging over USB to a relatively usable level [14]. What needs to be mentioned is that many customers are often confused by different standards and specifications and their power limits. Simply put, everything depends on the protocol used and ratings supported by the device and charger. When the protocol USB BC1.2 is the case, it does not matter if the USB 2.0 or any generation of USB 3.2 is used, because the amount of power is limited by specifications of this protocol. Newer specifications of USB, namely 3.2 Gen 1x1 (formerly known as USB 3.0) and 3.2 Gen 2x1 (formerly known as USB 3.1) bring further increases in maximum amount of power that can be physically transferred over this interface. There are also more recent revisions called USB 3.2 Gen 1x2 and Gen 2x2 that requires USB-C cable (because of dual-lane mode [15]. Further specifications of USB types and differentiation between

them are out of the scope of this thesis, however, more information is provided in the official USB IF documentation on their official website [16]. The important fact is that USB-C 2.0 cable and connector are suitable for Power Delivery and regular USB-A 2.0 cable and connector are suitable for Quick Charge. Standard USB-C cable rated for power delivery is able to carry at least 3A at 20V (60W) and high-power versions support up to 5A at 20V (100W). High-power USB-C cables must include so-called e-marker chip that sends the information about the cable's specifications to the device [17].

The basic principle of fast charging is communication based on a special protocol. To make fast charging successfully working, both the charged device and the power supply must support the same fast charging protocol. Today, many different fast charging protocols exist, but the most commonly used and widely known is Quick Charge by Qualcomm and USB Power Delivery. Quick Charge was one of the first widespread fast charging protocols that began to appear in smartphones. Not a long time after that, many smartphone manufacturers started to develop their own fast charging protocols and standards – whether based on Quick Charge or Power Delivery or their own technology. Since many high-end smartphones have Qualcomm processors, it is presumable that major manufacturers often include support for Quick Charge. But as mentioned, many of them actually invented their own fast charging protocols or rebranded Quick Charge or Power Delivery. The main factor in the decision for rebranding is often marketing purpose. Samsung, for instance, came with their own standard called Adaptive Fast Charging, which is based on and compatible with Quick Charge 2.0. Other manufacturers including Xiaomi, Oppo, OnePlus, Huawei and many other have custom fast charging standards as well – some of them compatible with Power Delivery or Quick Charge while other not.

3.3 Quick Charge

Quick Charge is a fast-charging protocol developed by Qualcomm, which is mainly known as SOC manufacturer, but their focus is highly broader – artificial intelligence, wireless systems, audio, automotive solutions and many other [18].

Quick Charge exists in various versions with the most recent being 5. The major differences between these versions are certainly the charging power, thus charging speed, and efficiency. Quick Charge, as every fast charge protocol, works on the principle of communication between the charger and the charged device. Based on the information from the charged device, the charged then can adjust the voltage and current supplied.

3.4 Power Delivery

USB Power delivery is a charging protocol developed by the organization called USB IF. Apart from being able to transfer data and connect devices and peripherals to laptop, it is possible to use USB not only to charge electronic devices from the laptop, but also to charge the laptop itself. USB PD requires USB-C cable, because of the presence of extra communication pins against USB-A or B. The maximum amount of power it is capable to transfer is 100W (20V, 5A) [19]. Depending on the charging power required by the charged device, PD has four ranges – 7.5W, >15W, >27W and >45W. For each power range, there are different voltage and current options. For instance, devices requiring charging power to 27W can be supplied with 5, 9 or 15V and 3 or 5A (depending on the cable - explained in the begging of chapter 3). All charging ranges are shown in Fig. 3.1. The most recent version of Power Delivery is 3.0, however the most common version today is 2.0. These two versions share the same power capabilities with the differences being only in communication messages supported [20].
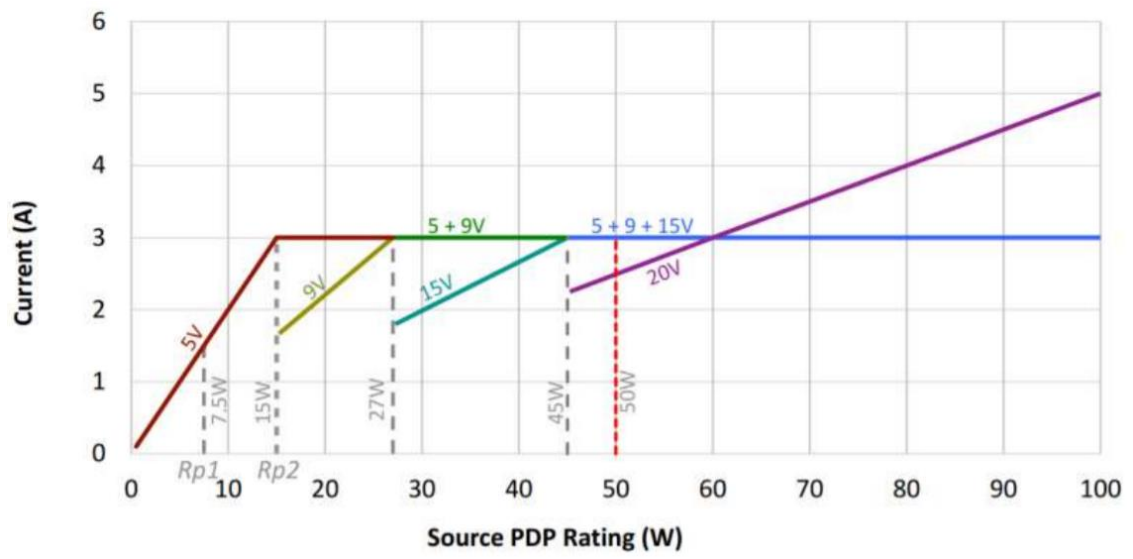
Fig. 3.2 Charging ranges of Power Delivery, taken from [21]

4. DESIGN

The main objective of this project is to create laptop power supply suitable for different types of on-board distribution network in vehicles. To realize this project, the DC-DC converter was used. The specific goal was to design power supply with possible input of 6V, 12V, 24V and 36V with the output ranging from 16 volts to 24 volts, which should cover most of laptop models today, since most of them in fact operate around 19 volts. The output power of this power supply should be up to 120W.

4.1 General design

The final design of power supply will support 6V – 36V input voltage range. Chosen buck-boost voltage controller supports input voltage from 3V up to 75V, so the theoretical upper limit of the resulting device is much higher than required. The next value of the on-board distribution network voltage that follows 36V is 48V. Therefore, the final design of the power supply and its components is designed for input voltage ranging from 6V up to 50V. The voltage of 48V can be seen in electric cars, but any transition of the on-board distribution network in general is in a relatively distant future. Although vehicles with 48V are slowly appearing in consumer sphere, 12V on-board voltage is still present alongside the 48V. The 12V on-board distribution network is used for a very long time and the transition to any different voltage will take a considerable amount of time [22].

The final solution of the project will therefore have a universal output for powering laptops and USB-C Power Delivery output due to the reason described in theoretical part of the thesis. Aside from laptops, the USB-A connector with support for Quick Charge 3.0 will be also present for charging smartphones and other gadgets (however, some smartphones also support Power Delivery). The last output of this power supply will be 12V automotive electrical outlet for connecting other 12V car accessories. The simplified block diagram of final design can be seen in the figure below.
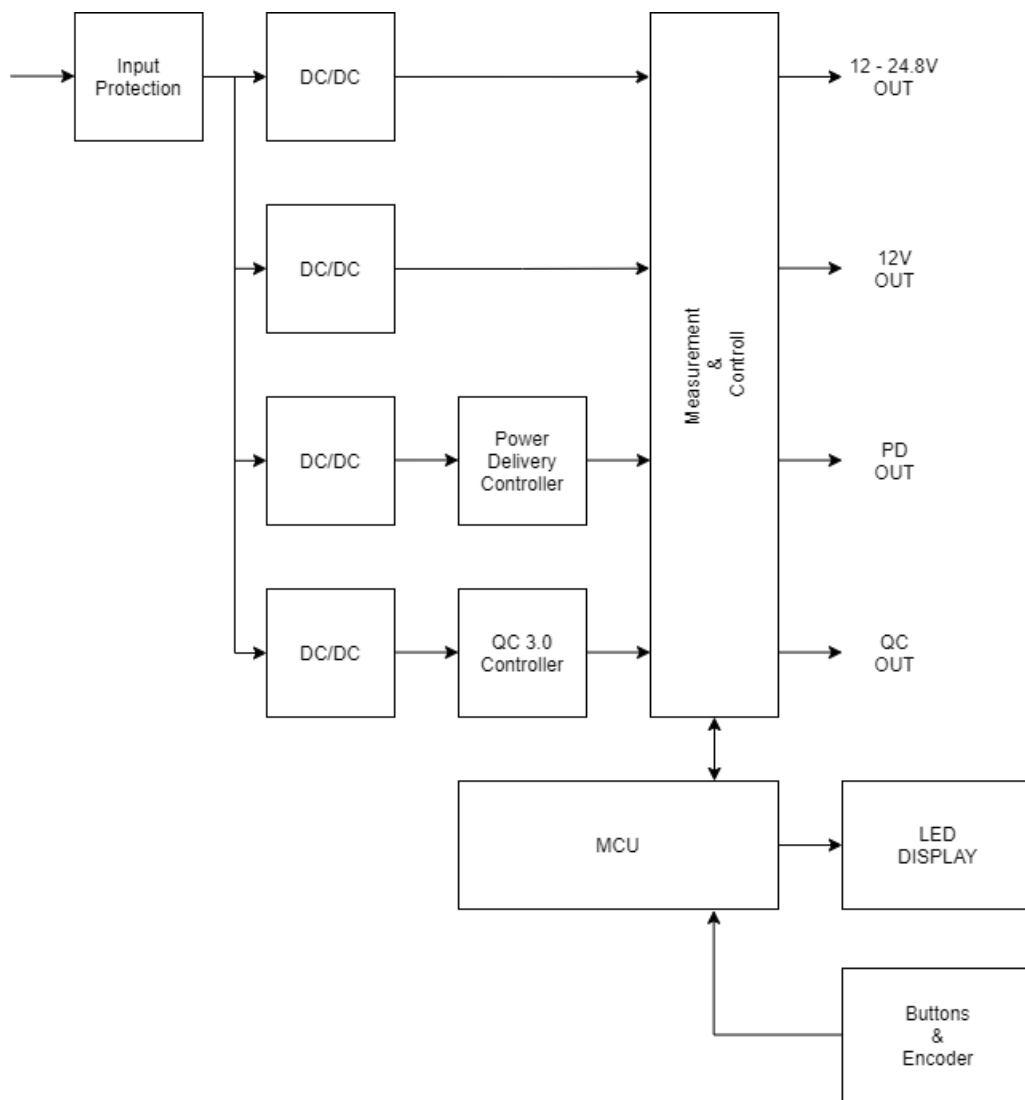
Fig. 4.1 General simplified block diagram

According to the simplified block diagram shown above, the final solution consists of input protection, four DC/DC converters, Power Delivery and Quick Charge controllers, measurement and control circuit, MCU, LED display and buttons with a rotary encoder for user interaction.

4.2 Individual blocks

4.2.1 Input protection

The input protection includes physical fuse and reverse polarity protection. The input fuse has a value of 15 amperes, fast reaction and serves as an addition to the electronic overload output protection controlled by the MCU. The blade type automotive fuse was considered as a suitable solution since the device is intended to be used in vehicles. Another part of the input protection is TVS and Schottky diodes to protect the device from reverse polarity input voltage and against overvoltage.

4.2.2 DC/DC converters

For the voltage conversion part of the circuit were considered separated DC/DC buck-boost voltage converter modules at first. However, obtained modules lacked the required and satisfactory parameters and it was almost impossible to find any usable modules with necessary properties. Due to that, the approach of designing own on-board DC/DC converter modules was decided. LM5118 Wide Voltage Range Buck-Boost Controller from Texas Instruments was chosen as a sensible and satisfactory solution for a reasonable price. It supports input voltage range from 3V up to 75V, which would allow us to cover very wide range of input voltages, but with respect to other parts and components, the input voltage range for the final power supply is limited to 50V. Among other features, this controller supports smooth transition between step-down and step-up modes, thermal shutdown, current limit and enable input. According to the datasheet, the efficiency should be in the range of 80 – 95%, which is acceptable for this device class. Theoretical output voltage range is 1.23V to 70V, where the output voltage range required for this power supply is from 3V to 25V.

4.2.3 Power Delivery controller

The Power Delivery circuit is controlled by STUSB4710, autonomous USB PD 2.0 controller. This integrated controller combines many features, including cable attach and

orientation detection, configurable start-up profile or integrated V_{BUS} voltage monitoring. The most useful feature of this integrated controller is no need for additional software control – full hardware Power Delivery control is included. This makes the integration of this chip into the power supply relatively simple. The output of this Power Delivery circuit is up to 45W along with all five PD charging profiles, which is enough to power vast majority of current portable laptops and, also to at least charge the not so portable models with higher power requirements in the off state.
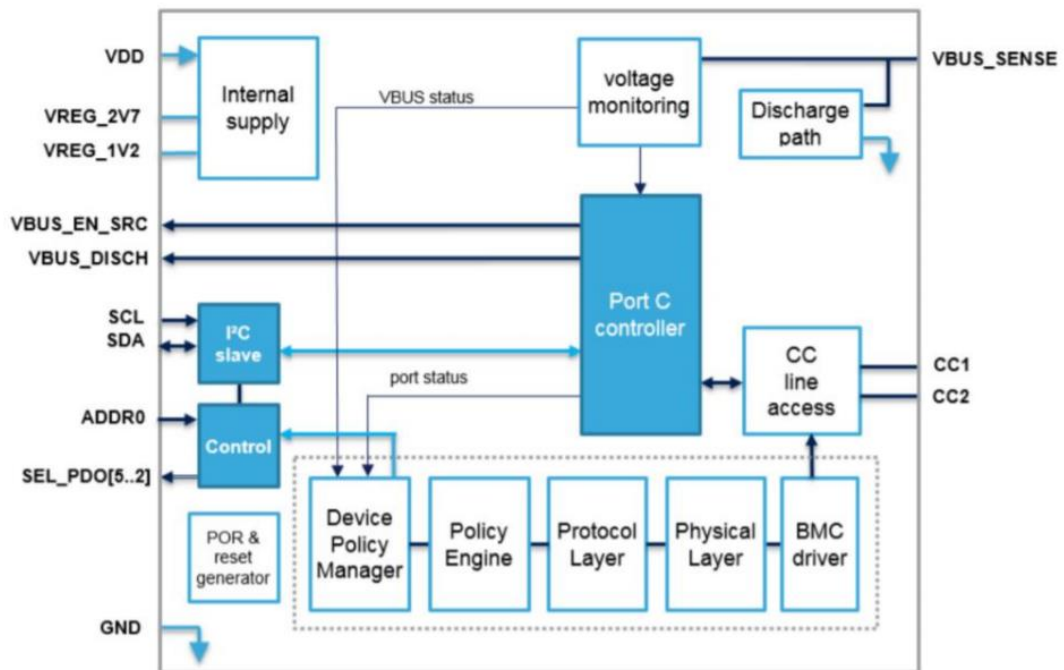
Fig. 4.2 Functional block diagram of STUSB4710, taken from [23]

4.2.4 Quick Charge controller

For Quick Charge 3.0 support for charging smartphones and other devices supporting this standard, the MP5034 USB Charging Port Controller was added. One of the advantages of this integrated circuit is that similarly to the STUSB4710, this circuit is fully autonomous, which allows simple integration to the final design. Besides Quick Charge,

MP5034 also supports BC1.2 protocol, which means it is able to charge non-QC devices with up to 1.5A at 5V. Additionally, it also supports 1.2V/1.2V and divider mode, which are both designed to charge devices of specific manufacturers that are not named due to licensing and therefore such labelling is preferred. This controller also includes input overvoltage protection and thermal shutdown. As determines the QC 3.0 standard, voltage is adjustable by 200mV in the range from 3.6V to 12V with maximum current of 3A.
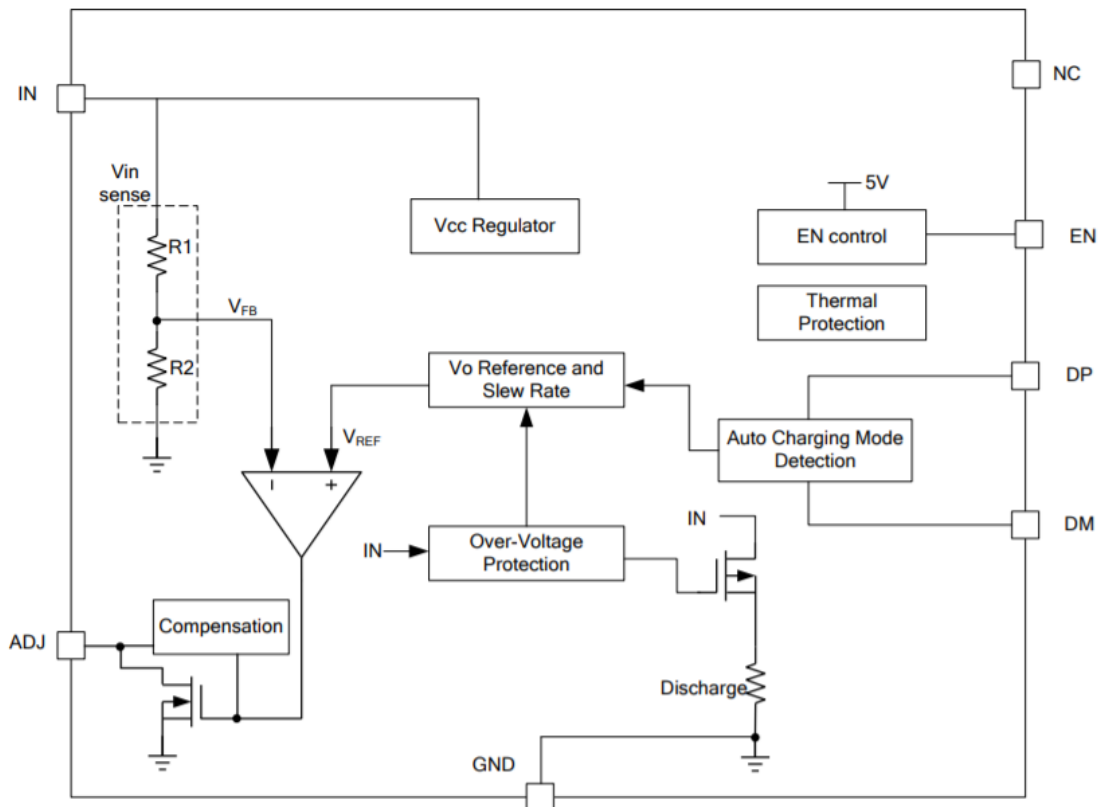
Fig. 4.3 Functional block diagram of MP5034, taken from [24]

4.2.5 Measurement and control circuit

The measurement and control circuit are realized with two INA Current monitoring chips by Texas Instruments connected to the MCU. INA3221, triple-channel current and voltage monitor with alert and warning outputs is supposed to measure the PD, QC and 12V automotive electrical outlet. It also has other useful features, but only the warning

output is implemented in this project. The circuit compares measured values to the desired, programmed value set in register and when the measured exceed the programmed one. When the measured current exceeded the programmed value, the warning output connected to the MCU triggers the relay on the concrete output results in cut off. INA226, single-channel current and power monitor with alert output is determined to measure the laptop output thanks to its higher bus voltage sense compared to INA3221 (0 – 36V). The principle there is identical with the INA3221 – the device triggers the alert output connected to the MCU in case that the current exceeds programmed limit, which results in deactivation of the laptop output. For the laptop output adjustment was chosen digital potentiometer MCP45HVX1. Each of the four outputs is connected through a separate relay, which is controlled by the MCU either to cut off or to activate individual outputs. The connection of the relays and the measuring circuits is presented in the Appendix A - Measured values.

4.2.6 Microcontroller unit

The MCU controlling the outputs and the overcurrent protection is Arduino Nano version 3. The device is based on ATmega328 microcontroller witch 2 kB SRAM and 32 kB flash memory. In case of input and output pins, 14 digital I/O pins and 8 analog input pins can be utilized. To increase the number of I/O pins and to simplify the design, MCP23008 8-bit expander is implemented on the front panel board for the user interface components. For more convenient realization, utilization of 3V3 version of Arduino Nano was decided.

4.2.7 Display and user interface

As a display unit, a graphic display DOGM128 from Electronic Assembly was chosen. This high-contrast LCD comes with resolution of 128x64 pixels, ST7565 controller, the possibility of different backlight colors combined with positive or negative display matrix, and voltage requirement of 3.3V. White backlight color along with the negative matrix were chosen thanks to its great appearance and good readability. User interface is realized with four buttons placed on a separate PCB along with rotary encoder for menu

navigation. With the rotary encoder, user will be able to navigate through the menu with different presets of voltages for different kinds of laptops, set the output voltage manually or change the displayed information. Thanks to four buttons, user will be able to turn on or off individual outputs, which will be indicated by a LED diode for each output.

4.3 Circuit diagram realization

The final diagram consists of four, basically independent LM5118 circuits. Therefore, the schema is divided into four blocks. Each contain one LM5118 circuit and specific circuit required for a particular output. The schematic part of the whole power supply was designed according to the datasheets of individual components. All components were chosen based on the desired output values and parameters of the circuit. The whole circuit diagram for this project was created in KiCad, free software for electronic design, updated to the version of 5.1.9.
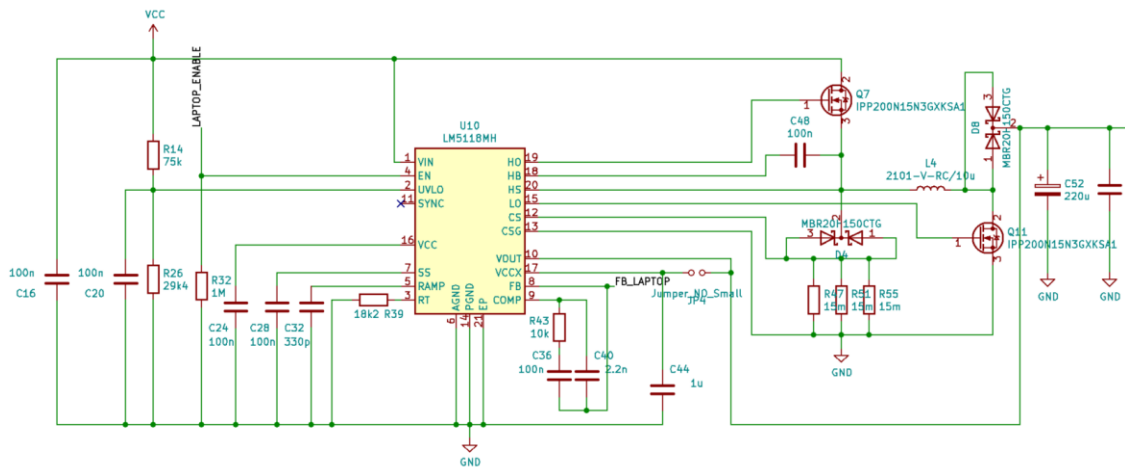
Fig.   4.4   The circuit diagram of the DC/DC part with LM5118 (laptop part)

The resulting circuit is based on a typical application schematic according to the datasheet with some necessary modifications. 100nF filtering capacitors were added to

the input as well as 220u and 100n capacitors on the output. Laptop enable pin is then connected to the MCU and feedback pin to the voltage divider on the laptop output.

R$_{39}$ represents the operating switching frequency resistor. The frequency of 300kHz was selected as a reasonable frequency for this circuit and the value of R$_{39}$ was calculated as follows:

$$R_{39} = \frac{6.4*10^9}{f} - 3.02*10^9 = \frac{6.4*10^9}{300k} - 3.02*10^9 = 18313.3 \ \Omega \ ,$$

(4.1)

A resistor with a value of 18k2 was selected.

The inductor selection is based on the frequency, load current, ripple current, input voltage and output voltage. The resulting value of the inductor was calculated based on the following assumptions:

V$_{IN(min)}$ = 6V; V$_{IN(max)}$ = 50V

V$_{OUT}$ = 3.6 – 24.8V

f = 300kHz

I$_{RIPPLE}$ = 3A (selected)

I$_{LOAD(max)}$ = 10A

Calculation:

$$L_{buck} = \frac{V_{OUT}*(V_{IN(max)} - V_{OUT})}{V_{IN(max)}*f*I_{RIPPLE}} = \frac{24.8*(50-24.8)}{50*300k*3} = 13.8 \ \mu H \ ,$$

(4.2)

$$L_{buck-boost} = \frac{V_{IN(min)}*V_{OUT}}{(V_{OUT}+V_{IN(min)})*f*I_{RIPPLE}} = \frac{6*24.8}{(24.8+6)*300k*3} = 5.4 \ \mu H.$$

(4.3)

An inductor with a value of 10µH was selected.

Resulting ripple current values based on the selected inductor were calculated as follows:

$$I_{RIPPLE(buck)} = \frac{V_{OUT}*(V_{IN(\max)}-V_{OUT})}{V_{IN(max)}*f*L} = \frac{24.8*(50-24.8)}{50*300k*13.8*10^{-6}} = 3.02A \ ,$$

(4.4)

$$I_{RIPPLE(buck-boost)} = \frac{V_{IN(min)}*V_{OUT}}{(V_{OUT}+V_{IN(min)})*f*L} = \frac{6*24.8}{(24.8+6)*300k*5.4*10^{-6}} =$$
$$= 2.98A \ .$$

(4.5)

The current sense resistor value calculation requires the calculation of the slope compensation of the controller represented by K.

$$K_{buck} = 1 + \frac{10}{V_{IN(\max)} - V_{OUT}} = 1 + \frac{10}{50 - 24.8} = 1.4$$

(4.6)

$$K_{buck-boost} = 1 + \frac{10}{V_{IN(min)}} = 1 + \frac{10}{6} = 2.7$$

(4.7)

For each particular output part of the final circuit, the current sense resistor value had to be calculated individually based on the output current and voltage of each output. For laptop, the output ranges from 16 to 24.8V with the power of 120W. The 12V output is limited to 7.5A. The Quick Charge output ranges from 3.6 to 12V with the maximum output current of 3A. In case of Power Delivery output, the voltage ranges from 5 to 20V with the maximum output current of 3A for 5 – 15V and 2.25A for 20V. The value of each current sense resistor is calculated using following formula:

$$R_{SENSE} = \frac{2.5*(1-M)}{10*\left(\frac{V_{IN(min)}+V_{OUT}}{V_{IN(min)}}*\frac{I_{OUT}}{\eta}+\frac{I_{RIPPLE}}{2}*K_{buck-boost}\right)} \ ,$$

(4.8)

where M represents a design margin and η is the efficiency of the converter. According to the datasheet of the LM5118, the design margin should be selected between 10 –30% (10% selected) and the efficiency η is 80%.

$$R_{SENSE(LAPTOP)} = \frac{2.5 * 0.9}{10 * \left(\frac{6 + 16}{6} * \frac{7.5}{80\%} + \frac{2.98}{2} * 2.7\right)} = 5.86 \, m\Omega \tag{4.9}$$

$$R_{SENSE(12V)} = \frac{2.5 * 0.9}{10 * \left(\frac{6 + 12}{6} * \frac{7.5}{80\%} + \frac{2.98}{2} * 2.7\right)} = 7 \, m\Omega \tag{4.10}$$

$$R_{SENSE(QC)} = \frac{2.5 * 0.9}{10 * \left(\frac{6 + 12}{6} * \frac{3}{80\%} + \frac{2.98}{2} * 2.7\right)} = 14.7 \, m\Omega \tag{4.11}$$

$$R_{SENSE(PD)} = \frac{2.5 * 0.9}{10 * \left(\frac{6 + 20}{6} * \frac{2.25}{80\%} + \frac{2.98}{2} * 2.7\right)} = 13.8 \, m\Omega \tag{4.12}$$

The selected value of current sense resistor must be the same or lower than the calculated value, therefore the values were selected as follows: $R_{SENSE(LAPTOP)}$ = 5mΩ, $R_{SENSE(12V)}$ = 5mΩ, $R_{SENSE(QC)}$ = 7.5mΩ, $R_{SENSE(PD)}$ = 7.5mΩ.

4.3.1 Laptop output

The laptop output consists of the mentioned LM5118 buck-boost controller and other components needed to control the output and select the desired voltage for different types of laptops.
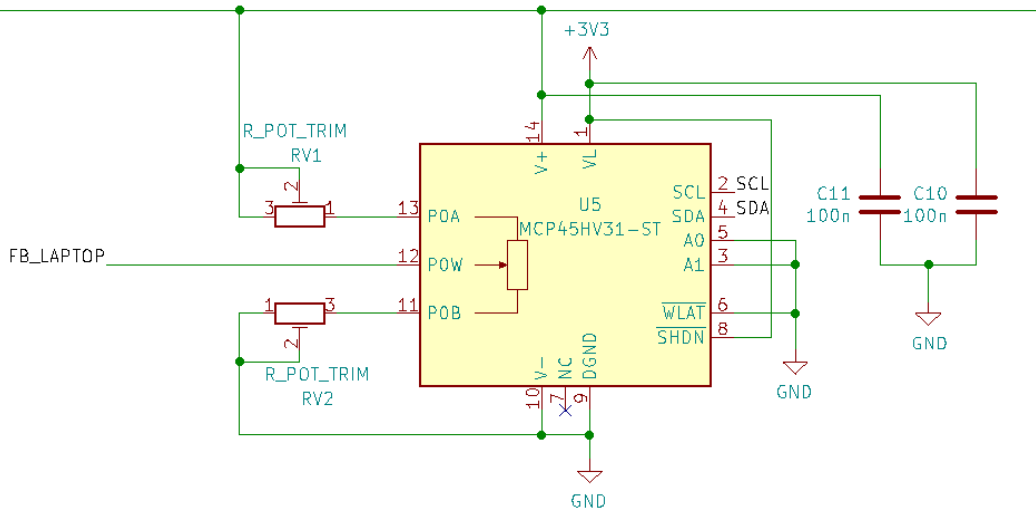
Fig. 4.5 The circuit diagram of the voltage control of the laptop output

As can be seen above (Fig. 4.5), the voltage control of the laptop output is realized using MCP45HV31 5kΩ digital potentiometer with I^{2}C serial interface. The potentiometer supports volage range from 10 to 36V, which ideally meets the desired requirements and can be powered from 3.3V and has a resolution of 128 bits, which is results in the step of less than 0.1V in the range of 16 – 24.8V. The final selected range of voltages for the laptop output is 16 – 24.8V, since it covers the most common laptop input voltages. The original intention was to utilize output voltage range from 12V to 24.8V with a step of 0.1V, but the increase of the minimum voltage was considered as a reasonable option afterwards, since the output current would be too high at a voltage as low as 12V, which is not worth the drawbacks in the form of heat dissipation and it would also mean a higher input current, which would be simply too much due to the theoretical efficiency of the DC/DC converter. The two trimmers (RV1 and RV2) serve to define the limits for the digital potentiometer. Two simple resistors would, of course, also serve this purpose, but trimmers were decided to use to for the possibility of changing the boundaries later, if necessary. Feedback pin of the LM5118 is connected to the wiper of the digital potentiometer and the I^{2}C bus pins of the MCP45HV31 are connected to the MCU. Calculations of the values that need to be set on the trimmers to achieve the range of 16 – 24.8V and the equations used are shown below.

$$\frac{V_{MAX}}{V_{FB}} = \frac{RV1 + RV2 + R_{DPOT}}{RV2}$$

<div align="right">(4.13)</div>

$$\frac{V_{MIN}}{V_{FB}} = \frac{RV1 + RV2 + R_{DPOT}}{RV2 + R_{DPOT}}$$

<div align="right">(4.14)</div>

$$\frac{V_{MAX}}{V_{FB}} = \frac{24.8}{1.23} = 20.16$$

$$\frac{V_{MIN}}{V_{FB}} = \frac{16}{1.23} = 13.01$$

$$RV1 = 19.16 * RV2 - 5k$$

$$20.16 = \frac{19.16RV2 - 5k + RV2 + 5k}{RV2 + 5k}$$

$$RV2 = 9.09k\Omega$$

$$RV1 = 169k\Omega$$

The last part of the laptop output circuitry is the INA226. Other outputs are utilizing the INA3221, but since it has only 3 sensing inputs, one of the outputs had to be supplemented by another monitoring integrated circuit. The I^{2}C bus pins of both INA226 and INA3221 are connected to the MCU.

4.3.2 12V output
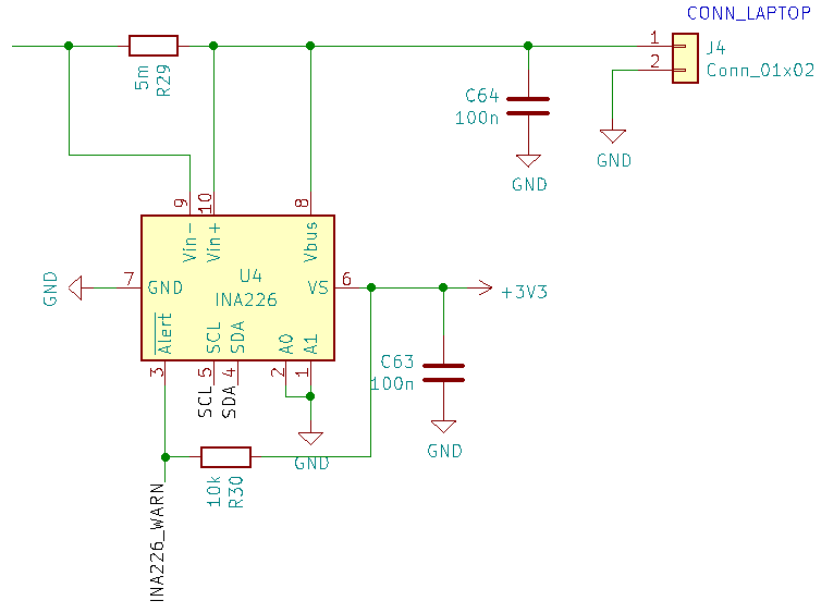
Fig. 4.6 INA226 connection

The 12V output part of the circuit also consists of LM5118 buck-boost controller, simple voltage divider for the 12V and a relay to switch the output on and off.
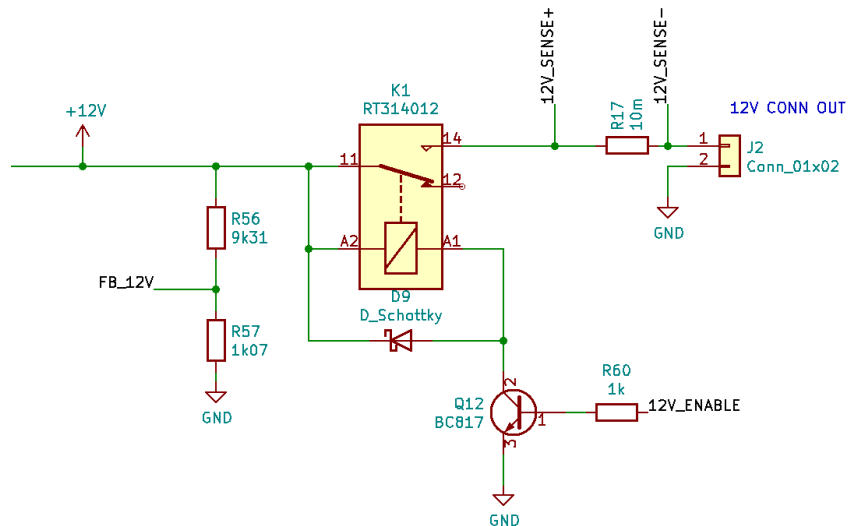
Fig. 4.7 The circuit diagram of the 12V output

As can be seen in the picture above, the relay coil is controlled by a bipolar transistor with base connected to the MCU, which can then trigger the relay and switch the output on and off. The 12V output circuitry is not controlled by the enable pin on the LM5118, because this circuit is needed to power the internal electronics. Therefore, the relay was a suitable option to control the output itself. The calculation for the voltage divider was performed by a basic calculation with the VFB voltage of LM5118 being 1.23V. The R_{17} resistor is a sensing resistor needed for the INA3221, which is connected to the 12V_SENSE pins.

4.3.3 Quick Charge output

The Quick Charge output utilizes the MP5034 charging port controller. The connection is simple with the need to calculate feedback resistors R_{21}, R_{22} and R_{25}.
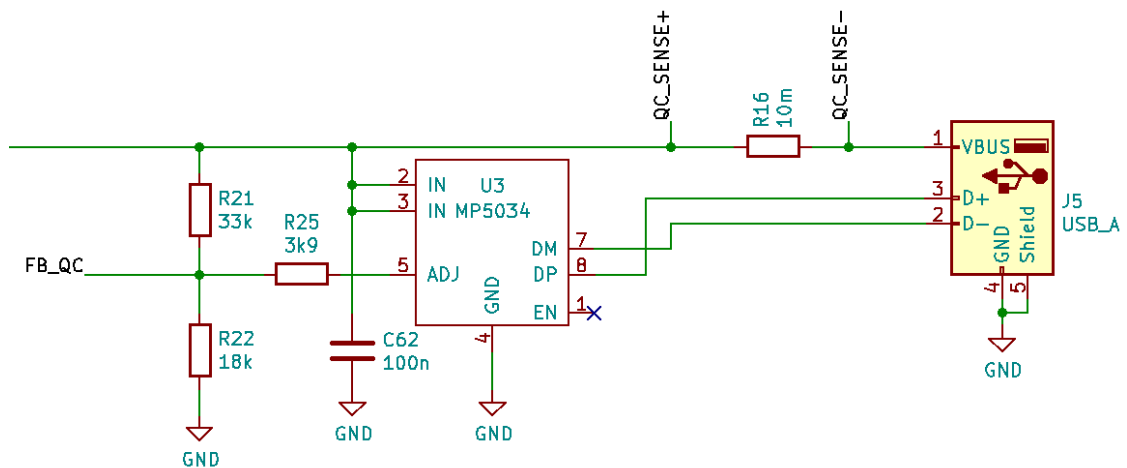
Fig.   4.8   The circuit diagram of the Quick Charge output

The MP5034 controls the voltage level for the Quick Charge compatible devices by the ADJ pin. When a higher voltage is required by a charged device, the controller sinks current via ADJ pin to adjust the voltage to the desired level. The value of R_{21} was set based on the following formula from the datasheet:

$$R_{21} = \frac{V_{OUT} - V_{FB}}{0.5}.$$

(4.15)

After substituting the feedback voltage od 1.23 and output voltage of 14V (absolute maximum from datasheet), the equation gives us a result of 25.54kΩ. Since the datasheets recommends value of more than 30kΩ for this resistor, the value of 33kΩ was used. Following calculations were made to determine the values of R_{22} and R_{25}:

$$R_{22} = \frac{V_{FB} * R_{21}}{V_{MIN} - V_{FB}} = \frac{1.23 * 33k}{3.48 - 1.23} = 18k\Omega$$

(4.16)

$$R_{22}//R_{25} = \frac{V_{FB} * R_{21}}{V_{MAX} - V_{FB}} = \frac{1.23 * 33k}{14 - 1.23} = 3.18k\Omega$$

(4.17)

$$R_{25} = \frac{R_{22}//R_{25} * R_{22}}{R_{22} - R_{22}//R_{25}} = \frac{3.18k * 18k}{18k - 3.18k} = 3.86k\Omega$$

(4.18)

4.3.4 Power Delivery output

The Power Delivery output uses STUSB4710 USB Power Delivery controller, which requires detectably more complicated circuitry than the previously described outputs. The controller sets the output voltage by grounding the individual SEL pins, which changes the value of the feedback voltage divider.
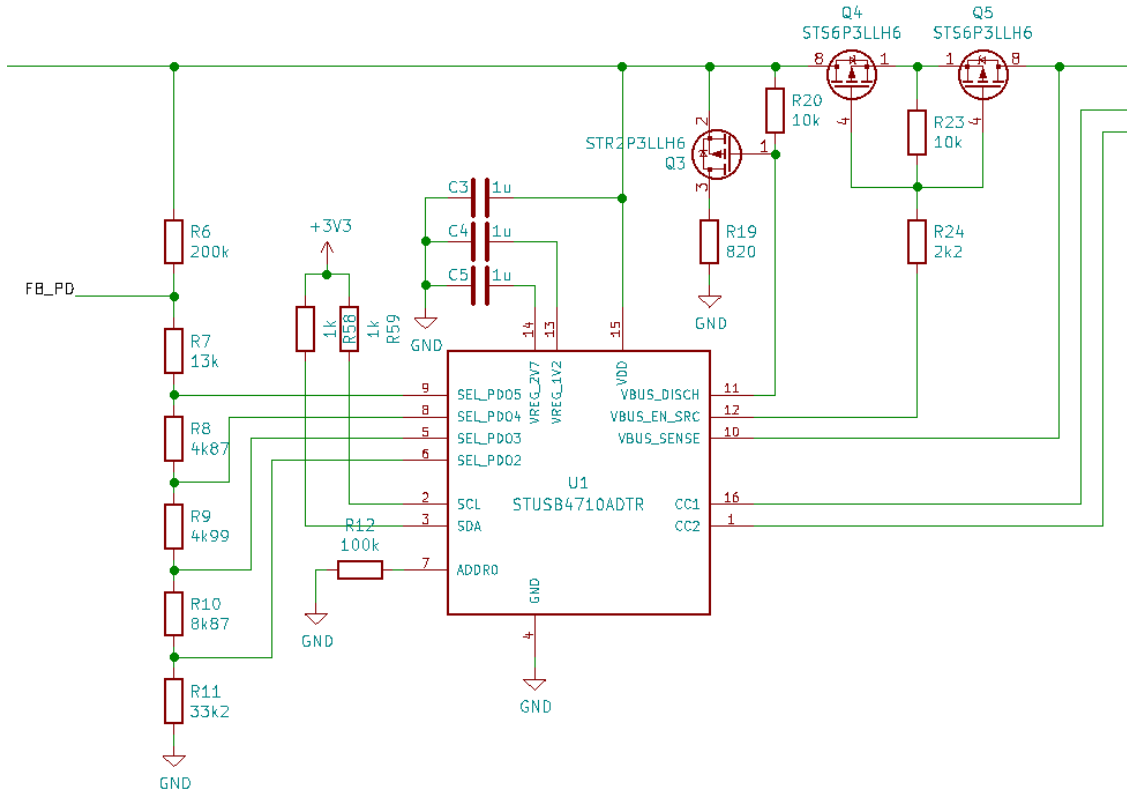
Fig. 4.9 The circuit diagram of the Power Delivery output

The resistors $R_7 - R_{11}$ had to be calculated based on the output voltage levels of the Power Delivery standard – 5, 9, 12, 15 and 20V. For R_6, the value of 200kΩ was selected and the V_{FB} is 1.23V. Following calculations were performed:

$$R_7 = \frac{R_6 * V_{FB}}{V_{OUT} - V_{FB}} = \frac{200k * 1.23}{20 - 1.23} = 13.1k\Omega\,, \tag{4.19}$$

$$R_8 = \frac{R_6 * V_{FB}}{V_{OUT} - V_{FB}} - R_7 = \frac{200k * 1.23}{15 - 1.23} - 13.1k = 4.76k\Omega\,, \tag{4.20}$$

$$R_9 = \frac{R_6 * V_{FB}}{V_{OUT} - V_{FB}} - R_7 - R_8 = \frac{200k * 1.23}{12 - 1.23} - 13.1k - 4.76k$$
$$= 4.98k\Omega \,, \tag{4.21}$$

$$R_{10} = \frac{R_6 * V_{FB}}{V_{OUT} - V_{FB}} - R_7 - R_8 - R_9 = \frac{200k*1.23}{9-1.23} - 13.1k - 4.76k -$$
$$4.98k = 8.82k\Omega \,, \tag{4.22}$$

$$R_{11} = \frac{R_6 * V_{FB}}{V_{OUT} - V_{FB}} - R_7 - R_8 - R_9 - R_{10} = \frac{200k*1.23}{5-1.23} - 13.1k -$$
$$4.76k - 4.98k - 8.82k = 33.59k\Omega \,. \tag{4.23}$$

The values of 13k, 4k87, 4k99, 8k87 and 33k2 were used based on the standardized resistor value chart. The rest of the schematic design is based on a typical application schema according to the datasheet with some necessary negligible modifications.

4.3.5 MCU and additional circuits

The MCU was chosen to be Arduino Nano v3. For the simplification of the design, the 3V3 version was decided to use.
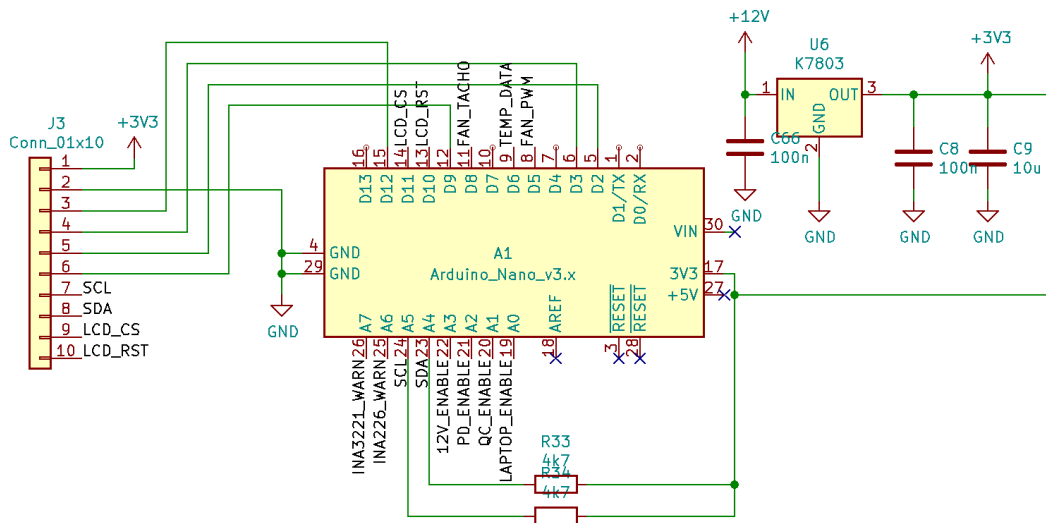
Fig. 4.10 The circuit diagram of the Arduino Nano connection

The powering of the Arduino is provided with the implementation of the small K7803 DC/DC converter. It provides 3.3V output for powering all the integrated circuits and parts on the PCB besides the Arduino that require it, such as both INA226 and INA3221, STUSB4710, the digital potentiometer, display and the 8-bit expander on the front panel PCB. As can be seen in the figure above, the K7803 is powered from the 12V power supply, because it eliminates the need for worrying about the input voltage range. It comes with the drawback that the 12V circuit needs to be active continuously and the output of it has to be switched on and off with the relay, which would not be the case if the K7803 was connected directly to the input. However, powering the converter from 12V was considered as a better and more suitable solution.

For the purposes of adjustable fan speeds and more sophisticated cooling, the connector for the PWM fan and temperature sensor are implemented in the schema. The selected temperature sensor is DS18B20 by Dallas. It offers 0.5°C accuracy in the temperature range from -10 to +85°C and is able to measure temperatures from -55°C up to +100°C with a programmable resolution from 9 to 12 bits. Both PWM fan control and temperature sensor are of course connected to the Arduino for the implementation in the control of the final device.
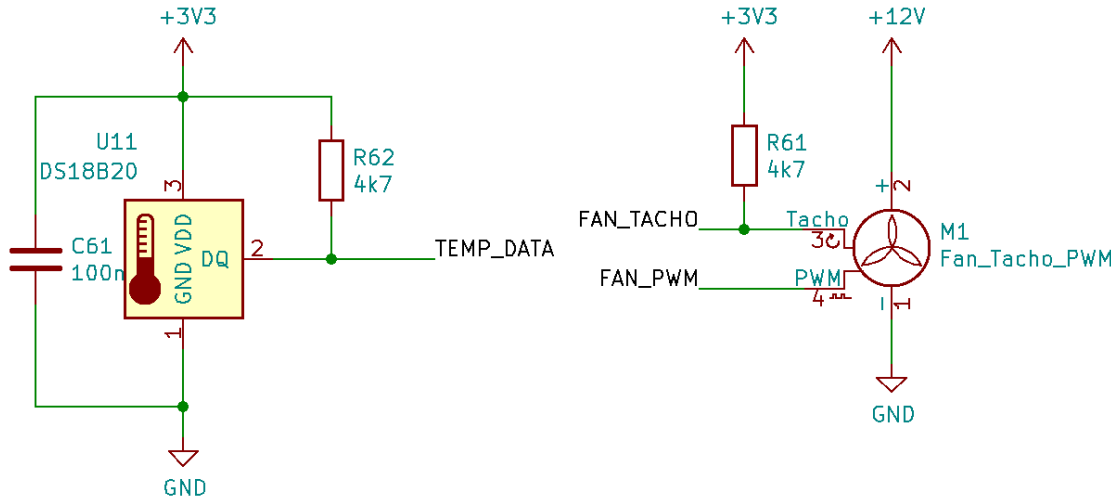
Fig. 4.11 The schematic connection of the temperature sensor and fan control

The display, buttons, diodes and rotary encoder are placed on the front panel. The buttons, LED diodes and rotary encoder are connected to the MCU on the main board by utilizing the I/O expander for better layout and connection. The display is connected directly to the MCU via connector that plugs to the main board. The connection of the display is based on the recommended connection listed in the datasheet of the display with the resistor R_8 being an exception due to the selected color of the backlight (white in this case).
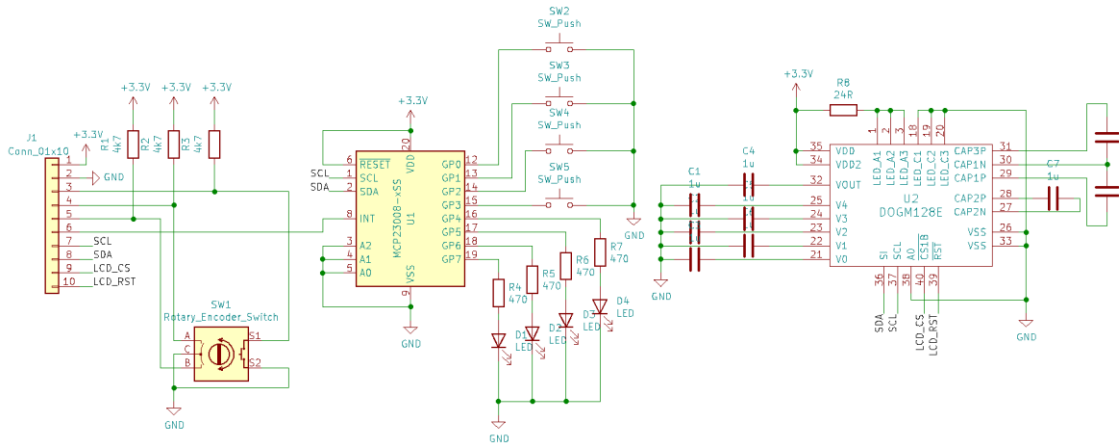
Fig.   4.12 The circuit diagram of the front panel PCB

4.4 PCB design

The PCB was designed by following general conventional rules. The placement of integrated circuits and components that surround them was decided and designed based on the recommendations listed in the particular datasheets. The main effort was to follow all recommendations and suggestions regarding the distance between the integrated circuits and their complementary components. The dimensions of the main board and the front panel were set based on the decided layout in the selected enclosure. The chosen metal enclosure is from 1455 series by Hammond. The layout in the enclosure is shown in the figure below. The PCB design was created using the same software as for creating the circuit diagram.
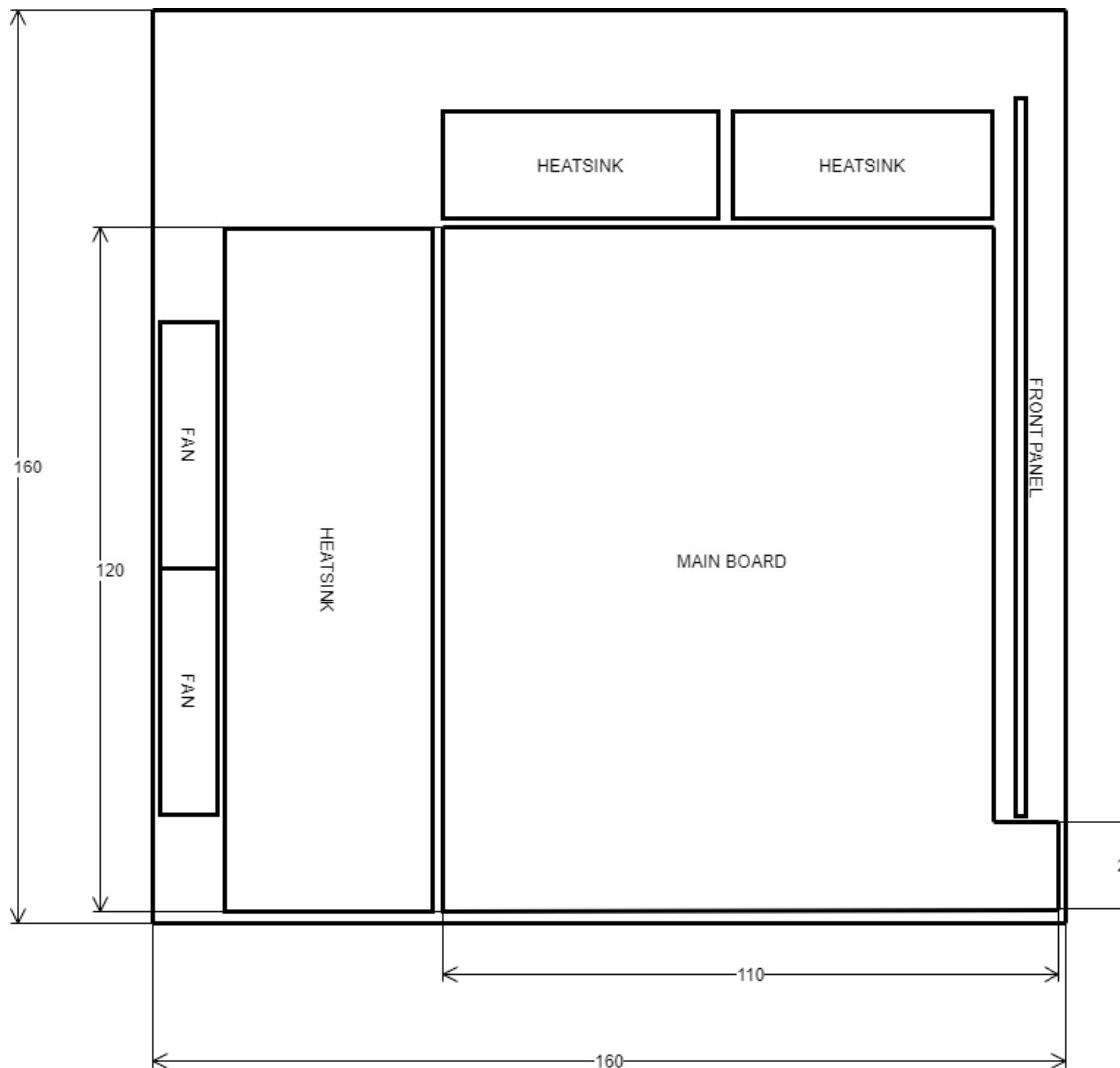
Fig.   4.13 The final layout in the enclosure

The width of the PCB traces was determined based on the nomograph provided in the document about PCB design by Minco (Fig. 4.14). All the recommendations about the width of the traces or the distance between individual components were met within the possibilities given by the size of the PCB and the whole device and the effort to fit all the components needed.
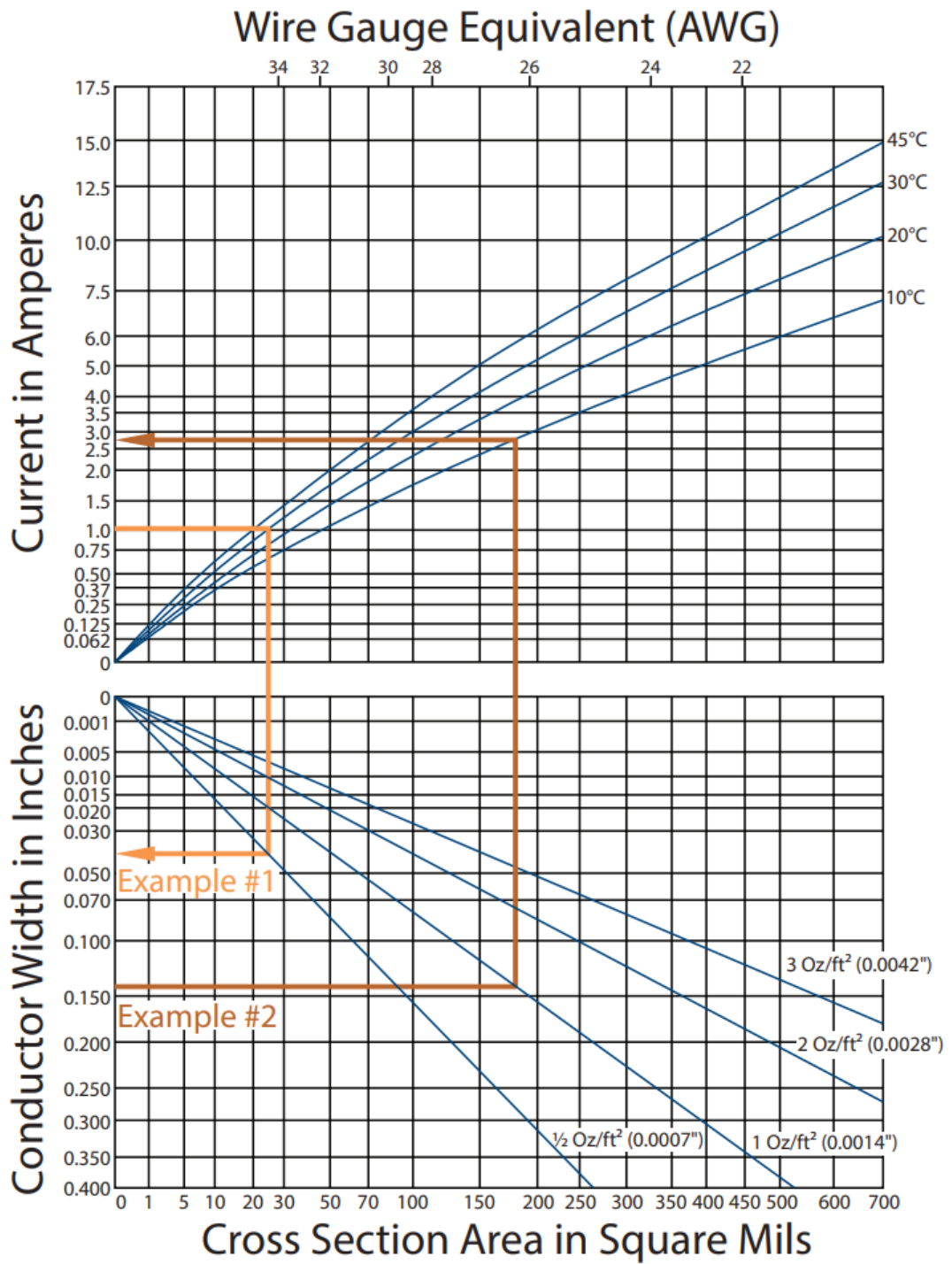
Fig.   4.14 Graph of standard recommendations of widths for PCB design,
taken from [25]

The figures below (Fig. 4.15 and 4.16) show the final renders of both the main board PCB and the front panel PCB.
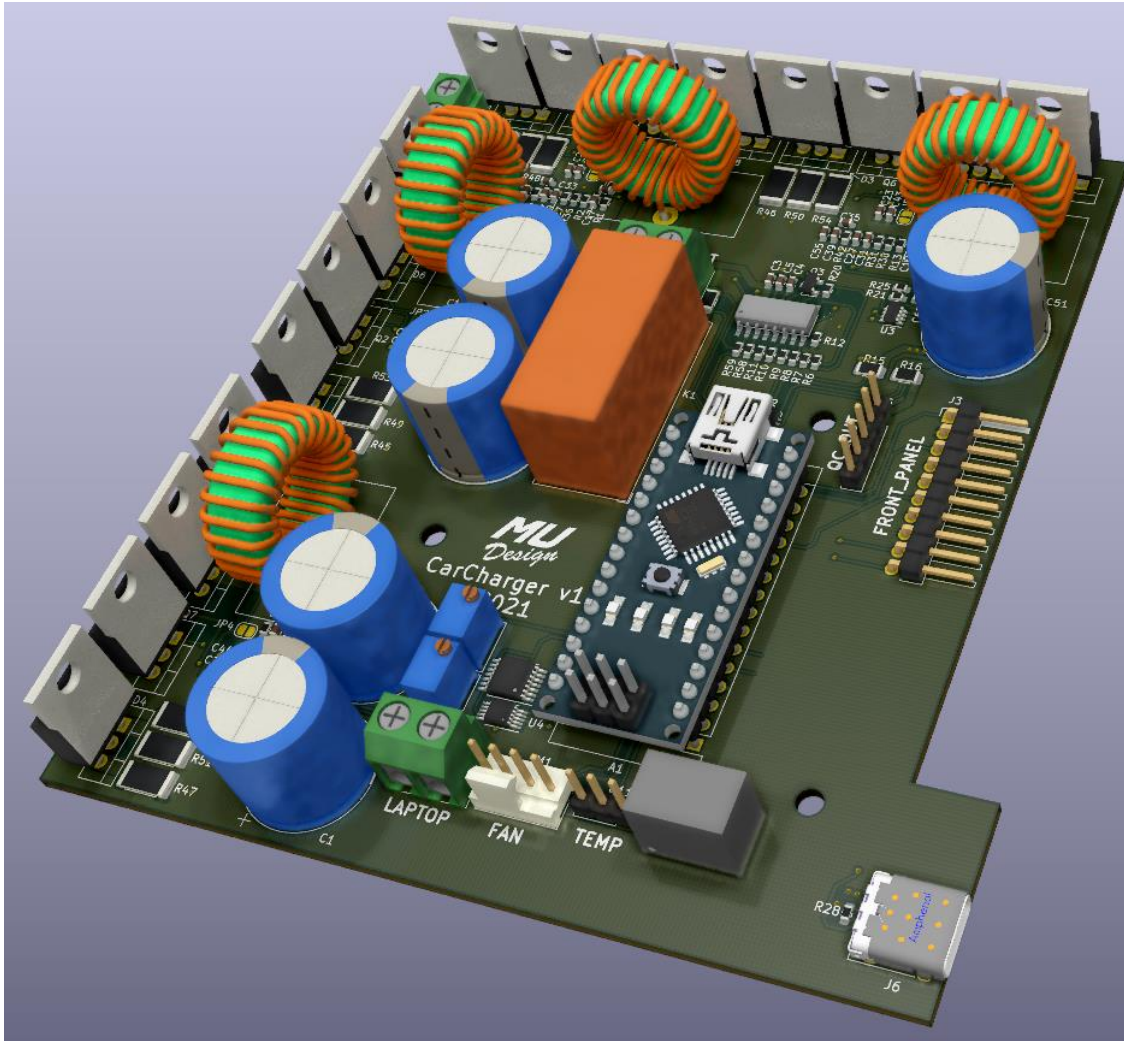
Fig. 4.15 The final render of the main board PCB
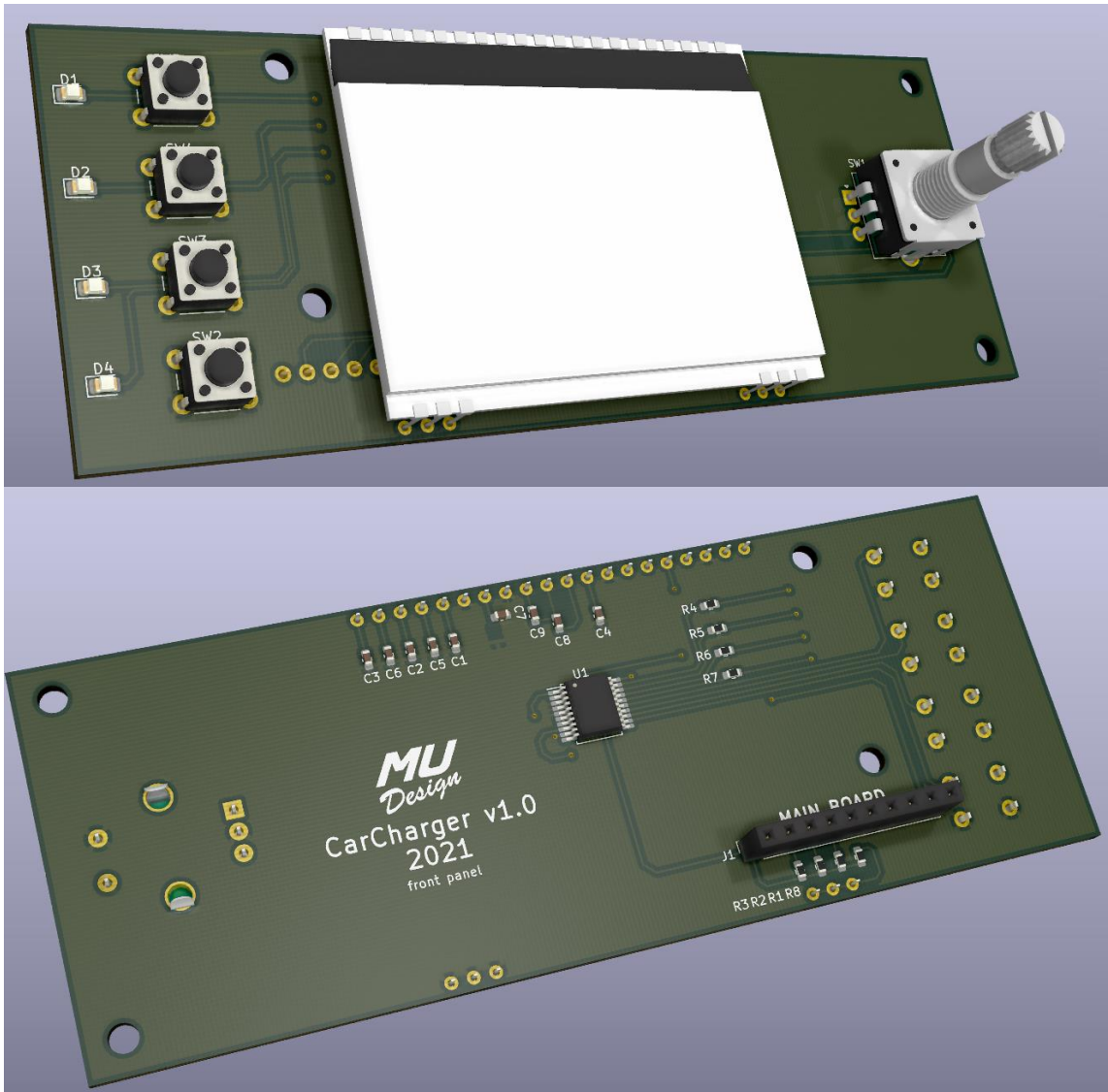
Fig.   4.16 The final renders of the front panel PCB (front and rear view)

4.5 Heat dissipation and cooling

The cooling of the device was designed based on the power dissipation by the MOSFETs and the diodes. For each component, the heat dissipation was calculated and the heatsinks were chosen based accordingly to these results. Other components that are prone to generate heat, such as coils and capacitors will be cooled by the airflow in the enclosure provided by the two intake fans. The calculation was performed based on the following formula:

$$T_j = P_{D(DIODE)} * (R_{jc} + R_{cs}) + P_{D(MOSFET)} * (R_{jc} + R_{cs})$$
$$+ (P_{D(DIODE)} + P_{D(MOSFET)}) * R_{sa} + T_a \quad , \tag{4.24}$$

where T_j is the junction temperature, P_D is power dissipation, R_{jc} and R_{cs} are thermal resistances (junction-case and case-junction), T_a is the ambient temperature and R_{sa} is the sink-ambient thermal resistance that we need to choose the heatsink. All the values required for the calculation were obtained from the datasheet of a particular component. The junction temperature of the MOSFET is 175°C and 150°C of the diode. Since both components will be placed on the same heatsink, the junction temperature of the diode is selected for the calculations.

$$P_{D(DIODE)} = 0.65V * 10A = 6.5W$$

$$P_{D(MOSFET)} = I^2 * R_{DS(on)} = 10^2 * 0.016 = 1.6W$$

$$150°C = 6.5 * (2 + 2.2) + 1.6 * (1 + 1.2) + (6.5 + 1.6) * R_{sa} + 25$$

$$R_{sa} = 11.63 \, °C/W$$

The calculation was performed for the laptop and 12V output circuits since they are designed to operate under the highest load. The Quick Charge and Power Delivery outputs have maximum load of 36W and 45W and therefore they will be seamlessly cooled by their placement between the bottom of the enclosure and a reasonably small heatsink. The calculation above resulted in 11.63°C/W for a one pair of MOSFET and diode. The PR173/50/SE heatsink obtained by TME with 1.8°C/W thermal resistance (modified to the required length using a milling cutter) along with two intake fans placed in front of the heatsink in the enclosure will serve as an ideally sufficient solution. The exhaust is provided by ventilation holes situated in the front right part of the bottom part of the enclosure to ensure that the air will flow through all components.

Fig.　4.17 Milling of the heatsink

5. ASSEMBLY AND OPERATION

The mounting of the components on the PCB was performed in the standard way from the smallest components to the larger. For the purposes of the first run of the DC/DC converters, the first circuit that was mounted to the working state was the 12V output circuit. After the tests and measurements for the purpose of ensuring that the converter behaves normally and the output is correct, the rest of DC/DC circuits were mounted and tested the similar way. The 3.3V circuit was tested before the sensitive components such as INAs or USB controllers were mounted and soldered to ensure that none of these devices would suffer a damage if anything were wrong with the circuit or any part would behave abnormally. Since the device is a prototype, manual soldering was considered as the most suitable procedure.

After the mounting and commissioning of the electrical part of the board, the logical part of the circuit followed. In case of Arduino, the original intention was to use the industrial clone by RobotDyn, which can be obtained in either 5V or 3V3 version. However, due to the complicated pandemic situation that affected the delivery and shipping of almost every good, this version of Arduino was not possible to obtain on time. As a solution, the regular original version of Arduino Nano was modified to be able to be powered from the 3V3 voltage level. Since the PCB is designed for the 3V3 version, the modifications of Arduino were only the removal of the default 5V regulator and the removal of the diode on the USB voltage input to ensure that there will be no 5V from the USB when connected to the computer. Then, the 3V3 pin on the Arduino was wired to the 5V pin.

In the process of the display connection, there was encountered an issue of wrong connection on the PCB. Due to the misleading labeling in the manufacturer's datasheet, it was assumed that the display communication is realized via I^2C. In fact, it is the SPI one-way communication with pins SI and SCL being the serial data in and serial clock pins and the A0 being the Data/Command pin. This design error was corrected by cutting the traces to the A0, SCL and SI pins of the display on the PCB and then rewiring them directly to the different pins on the Arduino.

During the first test of the Quick Charge output circuit, the DC/DC did not perform as expected and the output would drop with any load. The reason identified was in the slow voltage-change response of the controller. This resulted in the detection of undervoltage by the USB controller, which then cut off the output. This problem was solved by adding a 1nF capacitor in parallel to the upper resistor on the feedback voltage divider to improve the response of the controller. The capacitor was then added to the other three circuits as well to ensure the proper operation. Another modification was the addition of 470μF output filtering capacitor to the output of each DC/DC converter circuit to filter unnecessary spikes and to make the output more stable.

The last issue found was the instability of the Quick Charge and Power Delivery output in no load conditions. The USB charging controllers of both outputs are considerably sensitive due to tight specification of each standard, which was with a great probability the reason. The decided solution required adding a simple constant current sink utilizing an LM317 and an 8.2Ω resistor and placing it to the side of the main heatsink, which results in 152mA continuous load current. After this modification, both controllers operated normally and as expected.

5.1 Device assembly

After the modification of the enclosure, which involved cutting holes for the connectors, switches, display and fans, every component was fitted. For the input connector, the XT60 was considered to be a reasonable option due to its high current capabilities and standardization. In case of the laptop and 12V output on the front panel, the DC jack connectors were decided to use for their simplicity and based on the fact, that it will serve sufficiently for the purpose of a prototype. On the rear side of the power supply, the automotive fuse socket is mounted between the input connector and the power switch. The automotive type of fuse was considered as an ideal solution, since the device is intended to use in cars and in case of the blown fuse, the user would possibly have a replacement available without a need to buy a new one to get the device back in working condition immediately.

Fig.   5.1   Front and rear view of the assembled device
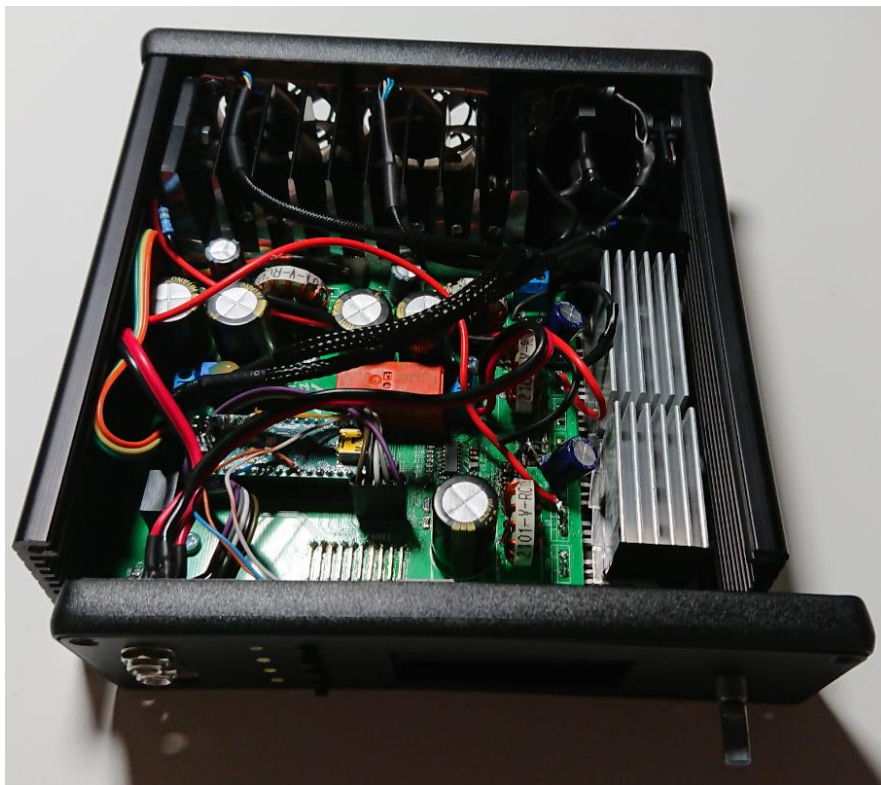
Fig.   5.2   Inside view of the assembled device

5.2 User interface

The user interface is realized with the display, rotary encoder to navigate through the menu displayed and four buttons to switch on or off individual outputs. The menu is designed in a user-friendly way to ensure simple and seamless operation. After turning on the device, the welcome screen appears and then the default menu. In the default screen, the user is informed about the amount of the total output power drained from all the outputs at that moment. On the line below, the currently switched-on outputs are shown (12V, Lap, QC, PD). Another displayed information includes the actual temperature inside the device as well as the actual fan speed in both RPM and PWM percentage.

Fig.   5.3   All six screens of user interface

The figure above (Fig. 5.3) shows all the available screens that user is able to scroll through by rotating the encoder. The screens for individual outputs display the output voltage, current and power of the particular output. The only exception is the laptop output screen, which displays in addition to the output values displays also the selected voltage. In the Laptop output screen, pressing the rotary encoder brings up the menu for the selection of the output voltage level. The user is able to choose from eight presets of laptop manufacturers (Acer, Asus, Dell, Fujitsu, HP, Lenovo, Samsung and Sony) that set the most common voltage level used by a given manufacturer and save it by pressing the encoder again. Selecting "Custom" brings up the selection menu, where is the user able to set any voltage in the range from 16 to 24.8V.

Fig.   5.4   Setting the laptop output voltage

The last part of the graphical user interface is the output overcurrent protection. If the output current of any output exceeds the hard-set limit, the MCU switches off the particular output and the notification containing the information which output reached the limit appears over the displayed screen. To ensure that the input will not be unnecesarily overloaded under any ciscumstances, the function of limitting the 12V output current was implemented. When the output current on the laptop output equals or exceeds 5A, the 12V output current limit is set to 1.5A. The information about this situation is then displayed at the bottom of the 12V screen.

5.3 MCU programming

The firmware of the MCU is written in C++ programming language with the limitations commonly used on embedded systems (no dynamic allocation, only classes (classic, inherited and virtual methods), which makes the program very modular and easy to update in the future.

The whole firmware is implemented with several classes. For the purpose of controlling the DC/DC converters, the basic class C_PwrSupply was created. It defines the basic interface for enabling the converters and returning the values of measured voltage, current and power. The rest of the methods is defined as virtual and are not implemented. For each converter, there is a derived class from C_PwrSupply that implements virtual methods according to the hardware configuration of each output circuit and additional methods (the voltage level setting in case of laptop output etc.) including the control of supporting voltage and current measuring circuits. The low-level

interface of the measurement circuits is implemented within seperate classes.

Another part is the cooling system. It processes the measured temperature and adjusts the fan speed accordingly using the PWM output. The actual speed of the fans is obtained from the tacho output and the measurement of the lenght of the incoming pulse. The fan speed curve is set to a default rate of 30% and then increases linearly with the increasing temperature. When 60°C temperature is reached, the fans start running at full power (100%). The default rate of 30% was considered to be ideal for silent operation while keeping minor constant airflow to cool other components such as coils and capacitors even when the power components (MOSFETs and diodes) do not operate at such power to warm up the heatsink and force the cooling regulation to increase the fan speed.

The user interface elements are realized with two classes, namely C_FrontPanel (buttons, LED indication and rotary encoder) and C_UI_Graphics (implementing a graphical user interface using a graphical display). The methods of both classes are called from the main loop of the program and the buttons are used to control the status of the outputs, which is then indicated by the LED diodes. Within the graphical environment, individual screens and menus (described in the previous chapter) are implemented always as separate methods. It is also possible to display notifications about the status of the output with a simple graphical effect, which is utilized in case of the overcurrent state of the output.

The last part of the firmware are additional classes that include the communication with the digital potentiometer, output monitoring integrated circuits (INA226 and INA3221) and the temperature sensor.

For the firmware development, the PlatformIO IDE development environment was used within the VisualStudio Code, which provides a comfortable and comprehensive solution for the development of the embedded firmware, including the possibility of using library files provided through the Arduino IDE. In addition to the basic libraries for the operation of the communication interface and inputs and outputs, other open-source libraries for the rotary encoder, temperature sensor and integrated circuits for voltage and current measurement were also utilized.

6. TESTING AND MEASUREMENTS

For the purposes of analyzing the resulting parameters of the device, measurements at no load as well as under load were performed. The equipment used for the measurements includes multimeter Proskit MT-1710, oscilloscope OWON SDS8102V, laboratory power supply Manson HCS – 3202, Quick Charge USB-A trigger, Power Delivery USB-C trigger, resistive load, laptop Lenovo ThinkPad T470s with support for USB-C Power Delivery charging, smartphone Sony Xperia XZ1 with support for both Quick Charge 3.0 and Power Delivery 2.0 and power bank Alza Power PBM10CF that also supports both Quick Charge and Power Delivery.

The first measurements performed were under no load to determine whether the outputs meet the requirements and specifications for all the input voltage levels (6V, 12V, 24V, 36V). In the table below (Table 6.1) is shown that the no-load output values measured for 12V input are correct and meet the requirements and specifications. The measurements for the rest of the input voltage levels can be found in the Appendix A.1.

Table 6.1 Measured values under no-load conditions for 12V input

$V_{IN} = 12V$, $I_{OUT} = 0A$		
Measured output	**Required voltage**	**V_{OUT} [V]**
12V output	$V = 12V$	11.97V
Laptop output	$V_{SET} = 16V$	16.04V
	$V_{SET} = 19.5V$	19.53V
	$V_{SET} = 24.8V$	24.80V
USB QC	$V_{QC} = 3.6V$	3.61V
	$V_{QC} = 5V$	5.07V
	$V_{QC} = 9V$	9.03V
	$V_{QC} = 12V$	11.98V
USB PD	$V_{PD} = 5V$	5.01V
	$V_{PD} = 9V$	8.98V
	$V_{PD} = 12V$	11.99V
	$V_{PD} = 15V$	15.00V
	$V_{PD} = 20V$	20.12V

The next measurements were performed for all input voltage levels with a resistive load at the output. A simplified brief overviews are shown in the tables below (Tables 6.2 – 6.5).

Table   6.2   Measured values under a resistive load for 6V input

V_{IN} = 6V, I_{OUT} ≠ 0A					
Measured output	**Required voltage**	**V_{OUT} [V]**	**I_{OUT} [A]**	**I_{IN} [A]**	**η [%]**
12V output	V = 12V	11.78V	1.70A	5.36A	46.7%
Laptop output	V_{SET} = 19.5V	19.50V	0.30A	3.73A	19.59%
USB PD	V_{PD} = 5V	4.80V	1.10A	1.47A	45.00%
	V_{PD} = 20V	18.35V	0.70A	5.17A	31.04%

Table   6.3   Measured values under a resistive load for 12V input

V_{IN} = 12V, I_{OUT} ≠ 0A					
Measured output	**Required voltage**	**V_{OUT} [V]**	**I_{OUT} [A]**	**I_{IN} [A]**	**η [%]**
12V output	V = 12V	11.90V	1.90A	2.33A	80.75%
Laptop output	V_{SET} = 19.5V	19.50V	0.40A	1.40A	46.43%
USB PD	V_{PD} = 5V	4.92V	1.20A	0.82A	60.25%
	V_{PD} = 20V	20.09V	0.52A	2.32A	37.69%

Table   6.4   Measured values under a resistive load for 24V input

V_{IN} = 24V, I_{OUT} ≠ 0A					
Measured output	**Required voltage**	**V_{OUT} [V]**	**I_{OUT} [A]**	**I_{IN} [A]**	**η [%]**
12V output	V = 12V	11.94V	1.80A	1.00A	89.55%
Laptop output	V_{SET} = 19.5V	19.50V	1.30A	2.50A	42.25%
USB PD	V_{PD} = 5V	5.00V	1.10A	0.40A	57.29%
	V_{PD} = 20V	20.32V	0.72A	1.01A	48.49%

Table   6.5   Measured values under a resistive load for 36V input

V_{IN} = 36V, I_{OUT} ≠ 0A					
Measured output	**Required voltage**	**V_{OUT} [V]**	**I_{OUT} [A]**	**I_{IN} [A]**	**η [%]**
12V output	V = 12V	11.96V	1.72A	0.68A	84.03%
Laptop output	V_{SET} = 19.5V	19.50V	1.20A	1.37A	47.45%
USB PD	V_{PD} = 5V	5.01V	1.10A	0.28A	54.67%
	V_{PD} = 20V	20.16	0.71A	0.70A	56.80%

As can be seen in the tables of measured results, the efficiency of the power supply is lower than expected. As expected, the DC/DC converters are apparently more efficient in the buck-boost or buck mode. The best results of efficiency are for the 12V output. The precise V_{OUT} voltage of the laptop output for each input voltage level is a result of

implementation of automatic laptop output voltage compensation. The negligible inaccuracy of the voltage levels for USB Power Delivery output are with the most probability caused by the very strict requirements for the values of the resistors of the voltage divider, which had to be chosen with a minimal deviation based on the available resistor values that can be obtained. Unfortunately, the Quick Charge output could not be measured under load, because the trigger was malfunctioning, probably due to the fact, that the Quick Charge standard is a licensed closed standard, and it was not implemented properly on the trigger. Therefore, the trigger did not work with the resistive load used for measuring the parameters of other outputs but worked seamlessly with the Quick Charge compatible device attached. The figure below (Fig. 6.1) shows the charging of the Xperia XZ1 from the Quick Charge output of the device. Since the licensing mentioned, it is not possible to find any information about what voltage, power or current would the device draw at a certain amount of battery charge. Therefore, the option of connecting the compatible device with the trigger attached to the Quick Charge output and setting the voltage manually was not considered as an ideal method due to the possible risk of damaging the connected device. All measurement results are shown in Appendix A - Measured values.

Fig. 6.1   Smartphone charging via the USB-A Quick Charge output

The output ripple was measured using the OWON oscilloscope on the laptop output. The screenshot below (Fig. 6.2) was taken with the 12V input voltage, output

load of 0.4A at the output voltage of 19.5V. The scale of the x axis is 10ms/Div and of the y axis is 50mV/Div. The measured peak-to-peak ripple is 82mV.
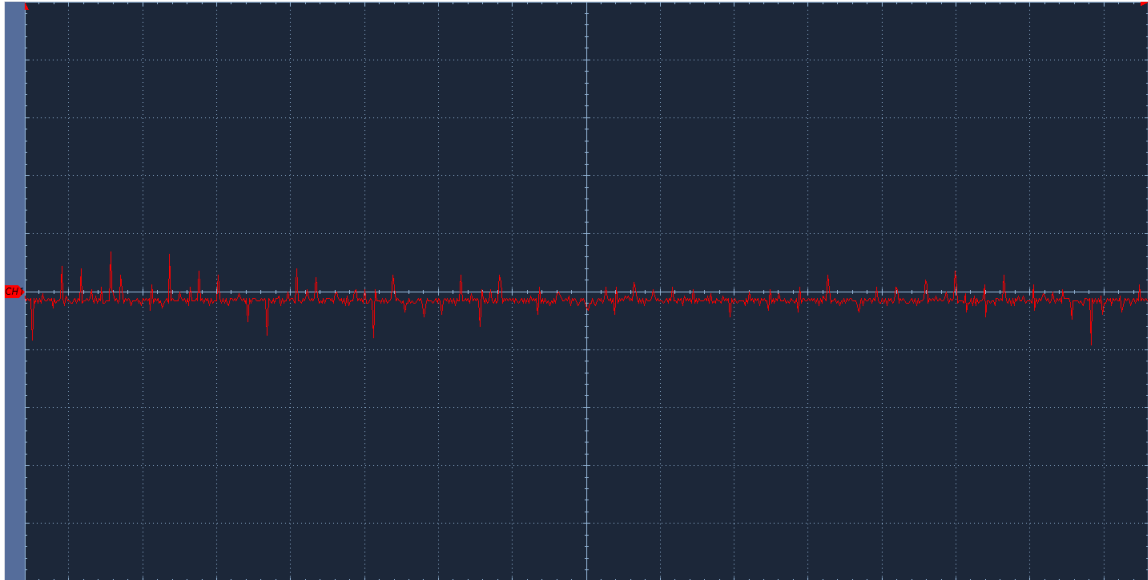
Fig.   6.2   The output ripple of the power supply

The last part of the testing and measurements was a maximum required output power test. Since any electronic load device could not be obtained, the test was performed with an old gaming laptop, Lenovo Y510p. The AC adapter of this laptop is rated for 8.5A at 20V, which results in maximum power of 170W and is suitable for this test. The figure below (Fig. 6.3) shows a total power drained by the laptop while running 3DMark with the battery taken out to maximize the power consumption. Due to the limitations of the laboratory power supply available, the test was performed at the input voltage of 36V. Due to the efficiency of the designed power supply, a lower voltage level would result in a higher input current, which is outside of the specifications of the laboratory power supply.

Fig. 6.3 The test of maximum output power

7. CONCLUSION

The main objective of this project was to design, assemble and test a universal laptop power supply for use in vehicles. Specified goals were the output power up to 120W, the input voltage from 6V to 36V (for 6V, 12V, 24V and 36V on-board distribution networks) and adjustable voltage output for laptops in the range from 16V to 24V. The final design meets all the requirements and in addition also implements Power Delivery output to improve current and future usability of the device in terms of laptop powering. The Quick Charge output and 12V output are also included to improve the versatility of the final device. The device also features comfortable and simple user interaction thanks to the LED display, switching buttons and rotary encoder. The thesis presents the theoretical design process, practical design process in a form of designing the circuit diagram and PCB layout, assembly of the device and final testing and measurements both with synthetic load and a real-world load.

The very first idea was to utilize modular DC/DC converters (one for each output), but due to the unsatisfactory efficiency and specifications of available converters, the approach of design a circuit including the DC/DC converters was decided. The used converters, LM5118, offer wide range of both input and output voltages and promise high efficiency. As can be seen in chapter 6, the efficiency of the finished device is not as excellent as expected. Nevertheless, the resulting device is capable of charging almost any laptop available (including those that support only the Power Delivery standard), while simultaneously charge any device that supports Quick Charge or any basic USB charging protocol.

The USB controllers for both Power Delivery and Quick Charge are very sensitive to the input voltage and other parameters due to the general specifications of each standard. Therefore, these controllers would probably more benefit from using DC/DC converters that have more precise specification and tighter tolerances. However, the controllers are successfully implemented and utilized in this project, and they operate without any issues in the final device.

The thesis proves the possibility of producing a device that combines old, legacy laptop charging method with modern fast charging standards in a reasonable-sized enclosure while providing a respectable output power. All this with the possibility to operate properly from all commonly used on-board distribution network levels. If a real production device should be manufactured on the basis of this project, it would probably benefit from changing some of the parameters. The 120W total output power is unnecessarily high for a device with this purpose. The power of 45W or 65W would be more reasonable because laptops are considerably more efficient these days and do not require such power. The optional requirement of the 12V output on the final device would be probably also omitted. These modifications would result in substantially smaller, more portable device while keeping the versatility and combination of old and modern charging standards. However, the resulting efficiency achieved in this project may with a great probability be the reason why such device does not exist yet.

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SYMBOLS AND ABBREVIATIONS

Abbreviations:

DC	Direct Current
AC	Alternating Current
USB	Universal Serial Bus
PD	Power Delivery
QC	Quick Charge
PFC	Power Factor Correction
PWM	Pulse Width Modulation
LPS	Limited Power Source
MCU	Microcontroller unit
I/O	Input/Output
PCB	Printed Circuit Board

LIST OF APPENDICES

Appendix A - Measured values

A.1 Tables of measured values under no load

$V_{IN} = 6V$, $I_{OUT} = 0A$		
Measured output	**Required voltage**	**V_{OUT} [V]**
12V output	V = 12V	11.92V
Laptop output	$V_{SET} = 16V$	16.01V
	$V_{SET} = 19.5V$	19.50V
	$V_{SET} = 24.8V$	24.80V
USB QC	$V_{QC} = 3.6V$	3.62V
	$V_{QC} = 5V$	5.05V
	$V_{QC} = 9V$	9.00V
	$V_{QC} = 12V$	11.97V
USB PD	$V_{PD} = 5V$	5.00V
	$V_{PD} = 9V$	8.97V
	$V_{PD} = 12V$	11.96V
	$V_{PD} = 15V$	15.01V
	$V_{PD} = 20V$	20.09V

$V_{IN} = 12V$, $I_{OUT} = 0A$		
Measured output	**Required voltage**	**V_{OUT} [V]**
12V output	V = 12V	11.97V
Laptop output	$V_{SET} = 16V$	16.04V
	$V_{SET} = 19.5V$	19.53V
	$V_{SET} = 24.8V$	24.80V
USB QC	$V_{QC} = 3.6V$	3.61V
	$V_{QC} = 5V$	5.07V
	$V_{QC} = 9V$	9.03V
	$V_{QC} = 12V$	11.98V
USB PD	$V_{PD} = 5V$	5.01V
	$V_{PD} = 9V$	8.98V
	$V_{PD} = 12V$	11.99V
	$V_{PD} = 15V$	15.00V
	$V_{PD} = 20V$	20.12V

$V_{IN} = 24V$, $I_{OUT} = 0A$		
Measured output	**Required voltage**	**V_{OUT} [V]**
12V output	V = 12V	11.99V
Laptop output	$V_{SET} = 16V$	16.00V
	$V_{SET} = 19.5V$	19.50V
	$V_{SET} = 24.8V$	24.80V
USB QC	$V_{QC} = 3.6V$	3.62V
	$V_{QC} = 5V$	5.06V
	$V_{QC} = 9V$	9.06V

	$V_{QC} = 12V$	11.97V
	$V_{PD} = 5V$	5.00V
	$V_{PD} = 9V$	8.99V
USB PD	$V_{PD} = 12V$	11.99V
	$V_{PD} = 15V$	15.01V
	$V_{PD} = 20V$	20.10V

$V_{IN} = 36V, I_{OUT} = 0A$		
Measured output	Required voltage	V_{OUT} [V]
12V output	V = 12V	11.97V
	$V_{SET} = 16V$	16.00V
Laptop output	$V_{SET} = 19.5V$	19.50V
	$V_{SET} = 24.8V$	24.80V
	$V_{QC} = 3.6V$	3.62V
USB QC	$V_{QC} = 5V$	5.08V
	$V_{QC} = 9V$	9.04V
	$V_{QC} = 12V$	11.98V
	$V_{PD} = 5V$	5.00V
	$V_{PD} = 9V$	8.98V
USB PD	$V_{PD} = 12V$	11.99V
	$V_{PD} = 15V$	15.00V
	$V_{PD} = 20V$	20.13V

A.2 Tables of measured values under a resistive load

$V_{IN} = 6V, I_{OUT} \neq 0A$					
Measured output	Required voltage	V_{OUT} [V]	I_{OUT} [A]	I_{IN} [A]	η [%]
12V output	V = 12V	11.78V	1.70A	5.36A	46.70%
	$V_{SET} = 16V$	16.00V	1.10A	4.40A	50.00%
Laptop output	$V_{SET} = 19.5V$	19.50V	0.30A	3.73A	19.59%
	$V_{SET} = 24.8V$	24.00V	0.40A	4.27A	28.13%
	$V_{PD} = 5V$	4.80V	1.10A	1.47A	45.00%
	$V_{PD} = 9V$	9.10V	1.50A	4.03A	30.77%
USB PD	$V_{PD} = 12V$	12.07V	0.59A	2.93A	30.35%
	$V_{PD} = 15V$	15.00V	0.61A	3.97A	28.79%
	$V_{PD} = 20V$	18.35V	0.70A	5.17A	31.04%

$V_{IN} = 12V, I_{OUT} \neq 0A$					
Measured output	Required voltage	V_{OUT} [V]	I_{OUT} [A]	I_{IN} [A]	η [%]
12V output	V = 12V	11.90V	1.90A	2.33A	80.75%
	$V_{SET} = 16V$	16.00V	1.20A	3.97A	40.34%
Laptop output	$V_{SET} = 19.5V$	19.50V	0.40A	1.40A	46.43%
	$V_{SET} = 24.8V$	24.80V	0.40A	1.98A	41.68%

	V_PD = 5V	4.92V	1.20A	0.82A	60.25%
	V_PD = 9V	8.78V	1.58A	1.63A	70.78%
USB PD	V_PD = 12V	11.68V	1.80A	2.25A	58.32%
	V_PD = 15V	15.11V	0.60A	1.75A	43.17%
	V_PD = 20V	20.09V	0.52A	2.31A	37.69%

V_{IN} = 24V, $I_{OUT} \neq$ 0A					
Measured output	**Required voltage**	**V_{OUT} [V]**	**I_{OUT} [A]**	**I_{IN} [A]**	**η [%]**
12V output	V = 12V	11.94V	1.80A	1.00A	89.55%
Laptop output	V_{SET} = 16V	16.00V	1.20A	1.50A	53.33%
	V_{SET} = 19.5V	19.50V	1.30A	2.50A	42.25%
	V_{SET} = 24.8V	24.80V	0.40A	1.10A	37.58%
USB PD	V_{PD} = 5V	5.00V	1.10A	0.40A	57.29%
	V_{PD} = 9V	8.89V	1.60A	0.78A	75.98%
	V_{PD} = 12V	11.94V	1.90A	1.20A	78.77%
	V_{PD} = 15V	15.00V	0.62A	0.70A	55.36%
	V_{PD} = 20V	20.32V	0.72A	1.01A	48.49%

V_{IN} = 36V, $I_{OUT} \neq$ 0A					
Measured output	**Required voltage**	**V_{OUT} [V]**	**I_{OUT} [A]**	**I_{IN} [A]**	**η [%]**
12V output	V = 12V	11.96V	1.72A	0.68A	84.03%
Laptop output	V_{SET} = 16V	16.00V	1.09A	0.98A	49.43%
	V_{SET} = 19.5V	19.50V	1.20A	1.37A	47.45%
	V_{SET} = 24.8V	24.80V	0.40A	0.61A	45.17%
USB PD	V_{PD} = 5V	5.01V	1.10A	0.28A	54.67%
	V_{PD} = 9V	8.94V	1.50A	0.60A	62.08%
	V_{PD} = 12V	11.97V	1.78A	0.80A	73.98%
	V_{PD} = 15V	15.00V	0.61A	0.49A	51.87%
	V_{PD} = 20V	20.16V	0.71A	0.70A	56.80%