WRepair Stations

Development of advanced protection mechanism within USB-C charging station to prevent electrical damage

EE3L11: Bachelor Graduation Project

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by

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Preface

This thesis submission is presented in partial satisfaction of the requirements for the Bachelor of Science in Electrical Engineering at Delft University of Technology. The goal of the thesis is to design a charging station. Although we are finishing our bachelor's soon, when receiving the proposal for this thesis we realized we had never truly considered the electrical safety and power quality and the potential challenges it poses. It reminded us just how vast the world of electrical engineering is. Throughout this project, we learned just how essential electrical safety and power quality are for power electronics. Designing a safe and high-quality electrical system was challenging, but it was also a fulfilling task with a direct relation to an emerging problem in the low-voltage power electronics sector.

I want to thank my supervisors, Ali Kaichouhi and Mark van Beusekom, for their invaluable guidance and support during this project. Their expertise and words of encouragement have been crucial to the development of this thesis. Our gratitude also goes to the faculty and staff of the Electrical Engineering Department with regard to providing the resources and knowledge needed for this research.

The academic environment they fostered has significantly contributed to my learning and growth. Additionally, our special thanks to our amazing colleagues for their sense of camaraderie and teamwork, which have made this journey both enjoyable and mentally stimulating, also an enormous thanks to our lovely family for their continued support and belief in our abilities, all of which have been a steady source of motivation. Many thanks to you all for your input and amazing support.

Amin Aynan
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Abstract

This thesis explores the design and implementation of electrical safety mechanisms for both human and machine safety, as well as power supply and power quality for the WRepair Powerstation. The WRepair Powerstation serves as a critical component in the electronics repair industry, providing essential charging and data transfer capabilities for various smart devices.

The primary goal of this project is to develop an intuitive power protection mechanism and a reliable power supply system that seamlessly connects all sub-modules of the WRepair Powerstation. Emphasis is placed on ensuring efficient and safe charging processes that safeguard both the machinery and human operators involved.

The technical aspects of this project involve the selection and integration of a suitable protection mechanism that can manage the power delivery and quality across the system. This includes identifying components that can handle the demands of multiple devices and ensuring consistent power quality to prevent any potential damage or safety hazards.

The overall objective of this thesis is to create a user-friendly and reliable powerstation that meets the high standards and needs of professionals in the electronics repair industry. By focusing on safety, efficiency, and reliability, the WRepair Powerstation aims to enhance the functionality and safety of electronic repair workspaces.

Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

Abbreviation	Definition
OCP	Overcurrent Protection
OVP	Overvoltage Protection
SCP	Short Circuit Protection
IEC	International Electrotechnical Commission
EMI	Electromagnetic Interference
UPS	uninterruptible Power Supplies
MCU	Microcontroller Unit
ESD	Electrostatic Discharge
DC	Direct Current
PD	Power Delivery
THD	Total Harmonic Distortion
PCB	Printed Circuit Board
PPTC	Polymeric Positive Temperature Coefficient
PTC	Positive Temperature Coefficient
GDT	Gas Discharge Tube
TVS	transient-voltage-suppression
EMC	Electromagnetic Compatibility
RCD	Residual Current Devices
PPE	Personal Protective Equipment
Pk-Pk	Peak To Peak
PoR	Program of requirements
IEEE	Institute of Electrical and Electronics Engineers
AC	Alternating Current
GFCIs	Ground Fault Circuit Interrupters
USB	Universal Serial Bus
EEA	European Economic Area
RED	Radio Equipment Directive
MAX	Maximum
EU	European Union
CE	European Conformity
eFuse	Electronic Fuses
IC	Integrated Circuit

1
Introduction

This chapter introduces the motivations behind this research on the Wrepair charging station (section 1.1), outlines the objectives and assignments (section 1.2), defines the problem to be addressed (section 1.3), reviews the state of the art (section 1.4), highlights the contributions (section 1.5) and presents the thesis structure (section 1.6). Through this comprehensive introduction, the foundation is set for the detailed exploration of the design and implementation of the power supply system presented in the subsequent chapters.

1.1. Motivation

This thesis is conducted on behalf of the client, WRepair. WRepair manufactures and distributes tools for the repair industry and lab environments. One of their flagship products is the WRepair Station. The WRepair Station, as shown in Figure 1.1a, is an essential tool for professionals seeking a streamlined and safe repair process in lab environments [88]. This research contributes to the development and improvement of WRepair's USB-C charging station as shown in Figure 1.1b. The USB-C charging station will be a unique product, offering not only the capability to charge multiple devices but also to facilitate data transfer between them. The station will feature intelligent power delivery (PD), optimizing charging efficiency for each connected device. Additionally, the station will provide real-time monitoring of electrical parameters via its dashboard, tailored for laboratory professionals. Besides, the data transferred between devices will be protected with robust security measures to ensure its integrity and confidentiality. Such stunning innovative design will result ultimately in higher customer satisfaction and a more powerful competitive advantage in the market.

(a) Wrepair Station

(b) USB charging station case

Figure 1.1: Wrepair

In recent years, USB-C technology has rapidly grown into a universal standard for charging and data transfer. USB-C charging hubs have become a high wanted solution for charging devices due to their flexibility and enhanced high performance. In contrast, this dependence has created a need for better power supply security. The main challenges in designing USB-C charging stations are ensuring power quality management and electrical safety. Power quality management refers to the regulation and efficiency of the power supply trough the system. Moreover, electrical safety encompasses both electrical machine safety and electrical human safety: Electrical machine safety involves implementing rigorous electrical safety standards to minimize risks such as machinery malfunctions. Advances in electrical technology have led to the development of sophisticated safety systems that protect electrical equipment. Additionally, electrical human safety consists of measures to prevent physical injuries from electrical hazards. Prioritizing human safety is essential to reduce accidents, ensure worker well-being, and maintain a safe working environment.Protecting individuals from the risks associated with electrical systems is paramount.

Therefore, safety in the system must address electrical surges, overcurrent, short circuits and thermal stress. These factors can lead to electrical failures, resulting in permanent damage to device hardware and safety risks for its users. With electronic devices becoming increasingly incorporated in daily life, there has never been a high demand for reliable and safe charging applications. Hence, there is an urgent need for sophisticated protection mechanisms that can reduce these risks and improve the durability of USB-C charging stations.

The motivation behind this thesis research originates from the necessity to address these challenges through the development of robust protection systems. By integrating advanced electrical protection mechanisms. This research aims to design and validate these protection mechanisms, ensuring that USB-C charging stations can operate safely and reliably under a variety of conditions.

1.2. Assignment

The primary objective of this project is to design a power station that can fit into existing WRepair stations, capable of powering various devices through USB-C. The power station case is shown in Figure 1.1b. The WRepair Power Station is designed to enhance existing WRepair stations by integrating six advanced fast USB-C charging and data-transfer functionalities into an all-in-one solution. This product is specifically tailored for laboratory specialists who require such a solution. Key features include fast charging, intelligent PD, data protection, device compatibility, overload protection, and energy efficiency. These elements ensure optimal performance, safety, and versatility, making the power station a reliable and efficient solution for all power and data transfer needs.

In the original BAP proposal, the following property demands were stated:

- Charging USB-C compatible devices mainly used in labratories.
- Displaying Power, Voltage, and Current on a touchscreen.
- USB-A and USB-C ports (6 total).
- Standard version: Charging ONLY & Plus version: Data Transfer in addition to charging.
- Charging station is compatible with WRepair stations through a docking station, can be built into all existing WRepair stations, and can also be used as a standalone device.
- USB-C ports output: MAX 140W & USB-A ports output: MAX 36W.
- Security: Protection against overloading, overcurrent, overheating, and short-circuits.
- Innovations such as: Multi-device charging, USB Power delivery, Fast charging, etc.
- Power division over and maximum output: to be determined later.
- 230V external power adapter.

1.3. Problem Definition

A USB-C charging station can be defined as: 'A device that supplies power to charge other electronic devices via USB-C connections. It offers multiple ports and includes safety mechanisms to protect both the devices and users.' According to Directive 2014/53/EU, modifying the RED 2014/53/EU, all charging ports and fast charging technologies must be standardized to USB-C ports by 2024 [12], [17]. These ports will be required to obtain the CE marking. The CE marking is necessary for goods sold in the European Economic Area (EEA). This means that USB Type-C will become the standard port for most essential electronic devices. All USB connectors and cables must comply with IEC 62680-1-3 standards. Additionally, all charging devices must meet IEC 62680-1-2 requirements for USB PD [17] [24]. Hence, safety analysis for these USB-C-compatible devices is important.

On this project, observance of European regulations and IEC standards makes certain that the designed USB-C power station meets the safety and stability criteria demanded by the European Union (EU). This alignments are the key as it ensures that this power station can be CE marked, allowing it to be sold within the EEA. Furthermore, meeting these standards enhances the reliability of the power station, increasing its appeal to both consumers and regulatory bodies.

According to requirements of IEC standards for USB-C PD, the electrical hazards that must be protected against include overvoltage due to power surges, overcurrent due to overloading, short circuits due to faulty connections, and ESD due to discharge between connections. These are various Practical harmful scenarios of hazards that can occur within the Wrepair USB-C charging station:

- **Overloading**: A USB-C charging station simultaneously charges multiple high-current demanding devices, causing inadequate heat dissipation. This can lead to melting of components, fire hazards, and damage to electronic devices being charged.
- **Overvoltage**: A USB-C charging station receives a sudden spike in mains voltage, overloading the voltage regulator and causing device failures. This can damage connected devices by supplying too high a voltage, leading to electric shocks or fire.
- **Short circuit**: A component with torn insulation touches metal parts inside the charger, causing a short circuit. Short circuits can produce sparks, leading to fire or explosion. They can also damage the devices connected to the charger.
- **Leakage current:** broken component insulation leds a small current to escape the intended current path, potentially causing malfunctions, shocks, and overheating. This can degrade electronic components, reduce their lifespan, and in severe cases, trigger fires or explosions. Devices affected by leakage currents may experience reduced performance and increased energy consumption.
- **ESD**: Touching the USB-C port after walking on a carpet can transfer static electricity, causing a spark that damages the charger's internal circuits or the connected device. ESD can damage sensitive electronic components inside the charger or connected devices.
- **Reverse current**: A plugged-in device drains power from the charging station Instead of receiving it, through a circuit fault in the charging station, resulting in overheating and a chance of fire. Additionally, when a USB-C adapter is connected to one of the charging station's USB-C ports, reverse current and ESD may occur and destroy the charging station.

Through Analyzing the electrical safety and power supply of USB-C charging stations will prevents potential hazards such as dangerous fires, electric shocks, and damage to devices. Electrical safety is a systematic approach to developing protections to prevent people, equipment, and property from harmful hazards associated with electricity. . It encompasses both human safety and machinery safety. To minimize electrical hazard risks, safety protections need to be taken into account. Hence, it is essential to understand how electrical risks arise and how to control them. By identifying and addressing safety and power-related risks, the reliability and durability of charging stations can be improved. This proactive approach ensures the safety of users and enhances the performance and lifespan of the devices.

The high-level requirements for electrical safety and power supply of the USB-C charging station are as follows:

The system ...

- must adhere to relevant International Electrotechnical Commission safety standards, ensuring the protection of humans, machinery, and laboratory environments.
- The system must safeguard equipment due to electrical malfunction and misuse.
- The system must ensure power quality management for power supply regulation in the USB-C charging station.

Incorporating these requirements into the Powerstation project is essential. Identifying potential electrical hazards is crucial for protecting users and devices as well as implementing safety measures to ensure the reliability, effectiveness and market-readiness of the Wrepair powerstation, ultimately leading to higher customer satisfaction. Further discussion on safety standards and technical measures will be provided in the subsequent sections.

1.4. State of the art

This section provides an overview of the current state of the art in electrical safety for USB-C charging hubs. Relevant safety mechanisms and components of similar products to the potential USB-C Wrepair charging station have been stated and will be compared in Table 1.1. Moreover, the potential electrical safety innovations in the Wrepair USB-C charging station will be discussed. By exploring these elements, an understanding of reliable charging solutions is gained.

Table 1.1: Comparison of Desktop Chargers: Satechi, UGREEN, Anker, and WRepair

	State Of The Art			**WRepair Station**
Component	**Satechi 165W GaN Desktop Charger [37]**	**UGREEN 300W Nexode 5-in-1 Charger [64]**	**Anker 150W GaNPrime 747 Charger [36]**	**WRepair Station Model**
Overvoltage Protection				
Zenner Diode	✓			
TVS Diode				✓
Film capacitors	✓	✓	✓	
Optocoupler (EL1019)		✓		
Synchronous rectifier controller (TEA1995)		✓		
Primary controller (XPDS2201)			✓	
Overcurrent Protection				
Fuse	✓	✓	✓	✓
Current Sense Resistors	✓			
Primary controller (XPDS2201)			✓	
Electrostatic Discharge				
ESD Protection Diodes	✓	✓	✓	
TVS Diode				✓
Overheating Protection				
Thermal pad	✓			
Primary controller (XPDS2201)			✓	
Synchronous rectifier controller (TEA1995)		✓		
Thermistors			✓	✓
Electromagnetic Interference				
Common Mode Choke	✓	✓	✓	

Component	Satechi 165W GaN Desktop Charger	UGREEN 300W Nexode 5-in-1 Charger	Anker 150W GaNPrime 747 Charger	WRepair Station Model
Ferrite Beads EMI mitigation in buck-converter	✓	✓	✓	✓

Safety in USB-C charging stations is crucial because unreliable power delivery can lead to several risks. Common issues include overcurrent, short circuits, overvoltage, and ESD, all of which can damage devices and pose hazards to users. To address these concerns for the USB-C charging stations, the safety protection mechanisms have been used to mitigate these risks in the compared USB-C charging. The protection components have been described in depth in section B.1.

According to the made comparison in Table 1.1, the WRepair Station represents a significant innovation in electrical safety design compared to alternative products. The safety design of the WRepair Station stands out due to its simplicity and multifunctional components, which offer substantial advantages in terms of cost efficiency and design footprint. The WRepair Station uses TVS diodes as multifunctional overvoltage and ESD protection components, reducing the need for separate components and simplifying the overall design. Additionally, the charging station uses fewer protection components for other protective mechanisms. This innovation leads to a simpler, more cost-effective, and compact design without compromising on safety and performance compared to alternative products. By integrating multiple protective functions into fewer components, the WRepair Station sets a new standard in the industry, providing enhanced protection and reliability while maintaining a competitive edge in cost.

1.5. Contribution

This thesis makes various contributions to the research of electrical safety and the development of reliable USB-C charging stations:

- **Integrated Protection Mechanisms:** Development of comprehensive protection systems like overvoltage protection (OVP), overcurrent protection (OCP), thermal protection, and electrostatic discharge (ESD) safeguards within a single USB-C charging station.
- **Enhanced Buck-Converter Design:** Optimization of buck converter technology to improve power regulation efficiency and reduce thermal stress, enhancing the overall performance of the charging station.
- **Simulation and Experimental Validation:** A strong methodology for the simulation and experimental validation of the effectiveness of protection mechanisms to guarantee the reliability of their operation in real life circumstances.
- **Safety and Reliability Framework:** Setting up a design framework for safer USB-C charging stations that can be used as a reference for any upcoming research and innovation in this field.

1.6. Thesis Overview

The thesis is organized into the following chapters, each addressing a specific aspect of the research:

1. **Introduction** provides an overview of the project, including the motivation, assignment, and problem definition
2. **Safety Standards** provide an in-depth analysis of the safety standards and protections necessary for designing a robust and reliable USB-C charging station
3. **Program of Requirements (PoR)** outlines the specific requirements for the design and implementation of the USB-C charging station, detailing the necessary features for the safety mechanisms, the safety of humans, and Power.
4. **Design Process** details the design process of the protection circuits and implementation of buck converters.
5. **Validation** Integration of additional protection mechanisms, and the prototyping and testing phase.
6. **Conclusion** Summarizes the project outcomes, provides recommendations, and addresses any challenges faced during the project, and future work.
7. **Bibilography** lists all the references and sources used throughout the project.

This structure ensures a logical flow of information, guiding through the project's development from inception to conclusion. The next chapter will delve into the safety standards applied to the USB-C charging stations

2
Safety Standards

This chapter gives a detailed look into the theoretical foundations necessary for understanding the IEC safety standards (section 2.1) and protections for USB-C charging stations(section 2.2-2.8). Eventually, the safety ranges of protection standards will be discussed (section 2.9). These standards are crucial to ensure devices used in various environments meet specific safety requirements, reducing risks like electric shock, fire, and equipment damage. The IEC standards are put in place to protect both the devices and their users. The coming sections will cover the key standards and their specific safety requirements.

2.1. IEC standards

The IEC develops and publishes international standards as guidelines for all electronic technologies. The relevant standards for USB-C charging stations have specifically been selected to ensure the safe performance of the USB-C charging station in laboratory environments. These standards have been stated in Table 2.1. Subsequently, the selected safety guidelines will be discussed in depth.

Table 2.1: Overview of Safety Standards and Key Requirements for USB-C Charging Stations

Standard	Scope	Key Requirements
IEC 62368-1 [6]	Safety requirements for audio, video, information, and communication technology equipment.	Protection against electric shock and thermal hazards.
IEC 62680-1-2/3 [12] [85] [86]	Universal serial bus interfaces for data and power - Part 1-2: Common components - USB Power Delivery specification.	Includes OVP, OCP, EMI and RCP to prevent hazards like electric shocks and thermal damage.
IEC 61000-4-2 [1]	Immunity of equipment to ESD.	Test levels and procedures for contact and air discharge, ESD immunity.
CISPR 22 [84] [44]	CISPR (the International Special Committee on Radio Interference) Standard for electromagnetic compatibility within Europe for Information Technology Equipment, CISPR 22.	EMI protection

- **IEC 62368-1** Addresses a number of safety requirements governing equipment relating to audio, video, information and communication technology. An essential consideration is the environmental protection against electric shock, which demands appliances to be constructed to prevent users from encountering dangerous voltages. In addition, it includes protection against thermal dangers, where devices must include measures to avoid overheating, which can lead to the occurrence of fire or burns.
- **IEC 62680-1-2/3** Contains the requirements for USB PD and USB Type-C cables and connectors. It guarantees devices and accessories using USB-C technology comply with high safety and performance standards. One important aspect is protection against electric shock, so USB-C devices must be designed to provide users with protection against hazardous voltages. Also, the standard includes measurements to prevent overheating. Together, this in-depth approach will effectively help to ensure the safety and reliability of USB-C technology for both everyday consumers and professionals.
- **IEC 61000-4-2** sets down the requirements in terms of how well devices resist ESD. It specifies on test levels and procedures for contact discharge, which involves direct discharges onto the surface of equipment, as well as air discharge that involves airborne discharges. Ensuring ESD immunity is crucial for devices to operate reliably in environments at risk of ESD and has an important role in user safety.
- **CISPR 22** establishes the requirements for electromagnetic compatibility (EMC) in information technology equipment. It outlines the limits and testing methods for measuring radio disturbances, ensuring that devices do not interfere with radio communications and other electronic equipment. Adhering to CISPR 22 is essential for ensuring that devices operate reliably without causing or being affected by electromagnetic interference, which is critical for the proper functioning and safety of electronic devices in various environments.

Observance of these standards guarantees the safety and durability of various electronic devices, particularly for USB-C charging stations. IEC 62368-1, for instance, aims to prevent users from electrical shock and thermal hazards in audio, video, and information technology devices. Likewise, IEC 62680-1-2/3 describes the requirements for safety and performance for USB PD and USB Type-C cables to ensure protection against electric shock and overheating. Furthermore, IEC 61000-4-2 sets standards for ESD immunity, which includes detailed test procedures for both contact and air discharge to ensure that devices operate reliably in ESD environments. Additionally, CISPR 22 establishes the requirements for EMC in information technology equipment, specifying limits and methods for measuring radio disturbances. This ensures that devices do not interfere with radio communications and other electronic equipment, thereby maintaining functionality and safety by preventing electromagnetic interference.

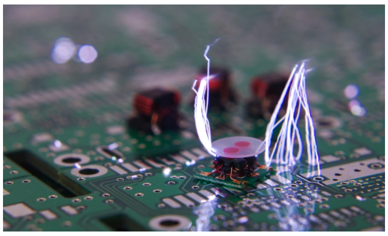
2.2. Overview electrical Hazards

According to the IEC standard in Table 2.1, several types of electrical hazards must be addressed to ensure the safety of users of the USB-C charging station equipment. The following listed malfunctions cause the key electrical hazard for devices and their users. In the following sections, these malfunctions will be analyzed in depth.

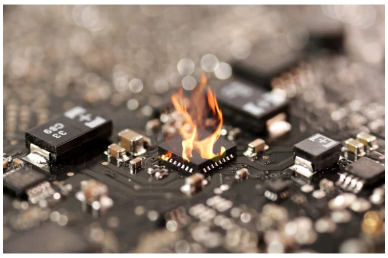
Table 2.2: Summary of Electrical Hazards

Key Electrical Hazard	Description
Electrical Shocks	Excessive voltage as well as current levels in equipment can lead to life-threatening electrical shocks, especially in damp environments or due to faulty insulation and wiring. These shocks can cause severe burns or even death [80].
Fire Hazards	Excessive voltage as well as current levels in equipment can generate significant heat, leading to fires. Electrical fires spread quickly through wiring and circuits, making it tough to control the blaze. Additionally, fighting electrical fires with water could be risky, since water conducts electricity which could shock the environment [22].
Malfunction and Damage of Equipment	Excessive voltage, as well as current levels in the equipment, can cause malfunctions in the system, leading to erratic behaviour or complete system failure. Damages in PCBs can occur by melting traces and burning components, leading to irreversible damage. Without adequate protection, vital components such as insulation material, electrical connections, and memory modules can be damaged. This would eventually result in expensive repairs [45].

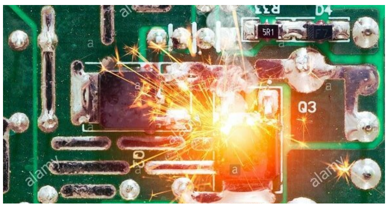
Frequent exposure to high currents and voltages significantly reduces the durability of electronics. Therefore, it is crucial to manage and prevent the key electrical hazard as shown in figures 2.1 to ensure the safety of electrical equipment and their users [39].



(a) Electrical shock to a circuit board [68]



(b) Burn on the PCB due to overheating [26]



(c) PCB Short Circuit [7]

Figure 2.1: Key electrical hazards

Adhering to the IEC standards in Table 2.1, risks will be minimized and user safety is enhanced. Additionally, according to IEC standards selected for a USB-C charging station in Table 2.1, the protection measures include overcurrent, short-circuit, leakage current, overheating, overvoltage, EMI and ESD. These safety protections will be discussed in the following sections.

Electric hazards can have severe effects on the human body, depending on the current's strength. In Table B.3 describes various types of damage caused by electrical hazards, including thermal hazards, shock hazards, muscle contractions, ventricular fibrillation, burns, and microshock. Each consequence is briefly explained to provide insight into the potential risks. In Table B.2 outlines how different current strengths (in mA) can cause specific physical reactions, ranging from mild sensation to severe health risks such as ventricular fibrillation and respiratory paralysis. Figure 2.2 illustrate that safety measures effectively reduce the likelihood of hazardous energy being transferred to a body part.

Figure 2.2: Model of likelihood reduction of energy transfer to bodypart

2.3. Overcurrent Protection

The overcurrent hazards and protection have been derived from IEC 62368-1 and IEC 62680-1-2/3 in Table 2.1 and these have been analyzed within this section. Overcurrent can be described as an electrical current flowing, exceeding the designed safety current limits. Overcurrent leads to excessive heat generation, potentially damaging the electrical components and posing severe risks which have been stated in Table 2.2. This can be caused by short circuit and overload. Hence, an overload (OCP) and short circuit protection (SCP) mechanism must be implemented to protect electrical equipment and its users from electrical hazards.

Overload protection guards against prolonged periods of excessive current that exceed the normal operating current to avoid overheating and damage to devices. Overload typically occurs when the system is subjected to a load greater than its designed capacity.

Short circuit protection deals with the sudden surge of current resulting from a direct connection between two points of different potential, causing a low resistance path which bypasses the designed circuit traces. This can occur for several reasons: damaged insulation, which can expose wires and create a direct connection between them; faulty wiring, where incorrect or degraded connections can lead to short circuits; and conductive materials coming into contact, such as when water or metal objects create a bridge between conductive parts This can lead to extremely high current flows that pose severe risks, like summarized in Table 2.2.

Figure 2.3 shows the current over time, with the x-axis representing time in seconds and the y-axis representing current in amperes. The current remains constant initially at a lower value, then abruptly increases to a higher value, and subsequently returns to the initial level. This pattern suggests an overcurrent event, possibly caused by a fault or sudden load increase in the system. The graph might represent a power system where a transient overcurrent occurred. The behaviour of the current provides insight into normal operation, the event itself, and the subsequent recovery, indicating the system's response to the overcurrent. Understanding such overcurrent events is crucial for designing protection systems and improving system reliability to prevent damage to electrical components and ensure safe operation.

The Figure 2.3 illustrates a theoretical example of the behavior of an OCP device. The X-axis represents time in seconds, and the Y-axis shows the current as a multiple of the rated current (I_r). The orange line depicts the current profile, which increases linearly over time. This theoretical example helps illustrate how protection settings are calibrated to prevent damage while allowing normal operations up to a defined threshold.

Key points include:

- **Horizontal Dashed Line at 5A:** From 0 to 5 seconds, the system operates within safe limits as the current increases linearly without exceeding 5 times Ir.
- **Vertical Dashed Line at 5s:** This indicates the time at which the current reaches the maximum limit and the overcurrent protection trips.
- **Red Shaded Area:** This highlights the trip action region where the protection device will activate to interrupt the current flow to protect the system from potential damage.. As shown the protection mechanism has some delay time in reality.

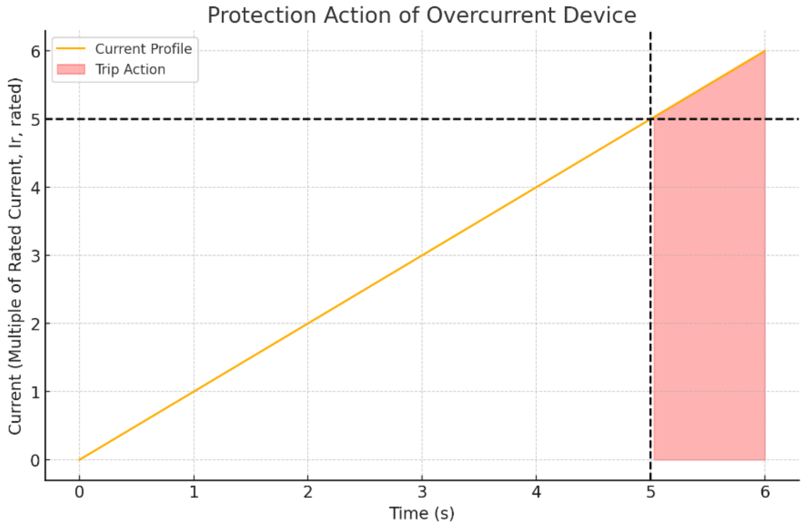


Figure 2.3: Overcurrent event

Fortunately, there are several protection mechanisms to prevent overload and short circuits and mitigate its dangers. The following protection mechanisms include both passive and active protection measures.

Passive protection:

- **Fuses** are designed to melt at a certain current level, interrupting the flow to prevent further damage. They provide simple and effective one-time protection [45].
- **Thermisors** respond to the temperature generated from excessive current and subsequently reduce the current flow by increasing its resistance to prevent overheating and fires [82].
- **Proper insulation** of wires and conductive materials can prevent accidental contact between conductive parts. This protective method can especially be applied to mitigate the risks of short circuits.

Active protection:

- **Circuit Breakers** automatically interrupt the flow when overcurrent is detected. They can be manually reset, offering reusable protection useful for long-term safety [60].
- **eFuses** offer better responses and precision than passive protection for electronics. These respond quickly to overcurrent and can reset automatically, providing continuous protection, especially in modern electronics where reliability is crucial. [45].

In conclusion, implementing the right protection mechanisms helps manage the dangers of overcurrent, ensuring the safety and durability of electrical and electronic systems.

2.4. Reverse Current Protection

The hazards and protection mechanisms associated with reverse current have been derived from IEC 62368-1 and IEC 62680-1-2/3, as outlined in Table 2.1. Reverse current is defined as the occurrence of unintended current in the opposite direction of the intended path, frequently due to faults or incorrect circuit connections. There are several causes for this phenomenon, which include broken components, improper circuit connections or malfunctioning equipment. After a period of time, the degradation or failure of high quality components may even result in the possibility of reverse current flow. Moreover, mistakes in circuit design or construction can result in connections that can cause current to reverse flow. Therefore, implementing effective reverse current protection mechanisms are crucial to ensure the safety and reliability of electrical equipment and users [5] [6].

Reverse current poses significant hazards for electronic devices and users, including damage to components, reduced efficiency, electrical shocks and fires, as detailed in Table 2.2. Component damage is one of the primary concerns, as reverse current can lead to overheating, short circuits, and permanent damage to sensitive electronics. Moreover, unintended reverse current paths can cause device malfunctions, disrupting normal operation and leading to potential safety risks. Furthermore, reverse current can contribute to energy losses and decreased overall efficiency.

In Figure 2.4 shows a simple circuit of reverse current protection using a diode. In the diagram, the power supply is correctly connected, with the diode forward-biased, allowing current to pass through. The green arrow indicates that the current flows through the load, enabling the "Very Important Circuit" to function normally. This protects the "Very Important Circuit" from potential damage. The purpose of the diode is to protect the circuit from damage when the power supply is incorrectly connected, by conducting in forward bias and blocking in reverse bias. This setup is crucial for protecting sensitive electronic components from potential damage due to reverse polarity.

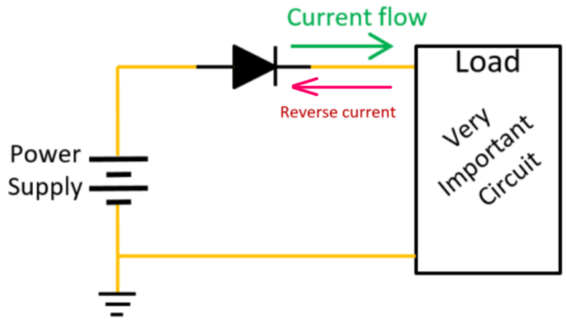


Figure 2.4: Reverse Current Protection using Diode [87]

Fortunately, several protection mechanisms can mitigate the dangers of reverse currents. These include both passive and active protection measures [83].

Passive Protection:

- **Diodes** are commonly used to prevent reverse current flow by allowing current to pass in only one direction. High-quality diodes ensure that reverse current does not affect the circuit [5].
- **Correct wiring practices** ensure that internal connections in the circuit, as well as external connections of the ports, are made properly, reducing the likelihood of reverse current paths [62].

Active Protection:

- **Reverse current protection ICs** ICs are integrated circuits (IC) specifically designed to detect and prevent reverse current. These ICs can automatically disconnect the circuit when reverse current is detected, providing immediate protection [5] [62].
- **Efuse** incorporate reverse current protection as part of their functionality, continuously monitoring the direction of current flow and shutting down the system if the reverse current is detected.

In conclusion, reverse current protection for USB-C ports ensures that unintended reverse current paths do not harm devices or users. By implementing high-quality diodes and reverse current detection components, the safety and reliability of USB-C charging stations and devices can be significantly enhanced.

2.5. Leakage Current Protection

The hazards and protection mechanisms related to leakage current have been derived from IEC 62368-1 and IEC 62680-1-2/3, as detailed in Table 2.1. Leakage current can be described as an unintended flow of electrical current through insulation or unintentionally alternative paths to ground. It stems from several sources such as failure of insulation, damaged components, or exposure to moisture. Over time, the insulation materials can degrade, allowing current to leak through unintended paths.

Besides, flaws in the electric components can lead to imperfections in the insulation, which may facilitate leakage. Also, Moist or humid environments can compromise insulation, leading to leakage currents. Hence, implementing effective leakage current protection mechanisms is essential to ensure the safety of electrical equipment and users [6].

Leakage current poses severe hazards for humans, such as electrical shocks, fire and device malfunction as stated in Table 2.2. Electrical shock is one of the primary risks associated with leakage currents, posing serious dangers to users. In addition, electrical risks can be caused by unintended current paths, causing device malfunction and disrupting the normal operation of devices. Furthermore, leakage currents contribute to reduced efficiency, leading to energy losses that decrease the overall efficiency. Fortunately, several protection mechanisms can mitigate the dangers of leakage current. These include both passive and active protection measures.

Passive Protection:

- **Proper grounding and bonding** practices ensure a controlled path for fault currents, enhancing overall safety. Grounding provides a low resistance path for fault current to the earth, while bonding ensures that all conductive parts are connected to the same electrical potential, reducing the risk of electric shock [53] [70].
- **Moisture-resistant materials and protective coatings** can prevent moisture-related leakage currents within humid environments [92].

Active Protection:

- **Ground Fault Circuit Interrupters (GFCIs)** sense current variations between poles and neutral wires. It disconnects the circuit automatically when a leakage current is detected. This provides immediate protection against electrical shocks. This mechanism is frankly used for products in humid environments [71].
- **Residual Current Devices (RCDs)** protect against electric shock and electrical fires by detecting and disconnecting electrical circuits when an imbalance in the current is detected [46].

In conclusion, leakage current protection for USB-C charging stations ensures that unintended current paths could potentially harm users or devices. By implementing high-quality insulation and leakage detection components, the safety and durability of USB-C charging stations can be significantly enhanced.

2.6. Overvoltage Protection

The hazards related to overvoltage and related safeguards are derived from standards IEC 62368-1 and IEC 61000-4-5, which are summarized in Table 2.1. Transient overvoltage arises when surges in the system surpass the rated voltage within the circuit. This can be caused by external factors, such as switching surges due to a sudden change in the load (turning on/off), or internal issues like insulation failure. Overvoltage poses several significant risks for electric equipment and its users among which: electric shocks, fire hazards, PCB malfunction and damage as summarized in Table 2.2. Additionally, the dielectric strength of substances can be compromised, which can lead to arcs and sparks. Repetitive exposure to overvoltage can also reduce the lifespan of electrical devices. Hence, it is essential to implement effective OVP strategies to ensure the safety and dependability of electrical systems and devices [6].

Figure 2.5 shows the voltage over time, with a significant peak indicating an event or anomaly. The x-axis indicates the time in seconds and the y-axis the voltage in volts. At the beginning , the voltage remains constant and then increases abruptly to a high value before returning to its original level. Such a pattern indicates an overvoltage or surge event, which may be caused by lightning strikes, circuit activity or other temporary disturbances. The graph might represent a power system where a transient overvoltage occurred. The voltage behaviour provides insight into normal operation, the event itself, and the subsequent recovery, indicating the system's resilience or the effectiveness of protective measures. An insight of such excess voltage events is essential for the design of protection systems and to improve system reliability in order to protect sensitive electronic equipment.

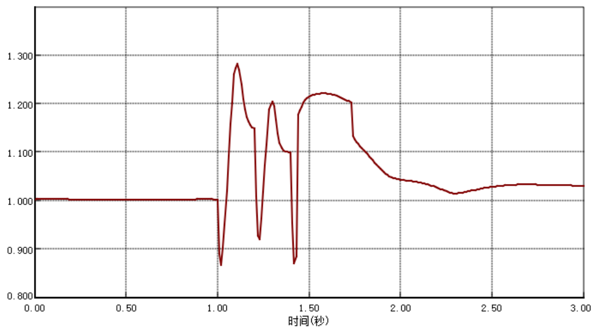


Figure 2.5: Overvoltage or surge event

Thankfully, there are various approaches to prevent surge events and mitigate the risks OVP is engineered to limit voltage surges to prevent equipment and system damage. Voltage control mechanisms, including voltage suppression components and voltage regulators, reduce voltage to safe levels or divert excess voltage from sensitive components according to IEC standards. The following protection mechanisms include both passive and active measures.

Passive protection:

- **Thyristor Surge Protectors (TSS)** are designed to protect sensitive electronic equipment from high-voltage spikes. They work by blocking or shorting to ground any unwanted voltages above a safe threshold. This mechanism prevents damage to the circuit and connected devices [29] [72].
- **Metal Oxide Varistors (MOVs)** are components that protect circuits by clamping voltage spikes. They change resistance with voltage changes, thereby absorbing excess energy and protecting sensitive components from overvoltage [27] [89] [76].

Active protection:

- **Transient Voltage Suppression (TVS) Diodes** are semiconductor devices that protect electronic circuits from transient voltage spikes by clamping the voltage to a safe level and absorbing the excess energy [18] [72] [76].
- **Voltage regulators** maintain a constant voltage level within a circuit and prevent in this way overvoltage [3] [75] [67].

In conclusion, appropriate protection mechanisms are crucial to managing the overvoltage threats and thereby preserving the safety and durability of electrical equipment.

2.7. EMI Protection

The hazards and protection mechanisms related to Electromagnetic Interference (EMI) have been derived from IEC 61000-4-2 and CISPR 22, as detailed in Table 2.1. EMI can be described as unwanted disturbances generated by external sources that affect electrical circuits through electromagnetic induction, electrostatic coupling, or conduction. These disturbances can stem from various sources such as switching power supplies, radio frequency transmitters, and other electronic devices. EMI can disrupt the normal operation of electronic equipment, leading to system malfunctions and even damage to sensitive electronic components, eventually resulting in reduced system performance.

Therefore, implementing effective EMI protection mechanisms is crucial to ensure the reliable performance and safety of electrical equipment and users [84] [44]. Several protection mechanisms can mitigate the risks of EMI.

- **Shielding and Grounding:** Proper shielding of cables and devices helps to block electromagnetic fields and reduce interference. Grounding provides a reference point for the circuit and minimizes the potential differences that can lead to EMI [9] [50].
- **Filter Design:** The use of EMI filters can effectively attenuate unwanted noise by filtering out high-frequency interference while allowing the desired signals to pass through. This is particularly useful in power supply circuits [90] [23] [63].

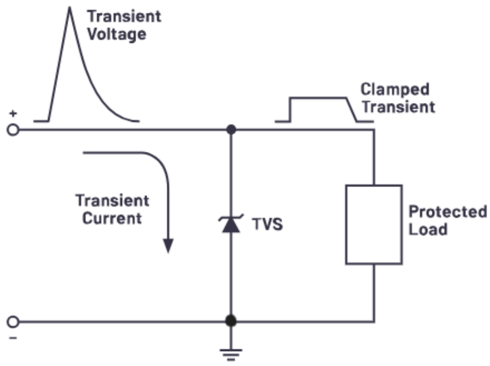
In conclusion, EMI protection for USB-C charging stations ensures that electromagnetic disturbances do not compromise the performance and safety of devices. By implementing robust shielding, grounding practices and filtering techniques, the reliability and efficiency of USB-C charging stations can be significantly enhanced.

2.8. ESD Protection

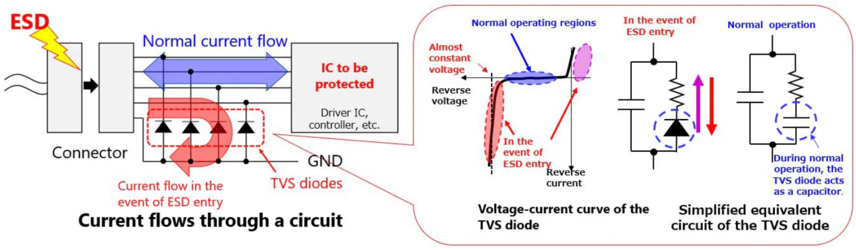
The hazards and defense devices related to electrostatic discharges (ESD) are derived from IEC 62368-1 and EC 61000-4-2, as shown in Table 2.1. ESD can be described as a sudden flow of electricity between two electrically charged objects caused by the triboelectric effect. The triboelectric effect is a phenomenon where certain materials become electrically charged after they come into contact and are then separated. This effect is a type of contact electrification. For USB-C charging stations, the triboelectric effect can be particularly relevant in understanding and mitigating potential ESD events, which can damage sensitive electronic components. ESD events can originate from different sources of the following examples in Table B.9 [55].

When an ESD event happens, the high stress can break the insulating films in semiconductor devices, such as transistors, diodes and IC. This breakage can lead to immediate defects or latent defects that shorten the life of the components. These occurrences can occur when one charged object comes into contact with another with a different potential, causing a rapid discharge of static electricity. Over a period of time, the build-up of static charges can lead to substantial voltage differences, which when released can cause damage to electronic components. Therefore, implementing effective ESD protection mechanisms is essential to ensure the safety and reliability of electrical equipment and users [6] [1].

Figure 2.6a and Figure 2.6b illustrate how a transition voltage suppression diode protects a load from ESD. In normal operating conditions, the TVS diode stays in a high-impedance state, operating effectively as an open circuit. It does not affect the normal operation of the circuit it will be protecting. When an ESD Event occurs, it introduces a high-voltage pulse into the circuit. Upon detecting the peak high voltage, the TVS diode quickly switches from a high-impedance state to a low-impedance state. This speedy switching is the key to its protection mechanism. The diode clips the voltage at a predefined safe level, known as the terminal voltage. This keeps the voltage from rising to a level that could damage sensitive circuit components. The TVS diode then offers a path for the surplus current that is generated by the ESD event. This excess current is routed away from the protected load and to the ground, thus effectively nullifying the harmful effects of the ESD event. As soon as the passing event is over, the TVS diode reverts to its high-impedance state, ready to protect against future voltage surges. The TVS diode then provides a path for the excess current generated by the ESD event. This excess current is diverted away from the protected load and routed to the ground, effectively neutralizing the harmful effects of the ESD event. Once the transient event is over, the TVS diode returns to its high-impedance state, ready to protect against future voltage spikes. This ensures that the normal operation of the circuit resumes without any interference from the protection device [58].



(a) Protecting against voltage surges and ESD [8]



(b) Cause of when ESD occurred and how the TVS reacted to this event

Figure 2.6: Combined figure

ESD poses severe hazards for electronic devices and systems, such as component damage, device malfunction, and reduced efficiency, as stated in Table 2.2. When an ESD event occurs, instant high voltage spikes can break down the insulating layers within semiconductor devices, such as transistors, diodes, and IC. This breakdown can lead to immediate failure or latent defects that reduce the lifespan of the components. Component damage is one of the primary risks associated with ESD, posing serious dangers to sensitive electronic parts. In addition, ESD can cause unintended current paths, like short circuits that lead to device malfunction and disrupt the normal operation of devices. Furthermore, ESD contributes to reduced efficiency. Fortunately, several protection mechanisms can mitigate the dangers of ESD. These include both passive and active protection measures.

Passive Protection:

- **ESD Protective Materials** using materials that are designed to dissipate static electricity can significantly reduce the risk of ESD. Proper material selection ensures static charges do not build up to dangerous levels [65] [91].
- **Proper Grounding and Bonding** practices ensure a controlled path for static discharge, enhancing overall safety and protecting electronic components. Bonding ensures that all conductive parts are connected to the same electrical potential, mitigating the risk of electric shock [53] [70].

Active Protection:

- **TVS Diodes** are designed to clamp and divert high-voltage spikes caused by ESD events, protecting sensitive components from damage. These devices react quickly to transient voltage spikes, providing immediate protection [25] [4] [35].
- **eFuse** includes ESD protection by monitoring any sudden faulty current through differently charged objects [57].

In conclusion, ESD protection for USB-C charging stations ensures that ESD do not harm users or devices. By implementing high-quality ESD protective materials and components, the safety and reliability of USB-C charging stations can be significantly enhanced.

2.9. Thermal Protection

The risks and protection devices related to overheating are deduced from IEC 62368- 1 and IEC 62680-1-2/3, presented in Table 2.1. Excessive thermal overheating can be described as the excessively increased temperature of electrical components, which may lead to the breakdown of components, decrease in efficiency or even cause a fire threat. There are several causes for this phenomenon, including high power, poor ventilation or poor thermal management components. As time passes, ongoing operation at high temperatures can corrode materials and components, which increases the chances of defects. Hence, implementing effective thermal protection mechanisms is essential to guarantee the safety and reliability of power equipment and users [6].

Overheating poses significant hazards for electronic devices and users, including component damage, reduced efficiency, and potential safety risks, as detailed in Table 2.2. Component damage is one of the primary concerns, as excessive heat can lead to overheating, short circuits, and permanent damage to sensitive electronics. Moreover, high temperatures can cause device malfunctions, disrupting normal operation and leading to potential safety risks. Furthermore, overheating can contribute to energy losses and decreased overall efficiency. Fortunately, several protection mechanisms can mitigate the dangers of overheating. These include both passive and active protection measures.

Passive Protection:

- **Thermal Insulation**Insulation utilizing thermal interface materials can significantly reduce the risk of overheating. Proper thermal insulation ensures efficient heat dissipation away from critical components [38] [56] [61].
- **Heat Sinks** are designed to absorb and dissipate heat from electronic components, enhancing overall thermal management and preventing overheating [69].
- **Ventilation** ensures adequate cooling by maintaining proper airflow within the device, preventing hotspots and reducing the risk of overheating [59].

Active Protection:

- **Temperature Sensors** continuously monitor the temperature of critical components. These systems can reduce the power output or shut down the charger if temperatures exceed safe limits [16].
- **Thermistors** are safety devices that automatically disconnect the power supply when the temperature exceeds a threshold by increasing its resistance and providing immediate protection against overheating. This temperature is dependent on the amount of current flowing through this component[48].

In conclusion, thermal protection for USB-C charging stations ensures that excessive heat does not compromise the safety and functionality of the devices. By implementing thermal insulation, heat dissipation components, and thermal sensitive components, the safety and reliability of USB-C charging stations can be significantly enhanced.

2.10. Safety Measures

Within this project, the safety & power group protects as well as supplies regulated power to the connected modules in USB-C charging stations, such as the Power delivery module, the microcontroller unit, and the Touchscreen. These modules consist of low-power sensitive electronic components. Hence they need to be protected. The modules in the charging station will be protected according to IEC 62368-1/IEC 61000-4-2 standards from Table 2.1 and taking into account their data sheets [6] [1] [73] [52]. The systematic safety measures for the system have been described in Table 2.3. By adhering to these safety measures, manufacturers can improve the functional performance and lifespan of their products and minimize any potential hazards to the device and its users

Table 2.3: Specific Safety Measures According to IEC 62368-1, IEC 61000-4-2 and CISPR22 [6] [1]

Safety Measures	**PD-Module Protection** [19]	**MCU Protection** [73]	**Touchscreen Protection** [52]
Overcurrent protection	10% margin above the nominal current after 16ms (15A)	10% margin above the nominal current (0.15A), unless otherwise has been stated in the datasheet [73]	10% margin above the nominal current (0.5A), unless otherwise has been stated in the datasheet [52]
Leakage current protection	ES1 leakage current limit of 2mA, due to V_{supply} < 60VDC [1]	ES1 leakage current limit of 2mA, due to V_{supply} < 60VDC	ES1 leakage current limit of 2mA, due to V_{supply} < 60VDC
Reverse current protection	Included	Included	Included
Overvoltage protection	20% margin above the nominal transient voltage (20V)	20% margin above the nominal transient voltage (3.3-5V), , unless otherwise has been stated in the datasheet [52]	20% margin above the nominal transient voltage (5V), unless otherwise has been stated in the datasheet [52]
EMI protection	Included	Included	(Not Included) Noise frequency range 150 kHz to 30 MHz reduction
ESD protection	Level 3 safety: 8kV contact voltage discharge, 15kV air discharge	Level 2 safety: 2kV contact voltage discharge, 4kV air discharge	Level 2 safety: 2kV contact voltage discharge, 4kV air discharge
Thermal protection	Automatically shut off exceeding the operating temperature range of 15-165 degrees Celsius after 100μ s	Included	Included

Overcurrent Protection

According to Joule's law the produced heat is proportional to the square it the current. For instance, A 10% increase in current results in a 21% increase in heat (1.2^2), whereas a 20% increase results in a 44% increase in heat (1.3^2). This margin allows the device to handle occasional spikes in current without triggering thermal shutoffs, ensuring stable operation while protecting against dangerous overcurrent conditions [42]. The margin of 10% for normal operation from Table 2.3 has been derived from its IEC standard. However, it states that when a manufacturer declares another safety range, their safety ranges need to be taken into account accordingly.

- **PD-Module Protection [19]**: This protection mechanism includes a 10% margin above the nominal current, which activates after 16 milliseconds (15A). This means that if the current exceeds the nominal value by 10%, the protection will kick in after 16ms to prevent damage. According to the PD-module's manufacturer the range's maximal rating is 16.5amps.
- **MCU Protection [73]**: Similarly, the MCU is protected with a 10% margin above the nominal current of 0.1A. This ensures that any slight overcurrent does not damage the MCU by providing a safety buffer.
- **Touchscreen Protection [52]**: The touchscreen also has a 10% margin above its nominal current of 0.5A, ensuring it is safeguarded against overcurrent situations.

Overvoltage Protection

According to Joule's law, the heat produced in a resistor is proportional to the square of the voltage (V^2). A 20% increase in voltage leads to a 44% increase in heat (1.2^2), and a 30% increase results in a 69% increase in heat (1.3^2). According to research managing thermal stress is essential to prevent overheating and ensure the longevity of electronic devices. The overvoltage margins are higher than the overcurrent margin, so the overvoltage would logically yield more overheating. However, the overvoltage spikes due to voltage errors have an overall far shorter duration than overcurrent level scenarios due to overloading. Hence the yield of overheating would be compromised. The margin of 20% for normal operation from Table 2.3 has been derived from its IEC standard. However, it states that when a manufacturer declares another safety range, their safety ranges need to be taken into account accordingly.

- **PD-Module Protection [19]**: The PD module is protected against overvoltage with a 20% margin above the nominal transient voltage of 20V. This means the module can handle voltage spikes up to 20% above its normal operating voltage without damage.
- **MCU Protection [73]**: The MCU's overvoltage protection includes a 20% margin above the nominal transient voltage, ranging from 3.3 to 5V. This protects the MCU from voltage spikes that could otherwise cause malfunction or damage.
- **Touchscreen Protection [52]**: The touchscreen is protected with a 20% margin above the nominal transient voltage of 5V, ensuring it remains functional even in the presence of overvoltage conditions. According to the Touchscreen's manufacturer the range maximal rating is 7V.

ESD Protection

The safety measures for ESD protection align with Level 2 safety standards, providing 4kV contact voltage discharge and 8kV air discharge thresholds. These levels ensure that the device can withstand typical ESD events encountered during handling and operation, thereby maintaining the integrity of the electronics in laboratory environments. The devices used in the laboratory must minimal meet the level 2 ESD protection requirement according to IEC 61000-4 as shown in Table 2.1.

- **PD-Module Protection [19]**: For the PD module, ESD protection is rated at Level 3 safety, which includes an 8kV contact voltage discharge and a 15kV air discharge. This high level of protection ensures that the module can withstand significant ESD events.
- **MCU Protection [73]**: The MCU has Level 2 safety for ESD protection, with a 2kV contact voltage discharge and a 4kV air discharge. This provides adequate protection for the sensitive microcontroller unit against electrostatic discharges.
- **Touchscreen Protection [52]**: The touchscreen also has Level 2 safety for ESD protection, with a 2kV contact voltage discharge and a 4kV air discharge, protecting it from potential ESD damage during user interactions.

Thermal Protection

- **PD-Module Protection [19]**: Thermal protection for the chips in the PD module involves automatic shutdown if the operating temperature exceeds the range of 15 to 165 degrees Celsius. This activation occurs after 100 microseconds, ensuring that the module does not overheat and get damaged according to its datasheet.
- **MCU and Touchscreen Protection**: Thermal protection specifics for the MCU and touchscreen are not stated, indicating that the protection measures might vary based on implementation or are included in a broader thermal management strategy. Since the MCU and Touchscreen are working on very low power rates, they would not need specific insulation to mitigate thermal risks.

These safety measures ensure that the PD module, MCU, and touchscreen are protected from common electrical hazards, including overcurrent, overvoltage, electrostatic discharge (ESD), and excessive heat, thus enhancing their reliability and longevity in various operational environments.

Additionally, the protection of USB-C output ports and the Power Delivery according to IEC 62680-1-2/3 [85] [86] will be mentioned. These internal module safety measurements are important to know when an all-in-one system on PCB will be designed instead of a design of different connected modules. The systematic safety measures for the system have been described in Table 2.4. These measures have been derived from the data sheet of the PD-module [19]. By adhering to these safety measurements, manufacturers can enhance the reliability and longevity of their products and mitigate potential hazards for the device and its users.

Table 2.4: Specific Safety Measures According to IEC 62680-1-2/3 [85] [86]

Safety Measures	Description
Overcurrent Protection	Current should not exceed 6.35A for USB PD
Overvoltage Protection	Supports voltages output from 5V up to 20V
Short-Circuit Protection	Mechanisms should detect and respond to short circuits between VBUS and GND
Thermal Protection	Devices must include thermal shutdown procedures to prevent overheating
ESD Protection	USB connectors and devices must withstand electrostatic discharges as specified by industry standards

3

Program of Requirement (PoR)

This chapter provides a detailed overview of the fundamental specifications for the PoR in Power & Safety research, which focuses on implementing the most advanced technical electrical safety and power quality protections. It outlines the essential features, functions, and constraints that the product must meet (section 3.1). In subsequent sections, these requirements are designed to satisfy the IEC requirements and expectations of the target audience (sections 3.3-3.4). Ultimately, the PoR ensures that the development process adheres to the selected IEC standards. These requirements are crucial to ensure that the product meets its intended purpose and delivers value to its users safely. The following sections will cover the key specifications and their specific criteria.

3.1. System Requirements

The high-level requirements for electrical safety and power supply are the following:

- The system must adhere to IEC 62368-1/IEC 61000-4-2, IEC 62680-1-2/3 and CISPR22 safety standards and regulations for human, machinery and laboratory environment safety, stated in Table 2.1.
- The system must safeguard equipment due to electrical malfunction and misuse.
- The system must ensure power quality management for power supply regulation in the USB-C charging station.

3.2. Electrical Safety

Ensuring electrical safety is crucial for protecting both equipment and its users from electrical hazards. Electrical safety is divided into two key areas: machine safety and human safety. It includes all measures designed to protect electrical equipment, users, and the environment from electrical hazards involving electricity. Understanding and adhering to IEC 62368- 1/IEC 61000-4-2 enhance the overall reliability and efficiency of industrial operations [6] [1]. The system must meet the following functional requirements.

The system must...

- Have machinery safety protection against electrical hazards for the stepdown converter, PD modules, MCU and touchscreen.
- Have OCP with a range of a 10 % margin above the nominal current.
- Have reverse current protection specifically in the PD-Module.
- Have leakage current protection of ES1 leakage current limit of 2mA DC.
- Have an OVP circuit with a voltage level limitation range of 20 % margin above the nominal operating transient voltage.

- Minimize the generation and emission of electromagnetic disturbances of frequency range 150 kHz to 30 MHz to ensure safe operation and to avoid interference with other equipment.
- Protect the user and lab environment from ESD hazard risk of 4 kV contact discharge and 8 kV air discharge need to be removed voltage spikes.
- Ensure the electrical system has thermal protection to prevent overheating, automatically shutting off when the temperature exceeds the normal operation temperature range as stated in Table 2.3.

3.3. Power Quality Managment

Power supply is essential in order to ensure that equipment and appliances are able to operate constantly and receive steady and reliable electrical power. Avoiding interruptions caused by problems such as voltage drops, and voltage spikes is essential. The consequence of poor power quality can lead to malfunctions in equipment, reduced efficiency and higher maintenance costs. The implementation of solutions such as power regulators is vital for the maintenance of power quality, thereby ensuring reliable and efficient operation of electrical systems in various applications. Power regulators help stabilize voltage, filter out electrical noise, and protect against power anomalies, contributing to the longevity and optimal performance of electrical equipment. The system must meet the functional requirements.

The system must...

- Have a DC input power source of 300 W containing 20V/15A.
- Have a step-down converter that converts regulated a voltage level of 5V.
- Minimally supply 280 W to the PD modules.
- Supply maximum 0.75 W to the MCU
- Supply maximum 2.5 W to the Touchscreen
- Maintain power conversion efficiency within (75-90)%

4
Design Process

This chapter, provides a detailed overview of the design process and the choices involved in designing the protection circuits. The design process plays a crucial role in the development of reliable and efficient electronic systems. The focus has been highlighted on the following specific main components: the design overview (section 4.1) and the design choices(section 4.2-4.5) and showcasing its final design (section 4.6). The entire designed system has been decomposed into each contained component, which is further discussed in the following sections.

4.1. Design Overview

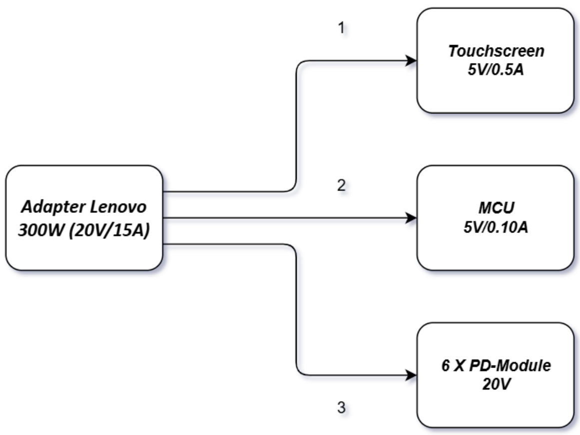


Figure 4.1: Initial design without safety measurements

The design overview without safety measures, as illustrated in 4.1, represents a straightforward configuration where an Adapter Lenovo 300W (20V/15A) [40] supplies power directly to three key components:

1. Nexion Touchscreen [52]
2. MCU [73]
3. 6 PD Modules [19]

Each subsystem operates at different voltage and current levels, necessitating appropriate power conversion and safety measures. This setup configuration is functional, whereas it lacks any form of protection for the subsystems, making it vulnerable to potential hazards due to overvoltages, power surges, short circuits, or other electrical faults. Operating without safety protection can lead to several significant hazards such as in Table 2.2: electrical; shocks; fire hazards and degradation of electrical components as stated in Table 2.2. Therefore, designing and implementing effective power management and safety mechanisms are crucial in modern electronic systems.

The next step involves implementing the safety measures from Table 2.3 in the initial design to mitigate the potentials hazards stated in Table 2.2. This enhanced design overview, illustrates in Figure 4.2 a centralized safety and power management module between the adapter and the other subsystems. This module significantly enhances the system's resilience to electrical faults by incorporating robust electrical safety mechanisms. All design subsystems are detailed in Table B.10. Besides, the Safety & Power module in Figure 4.2 has been designed to meet the program requirements outlined in chapter 3 with their safety measures to be examined in depth in the following sections.

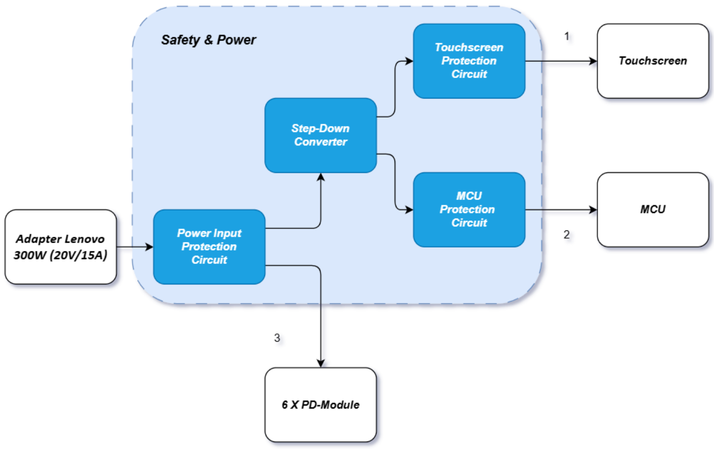


Figure 4.2: Safety & power design

4.2. Selection of Protection Components

In this section the comparisons among the potentially integrable protections components for overcurrent, overheating, overvoltage and ESD protection will be described, Implementing overcurrent and thermal protection reduces the risk of damage to the device and ensures its reliable operation, while also preventing potential hazards such as overheating and electrical fires. Implementing ESD protection reduces the risk of damage to the device and ensures its reliable operation, while also safeguarding users from electrical shocks.

Overcurrent & Thermal Protection

In Table B.4, potentially integrable protections components for overcurrent protection, including overload and short circuit protection, have been selected. These current limiting devices are temperature-dependent too. Hence they also protect against thermal overloads. These protection components will be compared to subsequently choose the best-fitting protection component for their use in the Safety & Power (Input power protection circuit; MCU protection circuit and Touchscreen protection circuit) design blocks. This comparison aims to safeguard the entire system from overcurrent risks, as stated in Table 2.2. The design choices for the overcurrent protection mechanism will be based on Table B.4 and they will be discussed in the next sections.

Overvoltage & ESD Protection

In Table B.5, potentially integrable protection components for ESD, including transient voltage suppressors (TVS) have been selected. These protection components will be compared to subsequently choose the best-fitting solution for safeguarding the entire system from ESD risks, as detailed in Table 2.1. The design choices for the overvoltage & ESD protection mechanisms will be based on Table B.5 and they will be discussed in the next sections.

4.3. Power Input Protection Circuit

The Power Input Protection Circuit, as depicted in Figure 4.3, is a critical component designed to safeguard electronic systems from various electrical faults. This circuit ensures the safe operation of downstream components by mitigating risks such as overcurrent, thermal overload, overvoltage, and ESD. The diagram provides a visual representation of how the protection circuit interfaces with other system components.

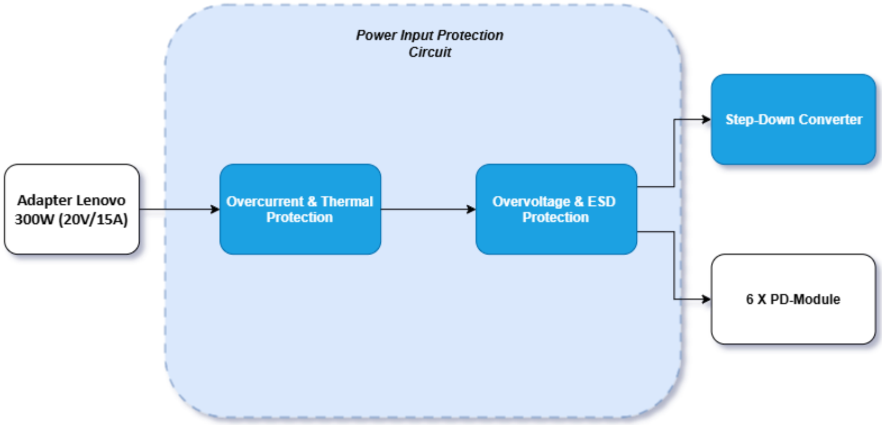


Figure 4.3: Input Protection Circuit

4.3.1. Overcurrent & Thermal Protection

Overcurrent can damage the internal electronic components of the PD-module when its outputs are overloaded. Exceeding the rated current limits for of minimal duration of 16ms can lead to problematic situations, according to the PD-module's datasheet [19]. The overcurrent protection component has been chosen from the component comparison stated in Table B.4. Comparing Table B.4 with the datasheet specifications of the 15A PD-module [19], the TR-3216FF15-R fuse component has been chosen. As it is compatible with the operational values of the PD-module, ensuring appropriate safety margins based on the requirements of chapter 3. The specifications of the selected fuse are described in Table B.6. Since the fuse limits the current input of this system, it is also protecting against overheating of the power traces. Furthermore, the specific advantages of choosing the fuse over other components are as follows:

- **Cost-Effectiveness**: Fuses offer a straightforward and cost-effective solution for overcurrent protection compared to more complex protection solutions like electronic fuses (eFuses) or circuit breakers.
- **High Breaking Capacity**:Fuses can interrupt high current faults. This means they can protect circuits against severe overcurrents by quickly melting and disconnecting the power supply. This is crucial in applications with high current potential, such as the 20V/15A input from the Lenovo adapter in your circuit. A fuse ensures that, in the event of a short circuit or severe overload, the circuit components remain protected from damage.
- **Fast Response Time**: Fuses react very quickly to overcurrents, making them effective at protecting sensitive components and humans from immediate damage due to high currents. This quick switching is important in applications where rapid response to fault conditions is critical, due to human usage.

4.3.2. Overvoltage & ESD Protection

Electrostatic discharge can damage the internal electronic components of the buck converter and PD-module. Comparing the components in Table B.5 with the datasheet specifications of the PD-Module [19] and Buck converter [79], the bidirectional SMBJ20CA TVS [14] has been chosen for overvoltage and ESD protection. As the TVS is compatible with the operational values of the PD-module and step-down converter, ensuring appropriate safety margins based on the requirements of section 3.2. The specifications of the selected TVS are described in Table B.6. The TVS is a reliable component in protecting the system and its user against overvoltage and ESD events from the power input. Unlike suppressor capacitors and varistors, the TVS do not degrade after repeated use. Futhermore, the specific advantages of choosing the fuse over the other components are as follows:

- **Fast Response Time**: TVS diodes react extremely quickly to transient voltage spikes, typically within picoseconds. This rapid response is crucial for protecting sensitive electronic components from sudden surges, such as electrostatic discharge, ensuring the longevity and reliability of the circuit.
- **Low Clamping Voltage**: TVS diodes provide a low clamping voltage, which means they limit the peak voltage to a safe level for the components in the circuit. This is particularly important in protecting low-voltage circuits and devices from being damaged by high-voltage transients.
- **Cost-Effectiveness**: TVS diodes offer a cost-effective solution for transient protection. They are relatively inexpensive compared to more complex surge protection devices, making them an economical choice for safeguarding electronics against voltage spikes.
- **Bidirectional and Unidirectional Options**: TVS diodes are available in both bidirectional and unidirectional configurations, providing flexibility in design to protect circuits from transients in either direction. For this design circuit has the bidirectional TVS been chosen, since it is compatible with protecting against positive as well as negative (ESD) voltage spikes. Normally, the bidirectional TVS is used for ciruits with an AC signal. However, since the product will be used in electrical labs according to the requirement in section 3.2, it is significant to protect against both positive and negative electro static discharge. The ESD event characteristics are namely always varying dependent on the situation.
- **High Peak Pulse Power Dissipation**: TVS diodes can absorb high levels of transient energy, dissipating it safely without damaging the diode itself. This high peak pulse power capability ensures that the TVS diode can handle severe transient events without failure.
- **Compact Size**: TVS diodes are available in small, compact packages, making them suitable for space-constrained designs. This compactness allows for easy integration into a wide range of electronic devices without significantly impacting the overall size or layout of the circuit board.

4.3.3. Protection Design

Figure 4.4 illustrates the input power protection circuit, which comprises a fuse and a TVS diode. Initially, a Lenovo adapter serves as the power source, located at the leftmost part of the circuit. Immediately following the adapter, a fuse is incorporated to safeguard the circuit against potential overload conditions and short circuits. The overcurrent protection component always needs to be placed directly in series with the input power source to prevent overcurrent events that could potentially damage the load circuitry or other protection components, such as the TVS diode. To the right of the fuse, the TVS diode is positioned in parallel with and adjacent to the load circuitry to monitor and shunt (ESD) transient voltage spikes. This positioning is essential because the TVS is connected to the same voltage level, enabling it to effectively protect against voltage spikes. In parallel, on the right side of the TVS diode, are the protected circuits: the PD module and the step-down converter. The PD module is installed to regulate the distribution of power towards the USB-C output, supplying power to the connected devices. At the far right, a step-down converter is implemented to reduce and regulate the voltage to the desired level suitable for its connected load.

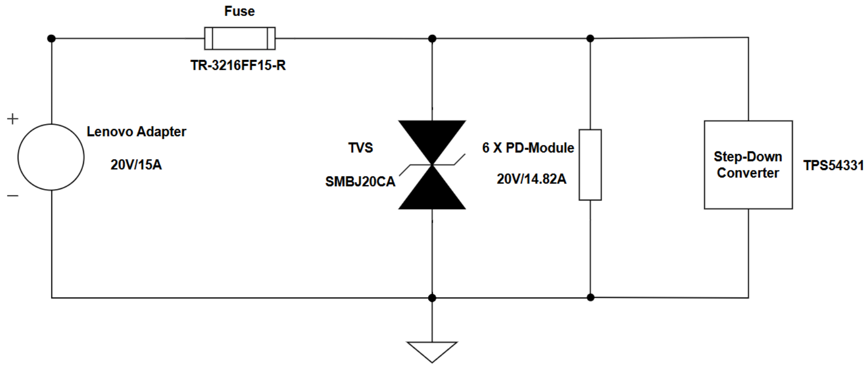


Figure 4.4: Circuit design of the Input protection

4.4. Stepdown Converter

A buck converter, also known as a step-down converter, is a type of DC-DC converter that reduces voltage from its input to its output. It is widely used in applications requiring a lower, stable output voltage derived from a higher input voltage. Buck converters are essential in modern electronic devices, providing efficient power conversion in modern electronics. This section presents the design of a buck converter using the TPS54331, a 3A, 28V input step-down DC-DC converter with Eco-mode. The focus will be on component selection, design calculations and efficiency analysis.

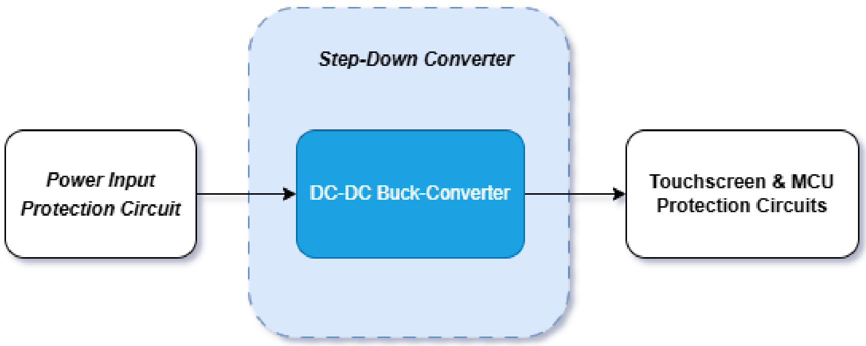


Figure 4.5: Step-Down Converter DC-DC design

The Lenovo 20V/15A adapter is significantly higher than the required 5V operating voltage for both the touchscreen and MCU. Without stepdown converter, the MCU and Touchscreen would be exposed to 20V, potentially causing immediate and catastrophic damage. Semiconductor components, such as diodes and transistors in the MCU and touchscreen, are designed to operate within specific voltage ranges. Hence, the step-down converter regulates the input 20V to a lower, stable output voltage that matches the operational requirements of 5V for the touchscreen and MCU according to section 3.3. Buck converters are highly efficient in converting higher voltages to lower ones and increases the current level at the output, essential for maintaining high efficient power levels in the system. They particularly achieve efficiencies around 75-95%, minimizing energy loss and heat generation, which is critical for the reliability and longevity of system components. This is crucial for optimizing the performance of the PD-module, as the current mainly is drawn by the PD-Module and the rest of the current capacity has been drawn by the touchscreen and MCU.

In addition, voltage regulators are another type of step-down converter. It is used to maintain a steady output voltage level no matter the changes in input voltage or load. Voltage regulators are critical to ensure that electronic devices have a constant and reliable voltage, which prevents damage and ensures constant performance. Nonetheless, their efficiency is less efficient than buck converters due to the fact that they dissipate the voltage difference between the regulator's V_{input} and V_{output} to heat.

Therefore, their efficiency is significantly lower, necessitating the inclusion of a voltage regulator with a heat sink. In Table B.8, the potentially integrable converters have been selected and compared for integration of the best-fitting step-down converter. These converters meet the requirements outlined in section 3.3 to supply the MCU and touchscreen with a stable 5V signal. The LMR51430 [32] and TPS54331 [79] are the best options for the USB-C charging station according to the following reasons from Table B.8:

- **90% efficiency** at 5V output
- **Compact size (in mm²)** also with additional circuitry.
- **Minimal thermal management** due to high efficiency and poor heat disipation
- **Cost-effectiveness** cost overall €1.35 per piece. This is obviously cheap as its function is essential within the circuit.

However, there was no simulation model of the LMR51430 buck converter, so the TPS54331 buck converter has been chosen to be implemented for supplying the MCU and Touchscreen in the USB-C charging station. The design process and component selection for a buck converter using the TPS54331 have been detailed in section A.1. Each electrical component was selected and calculated to ensure that the converter meets the specified requirements stated in section 3.3. The chosen components and calculated values ensure the converter's reliability and its 90% efficiency level within the intended application. In the Table 4.1 all components are listed.

Table 4.1: Component values and their importance/function in the buck converter design using TPS54331

Component	Symbol	Value	Importance/Function
Inductor	L_O	36.7 µH	Stores energy and smooths current flow
Input Capacitor	C_I	10 µF	Stabilizes input voltage and reduces ripple
Output Capacitor	C_O	0.79 µF	Reduces output voltage ripple and stabilizes output
Feedback Resistor	R_{o1}	52.5 kΩ	Sets output voltage via voltage divider
Feedback Resistor	R_{o2}	10 kΩ	Sets output voltage via voltage divider
Bootstrap Capacitor	C_{BOOT}	0.1 µF	Provides gate drive voltage for high-side MOSFET
Compensation Capacitor	C_1	4700 pF	Stabilizes feedback loop and sets low-frequency gain
Compensation Capacitor	C_2	39 pF	Improves phase margin by setting zero in compensation network
Compensation Resistor	R_3	49.9 kΩ	Sets mid-frequency gain and zero in compensation network
Slow Start Capacitor	C_{SS}	5 nF	Controls ramp-up rate of output voltage at startup
Input Voltage Divider Resistor	R_{en1}	333.33 kΩ	Sets UVLO start voltage
Input Voltage Divider Resistor	R_{en2}	26.35 kΩ	Sets UVLO stop voltage
Diode	$D1$	B340A	Provides path for inductor current during high-side switch off

4.4.1. Efficiency Verification

The efficiency of the buck converter has been depicted from the datasheet, accoringing to the 20v input volltage and output current 1A, the efficency will be around 88-90% [79]. The efficiency of the converter is calculated to ensure it meets the design specifications of 88% to 90%. The efficiency (η) is given by:

$$\eta = \frac{P_{OUT}}{P_{IN}} = \frac{V_{OUT} \times I_{OUT}}{V_{IN} \times I_{IN}} \tag{4.1}$$

The output power (P_{OUT}) is:

$$P_{OUT} = 5V \times 0.65A = 3.25W \tag{4.2}$$

For an efficiency of 88%:

$$\begin{aligned} P_{IN} &= \frac{P_{OUT}}{0.88} = \frac{3W}{0.88} \approx 3.69W \\ I_{IN} &= \frac{P_{IN}}{V_{IN}} = \frac{3.41W}{20V} = 0.185A \end{aligned} \tag{4.3}$$

For an efficiency of 90%:

$$\begin{aligned} P_{IN} &= \frac{P_{OUT}}{0.90} = \frac{3.25W}{0.90} \approx 3.61W \\ I_{IN} &= \frac{P_{IN}}{V_{IN}} = \frac{3.61W}{20V} = 0.181A \end{aligned} \tag{4.4}$$

These calculations confirm that the input current ranges from 0.181A to 0.185A, indicating that the design meets the efficiency requirements, stated in section 3.3

4.5. Touchscreen & MCU Protection Circuit

Figure 4.6 illustrates the overview of the Touchscreen protection and represents the MCU protection overview, which consists of overcurrent & thermal protection as well as a overvoltage & ESD protection circuit. The design choices for those safety mechanisms will be discussed in the next subsections.

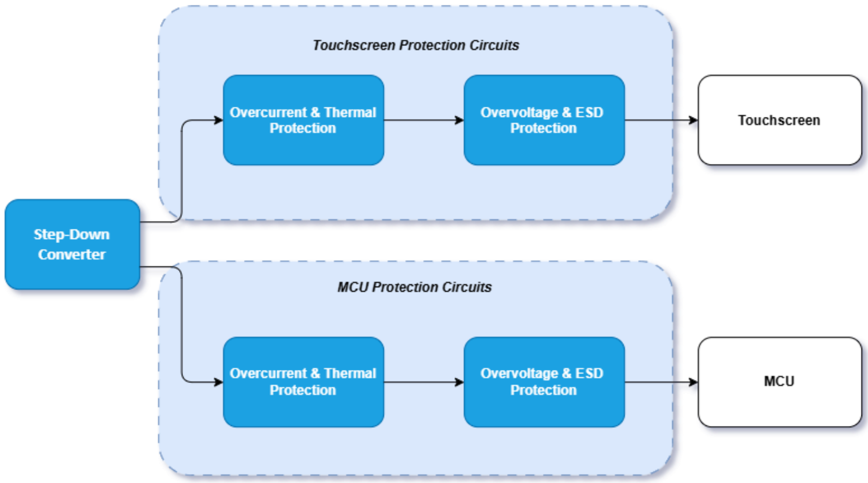


Figure 4.6: MCU & Touchscreen Protections Overview

Touchscreen

Electrical safety measures are crucial for touchscreens for several reasons. First and foremost, it protects the users. Touchscreens are directly touched by users, and a poorly insulated or defective circuit can cause electric shocks, which can be dangerous. This is especially important in laboratory environments where many electronic devices are being tested. Overvoltages, overcurrent, and ESD can damage the internal components of the touchscreen. For example, the touchscreen could suffer from inconsistent touch sensitivity or failing to register inputs correctly, significantly degrading the user experience. This poses a serious safety risk that must be avoided by implementing adequate protective measures according to section 3.2. Protecting the touchscreen from electrical faults and properly supplying 5V and 0.5A at its input significantly extends the lifespan and reliability of the device.

MCU

MCUs are vital components in USB-C charging stations, managing the complex tasks of power delivery and communication with connected devices. Ensuring their safety is crucial for reliable operation and protecting both the charging station and the user from potential electrical hazards. Continuous overstress can deteriorate the chemical compositions in the semiconductor materials leading to unstable system performance. For example, the MCU might exhibit unpredictable behaviour, causing malfunctions in the entire system it controls. This can manifest as random resets, unreliable data processing, and unexpected errors. This poses a serious safety risk that must be avoided by implementing adequate protective measures according to section 3.2. Protecting the MCU from electrical faults and properly supplying 5V and 0.15A at its input significantly extends the lifespan and reliability of the device.

4.5.1. Overcurrent & Thermal Protection

Overcurrent can damage the internal electronic components of the touchscreen and MCU, as they are designed to operate within specific current limits, and exceeding these limits can lead to problematic situations. The overcurrent protection component has been chosen from the component comparison Table B.4. Based on the datasheet specifications of the 0.5amps touchscreen [52] and of the 0.15amps MCU [73], the Littelfuse 1812L050 PPTC [20] and the Littelfuse 1206L016 PPTC [41] have been chosen respectively for the touchscreen and the MCU respectively. Their specifications of the selected PPTC component are described in Table B.11 (Touchscreen) and Table B.13 (MCU), meeting the requirements outlined in section 3.2. Furthermore, the specific advantages for the PPTC derived from Table B.4 are as follows:

- **Low current handling** The input currents of the MCU and touchscreen are relatively low, which aligns well with the typical current handling capacity of PPTC devices.
- **Automatically resetable** PPTC fuses reset after an overcurrent, ideal for touchscreen charging stations requiring easy maintenance and continuous operation.
- **Cost-effectiveness** PPTC fuses are cost-effective and hence suitable for commercial electronics. They generally cost between 0.20 to 5.00 euros.

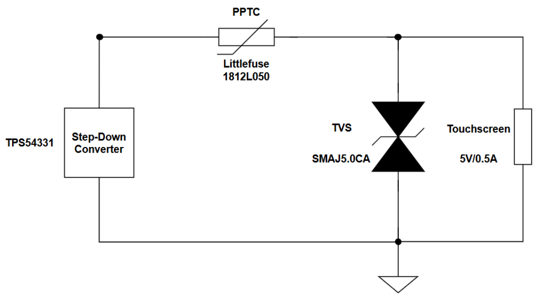
Considering the balance between cost, reusability, and suitability for low-current applications, a PPTC resettable fuse is the optimal choice for overcurrent and thermal protection for a touchscreen and MCU in a USB-C charging station.

4.5.2. Overvoltage & ESD Protection

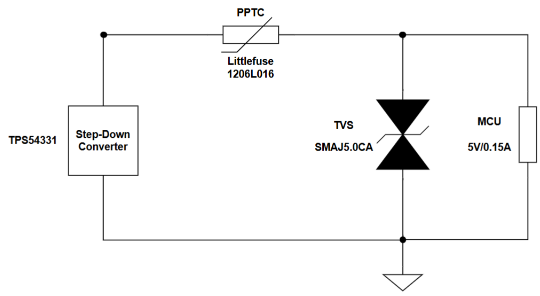
Electrostatic discharge can damage the internal electronic components of the touchscreen and MCU. The overvoltage & ESD protection component has been chosen from the component comparison Table B.5. As the discussed in section 4.3, the TVS diodes are ideal components for overvoltage and ESD protection in circuitry. Based on the datasheet specifications of the touchscreen [52] and the MCU [73], the SMAJ5.0CA TVS [47] has been chosen for overvoltage and ESD protection due to its overlapping operational values that are compatible with the touchscreen, meeting the requirements outlined in section 3.2.

4.5.3. Protection Circuit design

Figure 4.7a illustrates the touchscreen protection circuit combining the step-down converter, PPTC and TVS. This also holds for the MCU protection circuit in Table B.4. The step-Down Converter provides a regulated 5V input to supply the touchscreen. The PPTC is in series directly connected with the buck converter, offering overcurrent protection for the TVS and the loads by limiting the current flow in case of a short circuit, overload of malfunctioning buck converter. Subsequently, the bidirectional TVS diode is positioned parallel to the touchscreen, providing overvoltage and ESD protection by absorbing positive and negative (ESD) voltage spikes. Hence this protection circuit design ensures that the touchscreen and MCU operate reliably and safely, protected from both overvoltage, ESD, overcurrent and thermal threats.



(a) Touchscreen Protection Circuit



(b) MCU Protection circuit

Figure 4.7: Overview of Touchscreen & MCU protection circuits

4.6. Final Design

Figure 4.8 illustrates the final design consisting of the 20V/15A Lenovo adapter connected to the power input protection ciruit safegaurding (overcurrent and overvoltage protection) the six PD-Modules and the stepdown converter (buck converter). Subsequently, the stepdown converter reduces the the 20V level towards 5V to supply the touchscreen and MCU via their protection circuit path. The integrated protection circuits in this design protect the sytem and its connected devices against overcurrent, overvoltage, ESD, EMI and thermal hazards.

The protection components are spefically located. For instance, the overcurrent protection components (fuse and PPTC) are always directly connected to the adapter or the stepdown converter, as they protect the TVS and other circuit loads from excessive current levels. In addition, the overvoltage and ESD protection circuit are always parallel connected adjacent to the protected load in order to absorb quick voltage spikes.

Besides, an efficient controller is used to decrease the input voltage to the required levels for the touchscreen and MCU, ensuring a stable and regulated power supply. The buck converter design ensures smooth current flow, reduces ripple, filters out EMI noise frequencies and power stability for the MCU and touchscreen. Additionally, the PD-module and MCU are internally protected against EMI and reverse current. Also the connected loads are protected against reverse current events, so this protection has not been taken into account within this system. Futhermore, the manufactured PCB design must be well grounded and coated with a hydrophobic coating to avoid leakage current events. There are different coatings used in the industry, however the Acrylcoating is the most appropriate coating to apply at the PCB of the USB-C charging station. A comparison among some coatings have been described in table B.14. Acrylic coatings have been used in PCB design for indoor consumer/indsutrial electronics for years. They protect against leakage currents. HumiSeal 1B31 is a prime example of such a coating [28]. However for prototyping purposes, some safety measures need to be taken into account, as the coating is flamable and toxic [33]. Consequently, the acrylic coating will be used for this design.

In conclusion, this comprehensive design ensures the system is well-protected against overvoltage, overcurrent, leakage current, ESD, EMI, and thermal issues while providing a stable power supply to critical components. The integration of these protection mechanisms and the efficient buck converter design ensures the longevity and reliability of the touchscreen and MCU in various operating conditions.

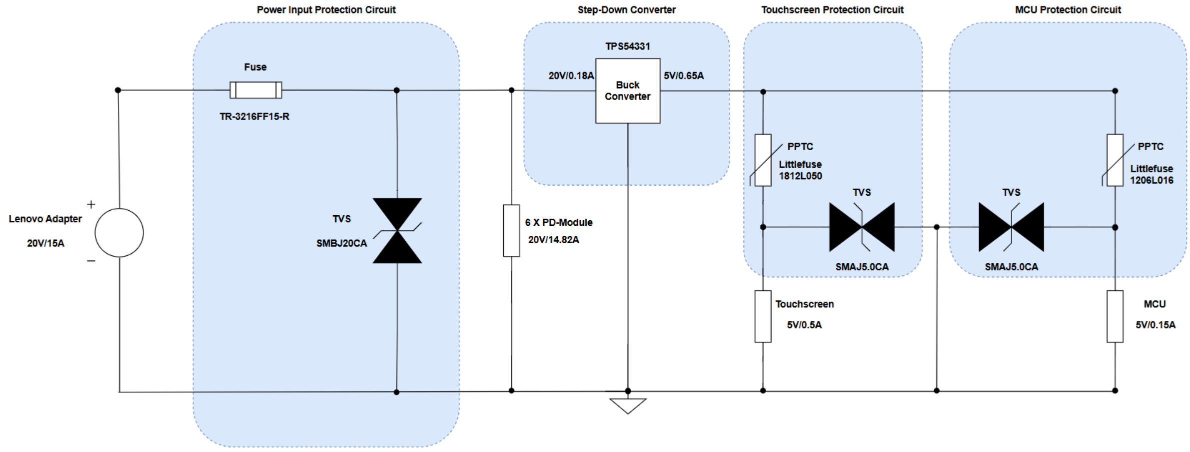


Figure 4.8: The final design

5 Validation

This chapter provides a detailed overview of the validation process and the results obtained from the simulations. The validation process plays a crucial role in confirming the reliability and efficiency of electronic systems. The focus has been highlighted on the following specific main components: the simulation setup (section 5.1) and the simulation results (section 5.2). Each component of the system has been tested and validated through simulations, and the results are discussed in the following sections.

5.1. Schematic Circuits

For validation purposes of the safety protection design, the LT-Spice simulation software has been utilized to asses the design performance results as outlined in chapter 3. The circuit in Figure 5.1 has been created in LT-Spice to simulate and analyze its performance characteristics, ensuring accurate validation of the design. Unfortunately, some components of the protection circuits were not found within the LT-Spice software, such as the main fuse in the input power protection circuit and the PPTC in the touchscreen as well as the MCU protection circuit. Instead of these components, alternative likewise protection components have been used to simulate the entire system. The fuse has been converted to a circuit breaker with the same configured characteristics and the PPTC has been changed by the PTC MF-RM040-Tamb23 with the same characteristics. The PTC is a non-resetable version of the PPTC, although is this not important for the simulation as the simulations have been done iterative.

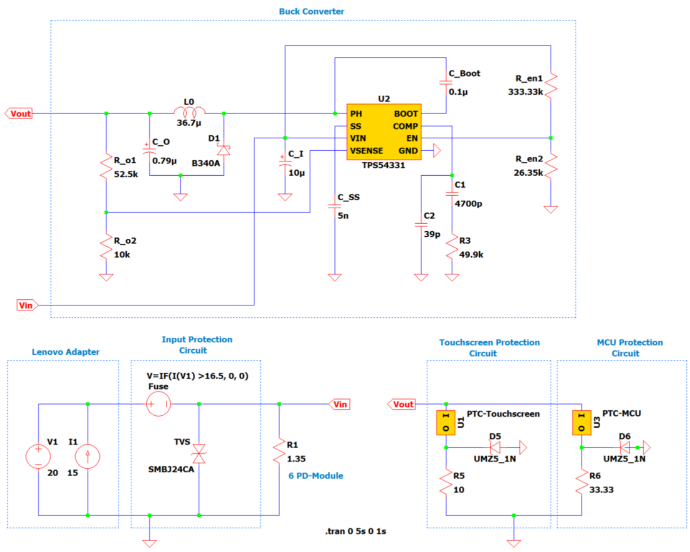


Figure 5.1: Final Circuits

5.2. Simulation validation

The validation process was integral to ensuring the reliability and effectiveness of the designed USB-C charging station. Simulations played a crucial role in testing the various protection mechanisms under different scenarios. The simulation results indicated that the protection systems functioned as intended, safeguarding against overcurrent, overvoltage transients.

For example, the simulations demonstrated that the PPTC fuses effectively interrupted the current flow during overcurrent events, while the TVS diodes provided robust protection against voltage spikes. The efficiency of the buck converter was also validated through simulations, confirming that it consistently maintained the desired output voltage and current levels with minimal ripple and high efficiency. These simulations were supported by practical tests, which further validated the theoretical predictions and ensured that the design met all specified requirements.

The protection mechanism circuits are expected to meet the program requirements during the simulations, as the component selection and rigorously calculation of components. Theoretically, this system should function as intended. Hence, the validation process should confirm that the system performs according to the established expectations.

Figure 5.2 consists of three subplots, each representing the current flow in different components of a USB-C charging station over time.

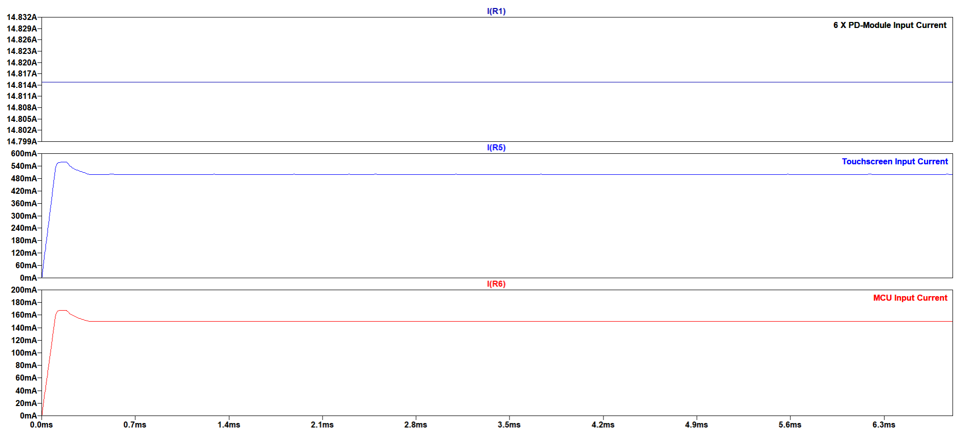


Figure 5.2: The current that flow in the PD-Module, Touchscreen & MCU

The details of each subplot will be explained as follows:

- **Top Subplot (PD-Module Input Current):** The 6 x PD-Module maintains a consistent and stable input current of approximately 14.814A, indicating reliable and efficient power delivery.
- **Middle Subplot (Touchscreen Input Current):** The graph shows the Touchscreen Input Current, which initially surges to around 540mA due to the 570KHz frequency switching of the buck converter. Subsequently, it stabilizes at approximately 480mA. This indicates a brief initial high current draw followed by a steady-state current.
- **Bottom Subplot (MCU Input Current):** The graph shows the MCU Input Current. It initially surges to around 180mA due to the 570KHz frequency switching of the buck converter. Subsequently, it stabilizes at approximately 120mA. This pattern indicates a brief initial high current draw during power-up, followed by a steady-state operating current.

Figure 5.3 consists of two subplots, representing the voltage input and output level of a buck converter over time. The details of each subplot will be explained as follows:

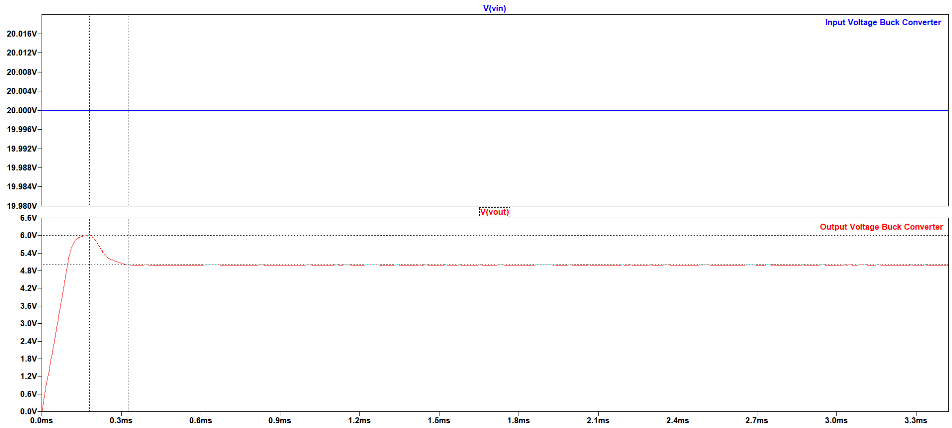


Figure 5.3: The input and the output voltage of the Buck converter

- **Top Subplot (Input Voltage Buck Converter):** The input voltage of the buck converter is very stable at 20V with minimal fluctuations. This indicates a consistent and steady input voltage, essential for reliable converter operation.
- **Bottom Subplot (Output Voltage Buck Converter):** The output voltage of the buck converter initially surges to approximately 6V due to the transient response of the frequency switching. This voltage-time rise is logical, since the buck converter consists of a inrush current limiting feature. Hence the current flows gradually through the converter, resulting in a gradually increase of voltage output. Additionally, at approximately 0.1ms the voltage has been clamped at 6V and it is stabilized at 5V as that is the normal operating voltage of the design according to the buck converter its data sheet [79].

Figure 5.4 consists of two subplots. Both subplots illustrate the behavior of input and output currents of the PTC for the touchscreen and MCU. The currents initially surge due to the transient response but then stabilize at a consistent value, indicating effective current regulation by the PTC components. This stability is crucial for the reliable operation of the touchscreen and MCU. The light blue line represents the input current of the PTC during an overcurrent event. The dark blue line shows the PTC mechanism during an overcurrent event in the ciruit and the red line illustrates the input current for the touchscreen or MCU. A decomposition of Figure 5.4 has been detailed in Figure C.2 and Figure C.1.

Figure 5.4: Overcurrent protection of MCU and Touchcreen

- **Top Subplot:** This subplot shows the input current of the PTC, Touchscreen overcurrent protection mechanism and output currents for the PTC Touchscreen.
- Input Current (light blue Line): Initially surges up to approximately 2.8A and then stabilizes around 0.6A. This stabilization occurs due to the overcurrent protection and overvoltage protection mechanism. Overcurrent events namely have a directly correlation with overvoltage events, since the load stays constant.
- Touchscreen protection circuit (Dark blue link) : Overcurrent protection mechanism has been presented by this signal. The current exhibits an initial negative spike to -2.8A at the same time of the overcurrent event of 2.8A. This negative current spike is, obviously drawn by the TVS, since that the overcurrent level probably caused a overvoltage level that tripped the TVS diode.
- Output Current (Red Line): Shows a stable of the normal operating current 0.5A accordinf to the touchscreen datasheet [52] after the initial fluctuations to the maximal operating current 0.6A.
- **Bottom Subplot:** This subplot shows the input current of the PTC, MCU overcurrent protection mechanism and output currents of the PTC of MCU.
- Input Current (light blue Line): Initially surges up to approximately 2.0A and then stabilizes around 0.5A. This stabilization occurs due to the overcurrent protection and overvoltage protection mechanism. Overcurrent events namely have a directly correlation with overvoltage events, since the load stays constant.
- Touchscreen protection circuit (Dark blue link) : Overcurrent protection mechanism has been presented by this signal. The current exhibits an initial negative spike to -2.4A at the same time of the overcurrent event of 2.4A. This negative current spike is, obviously drawn by the TVS, since that the overcurrent level probably caused a overvoltage level that tripped the TVS diode.
- Output Current (Red Line): Shows a stable of the normal operating current 0.1A according to the MCU datasheet [73] after the initial fluctuations to the maximal operating current 0.15A.

Figure 5.5 illustrates the overvoltage condition experienced by the MCU and Touchscreen. Initially, there is a rapid surge in voltage up to around 9V, which quickly drops to a stable voltage of approximately 5V. This behavior is indicative of an buck converter that activates its overvoltage protection and its inrush current limiting feature to mitigate the initial surge, ensuring that the voltage quickly returns to a safe operating level for the components involved. The stability at 5V suggests effective voltage regulation post-surge, crucial for the reliable operation of the MCU and touchscreen.

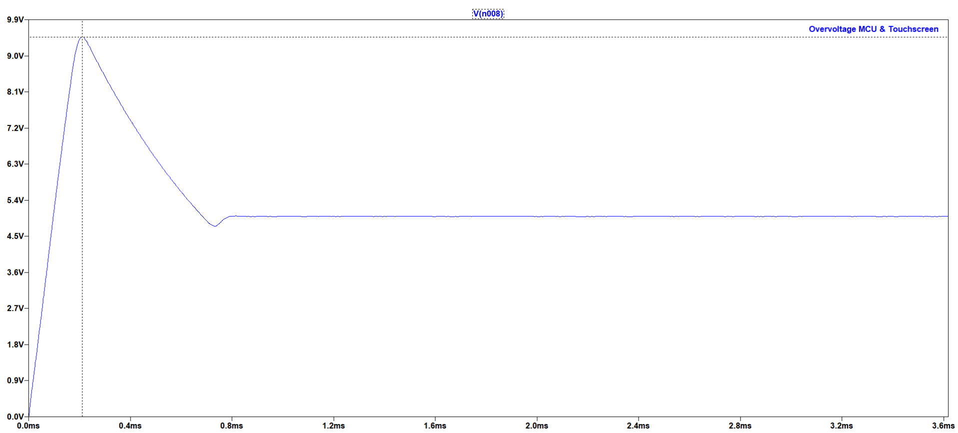


Figure 5.5: Overvoltage event at MCU and Touchscreen

Figure 5.6 illustrates the overvoltage protection behavior for the MCU and touchscreen. Initially, there is a rapid surge from 0V in voltage up to maximal clamping voltage, 6V due to the TVS diode operation mechanims [47] which quickly drops to the typical operating stable voltage of 5V. This behavior indicates that the overvoltage protection mechanism effectively mitigates the initial surge, ensuring that the voltage quickly returns to a safe operating level. The stability at 5V suggests effective voltage regulation post-surge, which is crucial for the reliable operation of the MCU and touchscreen.

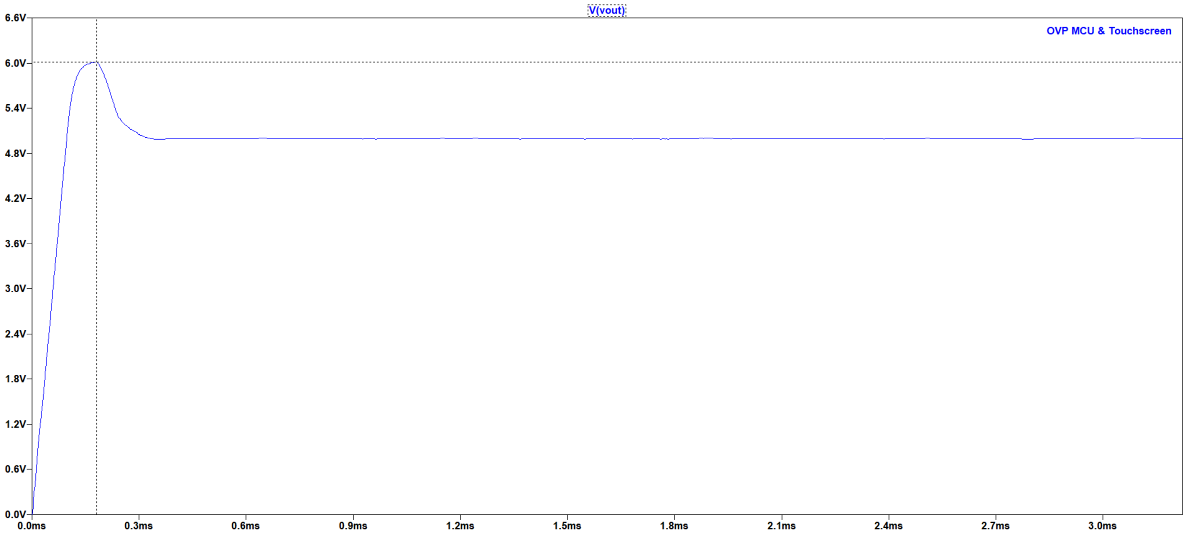


Figure 5.6: Overvoltage protection at MCU and Touchscreen

The protection mechanism circuits are expected to meet the program requirements during simulations, given the rigorous selection and precise calculation of components. The overcurrent and overvoltage transients have been successfully simulated and validated for this design. However, thermal protection has not been simulated in LTspice, as the software does not support this functionality. Nonetheless, overheating is typically a result of overcurrent and overvoltage events. Therefore, it can be theoretically assumed that when the overcurrent and overvoltage surges are protected, the system would also be protected from component overheating due to overcurrent causes. Theoretically, this system should function as intended. Hence, the validation process should confirm that the system performs according to the established expectations.

6 Conclusion

6.1. Summary

This thesis project focused on developing an advanced USB-C charging station integrated with comprehensive safety mechanisms to prevent electrical damage. The primary goals included ensuring efficient power delivery, protecting both devices and users, and meeting IEC safety standards. Key achievements of the project include the successful design and implementation of protection systems such as overcurrent, overvoltage, and electrostatic discharge (ESD) protection. Through simulations and practical implementations, the proposed solutions demonstrated high reliability and efficiency, thereby validating the design's effectiveness in real-world conditions.

Chapter 1: Introduction established the motivation for this project, highlighting the growing demand for efficient and safe charging solutions in professional settings. The primary objective was to design a power station that integrates advanced USB-C charging and data transfer functionalities into existing WRepair stations. The project aimed to tackle the challenges of maintaining electrical safety and power quality in USB-C charging stations.

Chapter 2: Safety Standards discussed in detail the relevant IEC safety standards essential for the project, including IEC 62368-1 for audio/video, information and communication technology equipment safety, IEC 62680-1-2/3 for USB power delivery specifications, IEC 61000-4-2 for ESD immunity and CISPR 22 for EMI requirements in infromation technology. These standards are crucial for protecting against electrical shocks, thermal hazards, overvoltage, overcurrent, EMI and ESD. Adherence to these standards ensures the safety and reliability of the charging stations and their users.

Chapter 3: Program of Requirements (PoR) specified the system requirements necessary for the USB-C charging station design. Key requirements included strict adherence to IEC standards, robust protection against various electrical hazards, and efficient power quality management. The system was designed to handle a DC input power of 300W, maintain an efficiency range of 75-90%, and incorporate comprehensive protections against overheating, overvoltage, overcurrent, leakage current, reverse current, EMI and ESD.

Chapter 4: Design Process provided a detailed account of the design process, including the selection of appropriate protection components and the final design configuration. The design involved developing protection circuits for power input, a step-down converter, and implementing protection mechanisms for the touchscreen and microcontroller unit. Key design choices included:

- **Power Input Protection Circuit**: Implemented overcurrent and thermal protection, overvoltage and ESD protection, ensuring safe power delivery to the system.
- **Step-down Converter**: Designed to convert 20V input voltage to a stable 5V, ensuring efficient power regulation and EMI noise filtering
- **Touchscreen and MCU Protection**: Included specific protection circuits to safeguard against overcurrent, overheating, overvoltage, and ESD, ensuring reliable operation of these critical components.
- **Final design**: The PCB design needs well grounded and hydrophobic coated to avoid leakage currents.

The final design integrated these protection mechanisms to enhance the system's safety and reliability.

Chapter 5: Validation presented the testing and simulation results, confirming the effectiveness of the protection mechanisms under various operational conditions. Key findings included:

- **Schematic Circuit Validation**: Detailed circuit designs were validated through simulations to ensure they met the specified protection requirements.
- **Simulation Testing**: Conducted to verify the system's response to overcurrent, overvoltage, and ESD events, ensuring the protection mechanisms functioned as intended.

The successful validation demonstrated that the USB-C charging station met all the specified safety and performance requirements outlined in chapter 3.

6.2. Discussion & Recommendations

The implementation of advanced protection mechanisms within the USB-C charging station significantly enhances its reliability and safety. Safety measures for overcurrent, leakage current, overvoltage, EMI, and ESD have been achieved through protection circuit mechanisms that ensure devices and users are safeguarded against electrical faults according to the safety standards in Table 2.3. Additionally, the design efficiency verification indicated that the design meets the required specifications, as detailed in section 3.3, maintaining efficiency between 88% and 90%. The project also highlighted the importance of proper component selection and design processes in achieving optimal performance.

The meticulous approach to component selection and circuit design contributed significantly to the project's success. For instance, the TPS54331 buck converter was selected for its ability to efficiently step down voltage while maintaining high efficiency. The choice of using a TVS diode for both overvoltage and ESD protection resulted in a space-efficient, cost-effective, and simple design, enhancing the overall reliability of the charging station. These choices were validated through simulations, confirming the system's ability to handle various load conditions and electrical disturbances. This design focused on creating simple yet high-performance protection mechanisms for the commercial USB-C charging station.

It is recommended to create a PCB design of this system to perform practical experiments to critically validate the performance and compare it with the stated requirements in chapter 3. Additionally, more electrical hazard protections can be incorporated, such as thermal protection and leakage current management. However, due to time constraints and changes in the project scope, manufacturing a comprehensive PCB was not completed. Initially aimed at delivering a final product, the project scope shifted to focus on a proof of concept to manage the project within the available timeframe. This shift allowed for focused literature research on electrical safety hazards, their safety measures, and the validation of essential components, ensuring robust core functionalities.

In conclusion, this thesis provides a detailed and systematic approach to designing a safe, reliable, and efficient USB-C charging station. By addressing key challenges in electrical safety and power quality management, this work significantly contributes to the development of advanced charging solutions for modern laboratory environments.

6.3. Future Work

While the current project successfully addressed the primary objectives, there are opportunities for further enhancement. Future work could focus on integrating and designing a comprehensive USB-C charger PCB, which includes the MCU and PD module, combining the buck converter and protection circuits into an all-in-one PCB solution.

Additionally, integrating an electronic fuse (eFuse) instead of a thermal fuse could significantly enhance system performance. A thermal fuse breaks after the tripping current is exceeded and needs to be replaced each time. In contrast, an eFuse provides precise and specific current limit trips faster than a traditional fuse and can reset itself automatically after tripping. Moreover, an eFuse offers protection against various types of faults, such as overcurrent, overvoltage, and thermal events. Although an eFuse is more expensive, this innovation would increase the product's lifetime and reduce overall repair costs, thus enhancing customer satisfaction.

Future research could also focus on further optimizing the design for even higher efficiency. Continuous updates to comply with evolving IEC standards will be essential to maintaining the safety and reliability of USB-C charging stations. Ultimately, the product must adhere to the most recent CE certification requirements to achieve CE certification, enabling the USB-C charging station to be sold in Europe.

References

[1] Accelonix. *IEC 61000-4-2 EMC Workshop September 2019*. Accessed: 2024-06-10. 2019. URL: https://accelonix.nl/wp-content/uploads/IEC-61000-4-2-EMC-Workshop-Sep-2019.pdf.

[2] *Acrylic Conformal Coatings*. Accessed June 26, 2024. MG Chemicals. 2023. URL: https://mgchemicals.com/category/conformal-coatings/acrylic-conformal-coatings/ (visited on 06/26/2024).

[3] United States Department of Agriculture. *Electric Program Bulletin 169-27: Guide to Developing a Quality Assurance Program for Design and Construction of Electric Systems*. Accessed: 2024-06-16. 2020. URL: https://www.rd.usda.gov/files/UEP_Bulletin_169-27.pdf.

[4] S. Amirtharajan and D. P. K. Ayyasamy. "Design and Implementation of Transient Voltage Suppression for Power Systems". In: *International Journal of Innovative Technology and Exploring Engineering (IJITEE)* 9.1 (2019). Accessed: 2024-06-16, pp. 91–96. URL: https://www.ijitee.org/wp-content/uploads/papers/v9i1/L26891081219.pdf.

[5] Analog Devices. *Reverse Current Circuitry Protection*. Accessed: 2024-06-16. 2023. URL: https://www.analog.com/en/resources/design-notes/reversecurrent-circuitry-protection.html.

[6] Standards Australia. *AS/NZS 62368.1:2018 Audio/video, information and communication technology equipment - Part 1: Safety requirements*. Accessed: 2024-06-10. 2018. URL: http://www.keylab.cn/uploadfile/image/Download/ASNZS%2062368.1_2018.pdf.

[7] Bhimsen. *Overcurrent or Short Circuit Protection*. Accessed: 2024-06-10. 2023. URL: https://electronics-fun.com/overcurrent-or-short-circuit-protection/.

[8] Diarmuid Carey. "How to Choose the Right Protection for Your Circuit". In: *Analog Dialogue* 187 (Mar. 2021). Accessed: 2024-06-17. URL: https://www.analog.com/en/resources/analog-dialogue/raqs/raq-issue-187.html.

[9] Scott Chambers. *Everything You Need to Know About EMI Shielding*. Accessed June 26, 2024. 2023. URL: https://www.strouse.com/blog/what-is-emi-shielding (visited on 06/26/2024).

[10] CircuitBread. *What is a Zener Diode and How Does it Work*. Accessed: 2024-06-23. 2024. URL: https://www.circuitbread.com/tutorials/what-is-a-zener-diode-and-how-does-it-work.

[11] OpenStax College. *Electric Hazards and the Human Body*. OpenStax College. 2023. URL: https://courses.lumenlearning.com/suny-physics/chapter/20-6-electric-hazards-and-the-human-body/ (visited on 06/25/2024).

[12] European Commission. *Impact Assessment Report Accompanying the Proposal for a Directive on the Harmonisation of the Laws of the Member States Relating to the Making Available on the Market of Radio Equipment*. Accessed: 2024-06-10. 2021. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX%3A52021SC0245.

[13] *Conformal Coating*. Accessed June 26, 2024. Coating.nl. 2023. URL: https://coating.nl/conformal-coating/ (visited on 06/26/2024).

[14] TE Connectivity. *Media Isolated Pressure Sensor M3200 Series Datasheet*. Accessed: 2024-06-23. 2022. URL: https://nl.mouser.com/datasheet/2/240/media-3319099.pdf.

[15] Eaton Corporation. *3216FF Surface Mount Fuse*. Datasheet. Accessed: 2023-06-24. Eaton Corporation. 2023. URL: https://nl.mouser.com/datasheet/2/87/eaton-3216ff-surface-mount-fuse-data-sheet-1608666.pdf.

[16] TDK Corporation. *How to Use Chip NTC Thermistors*. Accessed: 2024-06-16. 2023. URL: https://product.tdk.com/en/techlibrary/applicationnote/howto_chip-ntc-thermistor.html.

[17] Council of the European Union. *ST 10713 2022 INIT*. Accessed: 2024-06-10. 2022. URL: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://data.consilium.europa.eu/doc/document/ST-10713-2022-INIT/x/pdf.

[18] Stanisław Czapp. *Transient Surge Voltage Suppressors and Their Performance in Circuit Over-Voltage Protection*. Accessed: 2024-06-16. 2012. URL: https://www.researchgate.net/publication/257002605_Transient_surge_voltage_suppressors_and_their_performance_in_circuit_over-voltage_protection.

[19] Analog Devices. *MAX25432 Automotive Dual USB Type-C Charger*. Accessed: 2024-06-16. 2023. URL: https://www.analog.com/en/products/max25432.html.

[20] Mouser Electronics. *Media-3323076 Datasheet*. Accessed: 2024-06-23. 2024. URL: https://nl.mouser.com/datasheet/2/240/media-3323076.pdf.

[21] SparkFun Electronics. *LM7805 Datasheet*. Accessed: 2024-06-23. 2024. URL: https://www.sparkfun.com/datasheets/Components/LM7805.pdf.

[22] Versa Electronics. *Burnt Circuit Board? What Causes a PCB to Catch Fire?* Accessed: 2024-06-10. 2023. URL: https://versae.com/burnt-circuit-board-what-causes-a-pcb-to-catch-fire/.

[23] *EMI Filter Design for Reducing Common-Mode and Differential-Mode Noise in Conducted Interference*. Accessed June 26, 2024. 2023. URL: https://www.ti.com/lit/wp/slyy136/slyy136.pdf (visited on 06/26/2024).

[24] Directorate-General for Internal Policies European Parliament. *The impact of the COVID-19 pandemic on EU cohesion and EU cohesion policy*. Briefing. European Parliament, 2021. URL: https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/698819/EPRS_BRI(2021)698819_EN.pdf.

[25] Yang Gao et al. "Investigation of the Filter Amplifiers using the TVS Diode for ESD Protection". In: *2019 8th International Symposium on Next Generation Electronics (ISNE)* (2019), pp. 1–3. URL: https://api.semanticscholar.org/CorpusID:208039948.

[26] Matric Group. *Common PCB Defects: What Causes a Circuit Board to Burn?* Accessed: 2024-06-10. 2023. URL: https://blog.matric.com/common-pcb-defects-what-causes-a-circuit-board-to-burn.

[27] Prashanth S. Holenarsipur, N. Mohan, and D.J. Christofersen. "Thyristor-switched arrester for improved protection of power system equipment". In: *IEEE Power Engineering Society. 1999 Winter Meeting (Cat. No.99CH36233)* 2 (1999), 1009–1014 vol.2. URL: https://api.semanticscholar.org/CorpusID:110886014.

[28] HumiSeal. *HumiSeal 1B31 Acrylic Conformal Coating*. Accessed: 2024-06-26. 2024. URL: https://chasecorp.com/HumiSeal/products/acrylics/1b31/.

[29] "IEEE Guide for the Application of Surge Protectors Used in Low-Voltage (Equal to Or Less Than 1000 V, RMS, Or 1200 V, DC) Data, Communications, and Signaling Circuits". In: *IEEE Std C62.43-2004 (Revision of IEEE Std C62.43-1999)* (2005), 0_157. DOI: 10.1109/IEEESTD.2005.98652.

[30] Littelfuse Inc. *Fundamentals of Resettable Functionality in PPTC Devices*. Tech. rep. Accessed: 2024-06-26. Littelfuse, 2024. URL: https://m.littelfuse.com/~/media/electronics/technical_papers/resettable_ptcs/littelfuse_fundamentals_of_resettable_functionality_in_pptc_devices_technical_paper.pdf.pdf.

[31] Texas Instruments. *LM2596 SIMPLE SWITCHER Power Converter 150 kHz 3A Step-Down Voltage Regulator*. Accessed: 2024-06-16. 2023. URL: https://www.ti.com/lit/ds/symlink/lm2596.pdf?ts=1718639798898&ref_url=https%253A%252F%252Fwww.mouser.com%252F.

[32] Texas Instruments. *LMR51430 Datasheet*. Accessed: 2024-06-23. 2024. URL: https://www.ti.com/lit/ds/symlink/lmr51430.pdf?ts=1719139189881&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FLMR51430.

[33] Texas Instruments. *safety datasheet*. Accessed: 2024-06-27. 2013. URL: https://docs.rs-online.com/ad87/0900766b813aae54.pdf.

[34] Texas Instruments. *TLVM13630 Datasheet*. Accessed: 2024-06-23. 2024. URL: https://www.ti.com/lit/ds/symlink/tlvm13630.pdf?ts=1719072129413&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FTLVM13630.

[35] Texas Instruments. *Transient Voltage Suppressors (TVS) for ESD Protection*. Accessed: 2024-06-16. 2021. URL: https://www.ti.com/lit/ab/slvafr3/slvafr3.pdf?ts=1718535278811.

[36] Joey. *Teardown of Anker 150W GaNPrime 747 Charger (A2340)*. Accessed: 2024-06-10. 2023. URL: https://www.chargerlab.com/teardown-of-anker-150w-ganprime-747-charger-a2340/.

[37] Joey. *Teardown of Satechi 165W GaN Desktop Charger (ST-UC165GM)*. Accessed: 2024-06-10. 2023. URL: https://www.chargerlab.com/teardown-of-satechi-165w-gan-desktop-charger-st-uc165gm/.

[38] K. N. Kalam et al. "An Improved Fault Location Method for Distribution Networks Using Synchronized Voltage and Current Measurements". In: *IEEE Transactions on Power Delivery* 36.2 (2021). Accessed: 2024-06-16, pp. 882–892. DOI: 10.1109/TPWRD.2020.3026665. URL: https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9275351.

[39] Aaron Lee and Chad Flinn. *Overload and Overcurrent Protection*. Accessed: 2024-06-10. 2020. URL: https://pressbooks.bccampus.ca/basicmotorcontrol/chapter/overload-and-over-current-protection/.

[40] Lenovo. *Lenovo 65W USB-C GaN Adapter*. Accessed: 2024-06-16. 2023. URL: https://www.lenovo.com/nl/nl/p/accessories-and-software/chargers-and-batteries/chargers/gx21f23046?orgRef=https%253A%252F%252Fwww.google.com%252F.

[41] Littelfuse. *PTC 1206L Datasheet*. Accessed: 2024-06-23. 2024. URL: https://www.littelfuse.com/media?resourcetype=datasheets&itemid=2b6a1515-d4ee-4c83-8bd4-152b4901b8f5&filename=littelfuse-ptc-1206l-datasheet.

[42] R. A. Martins and A. P. B. Silva. "Joule's Experiments on the Heat Evolved by Metallic Conductors of Electricity". In: *Foundations of Science* 26 (2021). Published online: 20 June 2020, pp. 625–701. DOI: 10.1007/s10699-020-09681-1. URL: https://link.springer.com/article/10.1007/s10699-020-09681-1.

[43] Mallory McGuinness. *Polyurethane Conformal Coating Services for Electronics*. Accessed June 26, 2024. HZO. 2020. URL: https://www.hzo.com/blog/polyurethane-conformal-coating-services-for-electronics/ (visited on 06/26/2024).

[44] *Mitigating EMI for a CISPR 22-Compliant Power Solution*. Accessed June 26, 2024. 2023. URL: https://www.analog.com/media/en/technical-documentation/tech-articles/mitigating-emi-for-a-cispr-22compliant-power-solution.pdf (visited on 06/26/2024).

[45] MorePCB. *PCB Fuses and Overcurrent Protection: Circuit Guardians*. Accessed: 2024-06-10. 2023. URL: https://morepcb.com/pcb-fuses/.

[46] Jamie Morgan. *RCD ELCB RCBO RCCB Electric Shock Protection Explained*. Accessed: 2024-06-16. Dec. 2023. URL: https://esielectrical.co.uk/electric-shock-protection-rcd-elcb-rcbo-rccb/.

[47] Mouser Electronics. *Media 3319430 Datasheet*. Accessed: 2024-06-23. 2024. URL: https://nl.mouser.com/datasheet/2/240/media-3319430.pdf.

[48] Nighat Mumtaz et al. "Fillers and methods to improve the effective (out-plane) thermal conductivity of polymeric thermal interface materials – A review". In: *Heliyon* 10.3 (2024), e25381. ISSN: 2405-8440. DOI: https://doi.org/10.1016/j.heliyon.2024.e25381. URL: https://www.sciencedirect.com/science/article/pii/S2405844024014129.

[49] Author Name. *Selecting the Right Inductor Current Ripple*. Accessed: 2024-06-22. 2023. URL: https://www.power-and-beyond.com/selecting-the-right-inductor-current-ripple-a-5dd177b306832a38b56f5199a9dd8676/.

[50] Author's Name. *Using Grounding to Control EMI*. Accessed June 26, 2024. 2023. URL: https://www.mddionline.com/business/using-grounding-to-control-emi (visited on 06/26/2024).

[51] Nexperia. *Understanding the Basics of Zener Diodes*. Accessed: 2024-06-23. 2024. URL: https://efficiencywins.nexperia.com/efficient-products/understanding-the-basics-of-zener-diodes.

[52] Nextion. *NX3224K024_011 Datasheet*. Accessed: 2024-06-16. 2023. URL: https://nextion.ca/datasheets/nx3224k024_011/.

[53] nVent. *Grounding and Bonding for Electrical Safety and Lightning Protection*. Accessed: 2024-06-16. 2019. URL: https://www.nvent.com/sites/default/files/acquiadam/assets/H86962-USEN_0.pdf.

[54] Venkatesh Pampana. *Basics of eFuses (electronic fuses) for PCB*. Accessed: 2024-06-10. 2021. URL: https://www.pcbway.com/blog/PCB_Design_Tutorial/Basics_of_eFuses__electronic_fuses__for_PCB.html.

[55] Shuaihang Pan and Zhinan Zhang. "Fundamental theories and basic principles of triboelectric effect: A review". In: *Friction* 7.1 (2019), pp. 2–17. DOI: 10.1007/s40544-018-0217-7. URL: https://doi.org/10.1007/s40544-018-0217-7.

[56] MCL PCB. *Understanding PCB Temperature and Its Effects on Electronic Circuits*. Accessed: 2024-06-16. 2023. URL: https://www.mclpcb.com/blog/pcb-temperature/.

[57] PCBWay. *Basics of eFuses (Electronic Fuses) for PCB*. Accessed: 2024-06-16. 2023. URL: https://www.pcbway.com/blog/PCB_Design_Tutorial/Basics_of_eFuses__electronic_fuses__for_PCB.html.

[58] Phil's Lab - Altium Designer. *ESD Protection Basics with TVS Diodes*. Accessed: 2024-06-20. 2024. URL: https://resources.altium.com/p/esd-protection-basics-tvs-diodes.

[59] Olexandr Plakhtii et al. "Modeling of Thermal Ventilation Processes in Printed Circuit Boards of Power Sources". In: Dec. 2023, pp. 294–304. ISBN: 978-3-031-46876-6. DOI: 10.1007/978-3-031-46877-3_26.

[60] Bay Power. *What is Overcurrent Protection?* Accessed: 2024-06-10. 2021. URL: https://www.baypower.com/blog/what-is-overcurrent-protection/.

[61] ProtoExpress. *12 PCB Thermal Management Techniques to Reduce PCB Heating*. Accessed: 2024-06-16. 2023. URL: https://www.protoexpress.com/blog/12-pcb-thermal-management-techniques-to-reduce-pcb-heating/.

[62] ROHM Semiconductor. *Linear Regulators - Reverse Voltage Protection Application Note*. Accessed: 2024-06-16. 2021. URL: https://fscdn.rohm.com/en/products/databook/applinote/ic/power/linear_regulator/linearreg_reverse_voltage_appli-e.pdf.

[63] Bruce Rose. *EMI Filter Components: What They Are and How They Work*. Accessed June 26, 2024. 2022. URL: https://www.cui.com/blog/emi-filter-components-what-they-are-and-how-they-work (visited on 06/26/2024).

[64] Rusell. *Teardown of UGREEN 300W Nexode 5-in-1 Charger (CD333)*. Accessed: 2024-06-10. 2024. URL: https://www.chargerlab.com/teardown-of-ugreen-300w-nexode-5-in-1-charger-cd333/.

[65] ScienceDirect. *Electrostatic Discharge*. Accessed: 2024-06-16. 2023. URL: https://www.sciencedirect.com/topics/chemistry/electrostatic-discharge.

[66] Semtech Corporation. *ESD Protection for USB Type-C Interfaces*. Accessed: 2024-06-20. 2024. URL: https://blog.semtech.com/esd-protection-of-usb-type-c-interfaces.

[67] Cadence PCB Solutions. *A Quick Guide to Voltage Regulation*. Accessed: 2024-06-16. 2023. URL: https://resources.pcb.cadence.com/blog/2023-a-quick-guide-to-voltage-regulation.

[68] Cadence PCB Solutions. *Designing PCBs to Avoid Electrical Shock Fatigue*. Accessed: 2024-06-10. 2019. URL: https://resources.pcb.cadence.com/blog/2019-designing-pcbs-to-avoid-electrical-shock-fatigue.

[69] Cadence PCB Solutions. *The Electrical and Thermal Characteristics Influencing Thermal Interface Material Selection*. Accessed: 2024-06-16. 2021. URL: https://resources.system-analysis.cadence.com/blog/msa2021-the-electrical-and-thermal-characteristics-influencing-thermal-interface-materialselection.

[70] Rack Solutions. *How to Properly Ground Your Server Rack*. Accessed: 2024-06-16. 2023. URL: https://www.racksolutions.eu/news/blog/how-to-properly-ground-your-server-rack/.

[71] UL Solutions. *Understanding Ground Fault and Leakage Current Protection*. Accessed: 2024-06-16. July 2019. URL: https://code-authorities.ul.com/about/blog/understanding-ground-fault-and-leakage-current-protection/.

[72] STMicroelectronics. *AN574 Transient Voltage Suppressor (TVS), Thyristor Surge Suppressor (TSS) Crowbar Protection Comparison*. Accessed: 2024-06-16. 2020. URL: https://www.st.com/resource/en/application_note/an574-transient-voltage-suppressor-tvs--thyristor-surge-suppressor-tss-crowbar-protection-comparison-stmicroelectronics.pdf.

[73] STMicroelectronics. *STM32F411CE Datasheet*. Accessed: 2024-06-16. 2023. URL: https://www.st.com/resource/en/datasheet/stm32f411ce.pdf.

[74] Monolithic Power Systems. *Output Voltage Ripple Measurement and Reduction for DC-DC Voltage Regulators*. Accessed: 2024-06-23. 2024. URL: https://www.monolithicpower.com/learning/resources/output-voltage-ripple-measurement-and-reduction-for-dc-dc-voltage-regulators.

[75] Monolithic Power Systems. *Voltage Regulator Types*. Accessed: 2024-06-16. 2023. URL: https://www.monolithicpower.com/en/learning/resources/voltage-regulator-types.

[76] Dawood Talebi Khanmiri, Roy Ball, and Brad Lehman. “Design of a Hybrid MOV-TVS Diode Surge Protective Device”. In: July 2016.

[77] TDK Corporation. *General Technical Information*. Accessed: 2024-06-26. 2024. URL: https://www.tdk-electronics.tdk.com/download/531162/d78540dfe0589d2bd90cabef477c90b9/pdf-general-technical-information.pdf.

[78] TDK Corporation. *How to use PTC thermistors as current protection*. Accessed: 2024-06-26. 2024. URL: https://product.tdk.com/de/techlibrary/applicationnote/howto_ptc-limiter.html.

[79] Texas Instruments. *TPS54331 3-A, 28-V Input, Step-Down DC-DC Converter*. Accessed: 2024-06-22. 2023. URL: https://www.ti.com/lit/ds/symlink/tps54331.pdf?ts=1718944660872&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FTPS54331%253Fbm-verify%253DAAQAAAAJ_____9u8j8-2IvsgsSyFBAQtoPTP1j-JPOvOrSaL_wYMTtLRqrcAyEAqUs3YLEouqoQINcWHHqkYqT-cpcyioyJBMT7XND-3DkILwuIAv2hjuW6pR4hqC1ebq0xbMGq66Wh0k0irLZKTxzpVmv3HPIPYoqa3nFW2bcmVMLJu4XsiMaNH5FADyCr-HM_g6xtjWnn5XoYj7FrO0rL__5kp5XahhpKG-OlTRxg9Vkqarf799d_m2ixYltvmkn6y0r8-rsxs4Mcvw6b0cPcSLpNNL6SEx0xrCu8Y5AjcMClY5b5KLkG8SiQm.

[80] The Editors of Encyclopaedia Britannica. *Electrical Shock*. Accessed: 2024-06-26. 2024. URL: https://www.britannica.com/science/electrical-shock.

[81] *The Essential Guide to Conformal Coating*. Accessed June 26, 2024. Techspray. 2023. URL: https://www.techspray.com/the-essential-guide-to-conformal-coating (visited on 06/26/2024).

[82] Sunpower UK. *What is Thermal Protection?* Accessed: 2024-06-10. 2023. URL: https://www.sunpower-uk.com/glossary/what-is-thermal-protection/.

[83] UL News. *Underwriters Laboratories Publishes Paper on High-Tech Safety Standard IEC 62368-1*. Accessed: 2024-06-16. 2023. URL: https://eepower.com/news/underwriters-laboratories-publishes-paper-on-high-tech-safety-standard-iec-62368-1.

[84] *Understanding CISPR 22: EN 55022 EMC Standard*. Accessed June 26, 2024. 2023. URL: https://www.electronics-notes.com/articles/analogue_circuits/emc-emi-electromagnetic-interference-compatibility/cispr22-en55022-standard.php (visited on 06/26/2024).

[85] *Universal serial bus interfaces for data and power - Part 1-2: Common components - USB Power Delivery specification*. Accessed: 2024-06-16. International Electrotechnical Commission, 2018. URL: https://www.scribd.com/document/576002964/IEC-62680-1-2-2018.

[86] *Universal serial bus interfaces for data and power - Part 1-3: Common components - USB Type-C Cable and Connector Specification*. Accessed: 2024-06-16. International Electrotechnical Commission, 2021. URL: https://www.scribd.com/document/733260021/IEC-62680-1-3.

[87] Binary Updates. *Reverse Current Protection Using Diode*. Accessed: 2024-06-16. 2023. URL: https://binaryupdates.com/reverse-current-protection-using-diode/.

[88] WRepair. *WRepair: Professional Repair Services*. Accessed: 2024-06-07. 2024. URL: https://www.wrepair.com/.

[89] Yu Xiao et al. “Enhancing Current Sharing in Metal Oxide Varistors Using Dynamic U–I Characteristic Analysis”. In: *IEEE Journal of Emerging and Selected Topics in Power Electronics* 12.3 (2024), pp. 3115–3123. DOI: 10.1109/JESTPE.2024.3386975.

[90] Jordan Yates. *What Are EMI Filters?* Accessed June 26, 2024. 2023. URL: https://blog.knowlescapacitors.com/blog/what-are-emi-filters (visited on 06/26/2024).

[91] Azzeddine Zegadi, Djamel Benhaddou, and Miloud Sabour. “ESD Protection in CMOS Technology: Physical Analysis and Experimental Characterization”. In: *Journal of Electronics and Communication Engineering* 9.3 (2021). Accessed: 2024-06-16, pp. 95–105. URL: https://www.scirp.org/journal/paperinformation?paperid=110899.

[92] Ehsan Zeynali, Ryan Bridges, and Behzad Kordi. “Electrical Insulation of Conformally Coated Printed Circuit Boards: An Overview and a Study of the Influence of Pollution”. In: *IEEE Electrical Insulation Magazine* 37.2 (2021), pp. 6–17. DOI: 10.1109/MEI.2021.9352711.

A

Appendix

A.1. Buck-Converter component calculations

The selection and calculation of each component in the buck converter are critical to ensure proper functionality and efficiency. The following sections detail the selection and calculation of each component required for the buck converter design, including their importance, function, and reasons for selection over other components.

Design Specifications

The design of the TPS54331 buckconverter has been visualised in Figure A.1. The design specifications are as follows:

- **Input Voltage (V_{IN})**: 20V
- **Output Voltage (V_{OUT})**: 5V
- **Output Current (I_{OUT})**: 0.65A
- **Efficiency (η)**: 88% to 90%
- **Switching Frequency (f_{SW})**: 570 kHz

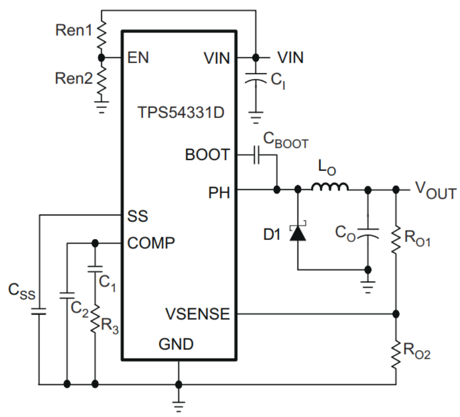


Figure A.1: Step-Down Converter Circuit Overview

A.1.1. Inductor (L_O)

Importance and Function: The inductor in a buck converter stores energy when the switch is on and releases energy to the load when the switch is off, smoothing the current flow to the output. The inductor value is crucial as it affects the ripple current, efficiency, and overall performance of the converter. A properly sized inductor ensures minimal ripple and stable output, preventing excessive current fluctuations that could harm the load or reduce efficiency.

Calculation: The inductor value is calculated using the formula:

$$L_O = \frac{V_{OUT} \times (V_{IN} - V_{OUT})}{V_{IN} \times \Delta I_L \times f_{SW}} \tag{A.1}$$

Where:

- $V_{IN} = 20V$
- $V_{OUT} = 5V$
- ΔI_L (inductor ripple current) is chosen as 30% [49] of I_{OUT}, which is 0.195A.
- f_{SW} (switching frequency) is 570 kHz.

So the value of the inductor is:

$$L_O = \frac{5V \times (20V - 5V)}{20V \times 0.195A \times 570kHz} \approx 36.7\mu H \tag{A.2}$$

A.1.2. Input Capacitor (C_I)

Importance and Function: The input capacitor stabilizes the input voltage and supplies current to the inductor during the switch-on period. It filters out noise and suppresses voltage spikes that can occur during switching, ensuring a consistent input voltage for efficient operation. The capacitor's low equivalent series resistance (ESR) and high RMS current rating are critical for minimizing input voltage ripple and maintaining stable operation.

Calculation: The RMS current requirement for the input capacitor is calculated as follows:

$$I_{C_I(RMS)} = I_{OUT} \times \sqrt{\frac{V_{OUT}}{V_{IN}} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right)} \approx 0.26A \tag{A.3}$$

Selection Reason: A 10µF, 25V ceramic capacitor (X7R dielectric) is chosen for its low ESR and high RMS current rating. Ceramic capacitors with X7R dielectric are preferred due to their stability over a wide temperature range and their ability to handle high ripple currents, making them more reliable and efficient for this application compared to other types like tantalum or aluminum electrolytic capacitors.

the reasons that have been used for 10µF:

- **Sufficient Filtering:** 10µF provides adequate capacitance to filter out high-frequency noise and reduce input voltage ripple, ensuring a stable input for the converter. The 10µF input capacitor effectively filters high-frequency noise and switching transients primarily around the 570 kHz switching frequency of the TPS54331, as well as higher-frequency EMI conducted harmonics of 150 kHz to 30 MHz. Its low impedance at these frequencies ensures that voltage spikes and noise are minimized, providing a stable input voltage for the converter. This stability is critical for efficient operation, protection of sensitive components, and overall reliability of the buck converter system.
- **RMS Current Handling:** With the RMS current calculated at approximately 0.26A, a 10µF capacitor with low ESR is capable of handling this current without significant heating or voltage drops. Heating in capacitors is caused by the internal resistive losses due to the RMS current passing through the capacitor's equivalent series resistance. Excessive heating can degrade the capacitor's performance over time, potentially leading to failure. Capacitors with high ESR will dissipate more power as heat, which can affect the reliability and longevity of the component. Besides, voltage drops across the capacitor due to its ESR can reduce the effectiveness of the capacitor in filtering out noise and stabilizing the input voltage. Significant voltage drops can result in inadequate filtering, leading to higher ripple on the input voltage. This can affect the performance and stability of the buck converter.

- **Design Practice:** 10μF is a standard value used in many buck converter designs and also in this type, ensuring compatibility and reliability.

A.1.3. Output Capacitor (C_O)

Importance and Function: The output capacitor filters the output voltage, reducing ripple and ensuring a stable DC output. It helps maintain the voltage during load transients, providing immediate charge or discharge to the load. A properly selected output capacitor ensures low voltage ripple, which is essential for the reliable operation of sensitive electronic components.

The output capacitor (C_O) in a buck converter is important for several reasons:

- **Voltage Ripple Reduction**: The output capacitor smooths out the voltage fluctuations (ripple) caused by the switching operation of the converter. Minimizing output voltage ripple is essential for providing a stable DC voltage to the load. Excessive ripple can interfere with the proper operation of sensitive electronic components connected to the converter's output.
- **Load Transient Response**: C_O helps to maintain the output voltage during sudden changes in the load current (load transients). When the load suddenly increases, the capacitor can supply the additional current momentarily, helping to keep the output voltage stable until the converter adjusts to the new load condition. This prevents voltage dips that could disrupt the operation of the load.
- **Stability of the Control Loop**: The output capacitor, in conjunction with the feedback loop, influences the frequency response and stability of the converter's control system. A well-chosen C_{OUT} ensures that the feedback loop remains stable, preventing oscillations and ensuring reliable operation of the converter. Proper capacitor selection is critical to maintaining a balance between adequate filtering and control loop stability.

Calculation: The output ripple voltage can be estimated using the formula:

$$\Delta V_{OUT} \approx \frac{\Delta I_L}{8 \times f_{SW} \times C_O} \tag{A.4}$$

It is assuming a ripple of 0.05V. The assumption of 0.05V for the ripple voltage is based on balancing the need for low output voltage ripple with practical capacitor values and cost. A 1% ripple [74](0.05V for a 5V output) is a common design target that ensures good performance without excessively large or expensive capacitors. This level of ripple is acceptable for most applications and helps in selecting capacitors that are reasonably sized and cost-effective while still maintaining stable output voltage. So the C_o will be:

$$C_O \approx \frac{0.18A}{8 \times 570kHz \times 0.05V} \approx 0.79\mu F \tag{A.5}$$

A.1.4. Feedback Resistors (R_{o1} & R_{o2})

Importance and Function: The feedback resistors set the output voltage by creating a voltage divider network that feeds a fraction of the output voltage back to the error amplifier. Proper selection of feedback resistors is essential to achieve the desired output voltage and ensure accurate voltage regulation. This network controls the feedback loop, maintaining the output voltage at the specified level by adjusting the duty cycle of the switching signal.

Calculation: The relationship between the output voltage and the resistor divider is given by:

$$V_{OUT} = V_{REF}\left(1 + \frac{R_{o1}}{R_{o2}}\right) \tag{A.6}$$

Where V_{REF} is 0.8V for the TPS54331. Rearranging for $\frac{R_{o1}}{R_{o2}}$:

$$\frac{R_{o1}}{R_{o2}} = \frac{V_{OUT}}{V_{REF}} - 1 \tag{A.7}$$

For $V_{OUT} = 5V$:

$$\frac{R_{o1}}{R_{o2}} = \frac{5V}{0.8V} - 1 = 5.25 \tag{A.8}$$

Choosing $R_{o2} = 10k\Omega$:

$$R_{o1} = 5.25 \times 10k\Omega = 52.5k\Omega \tag{A.9}$$

The Feedback Resistors R_{o1} & R_{o2} in a buck converter is important for several reasons:

- **Achieving Desired Output Voltage**: The ratio $\frac{R_{o1}}{R_{o2}}$ must be precise to set the output voltage accurately. Using values of 52.5 $k\Omega$ for R_{o1} and 10 $k\Omega$ for R_{o2} achieves the required ratio closely, ensuring that the output voltage is regulated to 5V.
- **Precision and Availability**: Standard resistor values are chosen because they are readily available and offer high precision, which is essential for maintaining accurate voltage regulation over varying conditions.
- **Stability and Performance**: High-quality resistors with low-temperature coefficients are selected to ensure stability and consistent performance of the voltage divider network. This ensures that the feedback voltage remains stable, providing reliable regulation of the output voltage.

A.1.5. Bootstrap Capacitor (C_{BOOT})

Importance and Function: The bootstrap capacitor C_{BOOT} plays a critical role in the operation of the high-side MOSFET in a buck converter. The high-side MOSFET requires a gate drive voltage higher than the input voltage to fully turn on, which is provided by the bootstrap circuit. The bootstrap capacitor is essential for:

- **Gate Drive Voltage**: The high-side MOSFET in a buck converter needs a gate voltage that is higher than the source voltage (which is the input voltage) to turn on fully. The bootstrap capacitor provides this necessary voltage boost.
- **Switching Efficiency**: By ensuring that the high-side MOSFET is fully turned on during the on-time, the bootstrap capacitor helps minimize the on-resistance (R_{DS}(on)) of the MOSFET, reducing conduction losses and improving the overall efficiency of the converter.
- **Maintaining Bootstrap Voltage**: The capacitor charges to the input voltage minus the diode drop when the low-side MOSFET (or the body diode) is on. During the high-side switch on-time, this stored charge provides the required voltage to keep the high-side MOSFET turned on. Without a properly sized bootstrap capacitor, the voltage may drop too quickly, leading to incomplete switching and reduced efficiency.

Choosing the Capacitor Value: The value of the bootstrap capacitor is typically recommended in the datasheet of the buck converter IC. For the TPS54331, a 0.1μF capacitor is suggested. This recommendation is based on the following considerations:

- **Sufficient Charge Storage**: The capacitor must store enough charge to supply the gate drive current of the high-side MOSFET during the entire on-time period. A 0.1μF capacitor is large enough to maintain the required voltage without significant droop, ensuring reliable MOSFET operation.
- **Quick Charging**: The bootstrap capacitor needs to recharge quickly during the off-time of the high-side MOSFET. A 0.1μF capacitor provides a balance between sufficient charge storage and quick recharge capability, fitting well within the switching frequency of 570kHz used in the TPS54331.
- **Standard Value and Availability**: 0.1μF is a standard capacitor value, making it readily available and cost-effective. It ensures compatibility with various design requirements and simplifies the sourcing process.
- **Stability and Reliability**: Ceramic capacitors with X7R dielectric are preferred for the bootstrap capacitor due to their stability over a wide temperature range and low equivalent series resistance (ESR). This ensures consistent performance and longevity in the application.

A.1.6. Compensation Network (C_1, C_2, and R_3)

Importance and Function: The compensation network, consisting of C_1, C_2, and R_3, is crucial for stabilizing the feedback loop of the buck converter and ensuring optimal transient response. The compensation network shapes the frequency response of the control loop, affecting the converter's stability and performance. Specifically, it ensures:

- **Loop Stability**: Proper compensation prevents oscillations and instability in the output voltage. This is essential for maintaining reliable and predictable operation of the converter across various load conditions.
- **Optimal Transient Response**: The compensation network helps the converter respond quickly to changes in load current, minimizing deviations in the output voltage. This is important for applications with dynamic loads, where fast and accurate voltage regulation is required.
- **Control Loop Performance**: By shaping the gain and phase characteristics of the control loop, the compensation network ensures that the phase margin and gain margin are sufficient to maintain stability and performance.

Choosing the Values: For the TPS54331, typical values for the compensation network components are provided in the datasheet to achieve desired performance:

- C_1 **(4700 pF)**:
  - **Function**: C_1 sets the dominant pole of the compensation network, determining the low-frequency gain.
  - **Importance**: This capacitor helps establish the necessary gain at low frequencies to ensure proper regulation and reduce steady-state error.
  - **Chosen Value**: 4700 pF is chosen as it provides a good balance for establishing the dominant pole while maintaining sufficient bandwidth for dynamic response.
- C_2 **(39 pF)**
  - **Function**: C_2, in conjunction with R_3, sets a zero in the compensation network, improving phase margin.
  - **Importance**: Adding a zero helps counteract the phase lag introduced by the inductor and output capacitor, enhancing the overall phase margin and stability.
  - **Chosen Value**: 39 pF is selected to place the zero at a frequency that effectively improves phase margin without compromising the high-frequency response.
- R_3 **(49.9 kΩ)**:
  - **Function**: R_3 sets the mid-frequency gain of the compensation network, affecting the bandwidth and transient response.
  - **Importance**: The resistor sets the frequency of the zero introduced by C_2 and adjusts the gain to ensure adequate phase margin and dynamic performance.
  - **Chosen Value**: 49.9 kΩ is chosen based on typical design practices and recommendations from the datasheet. This value ensures the zero is placed appropriately to balance stability and transient response.

Why These Specific Values: The values of C_1, C_2, and R_3 are chosen based on the recommendations from the TPS54331 datasheet [79], which are derived from extensive testing and optimization for typical applications. These values ensure that the compensation network provides the necessary phase margin and gain margin to maintain stability and performance under various operating conditions. Using these typical values simplifies the design process, as they are tested to work well with the TPS54331's internal control architecture and typical output characteristics.

A.1.7. Slow Start Capacitor (C_{SS})

Importance and Function: The slow start capacitor (C_{SS}) is essential for controlling the rate at which the output voltage rises during startup. This functionality is crucial for several reasons:

Inrush Current Limitation: The slow start capacitor helps to limit the inrush current at startup. Without this control, the sudden application of power could result in a large inrush current that may stress and potentially damage the converter and the load.

Voltage Overshoot Prevention: By gradually increasing the output voltage, the slow start capacitor prevents overshoot. A sudden rise in voltage can lead to an overshoot above the desired output voltage, which can be harmful to sensitive components in the load.

Soft Start Functionality: The capacitor implements a soft start feature, ensuring that the output voltage ramps up smoothly. This smooth ramp-up is beneficial for maintaining the stability and longevity of both the converter and the load.

Calculation: The value of the slow start capacitor is chosen based on the desired startup time (T_{SS}). The relationship is given by:

$$T_{SS} = C_{SS} \times \frac{0.8V}{2\mu A} \tag{A.10}$$

Where:

- V_{REF} is the reference voltage (0.8V for the TPS54331).
- I_{SS} is the soft start charging current (2 μA).

Desired Startup Time: A startup time of 2 milliseconds is chosen based on typical application requirements and to ensure the converter and load are protected during power-up. This value is a common choice for many DC-DC converters, balancing the need for a smooth ramp-up with the desire for the converter to reach its operating point quickly.

$$C_{SS} = 2ms \times \frac{2A}{0.8V} = 5nF \tag{A.11}$$

Selection Reason:

The reason why 2ms has been selected [79]:

- **Controlled Ramp-Up**: A 2 ms startup time ensures that the output voltage increases at a controlled rate, preventing sudden surges in current and voltage that could damage the converter or the load. It provides enough time for the output to stabilize without taking too long.
- **Protection**: This startup time helps in protecting the components by avoiding large inrush currents that could potentially damage sensitive electronic components during the power-up phase.
- **Design Recommendations**: The value of 2 ms is often recommended in datasheet for typical applications, ensuring compatibility with the internal control circuitry and providing a balance between too fast and too slow of a start.
- **Performance and Reliability**: A 2 ms startup time provides a good balance between fast response and system protection, ensuring consistent and reliable operation across different operating conditions.

The reason that it should be 5nF [79]:

- **Controlled Ramp-Up**: A 5 nF capacitor ensures that the output voltage increases at a controlled rate, preventing sudden surges in current and voltage that could damage the converter or the load.
- **Design Recommendations**: The value of 5 nF is recommended in the TPS54331 datasheet for typical applications, ensuring compatibility with the internal control circuitry and providing a balance between too fast and too slow of a start.
- **Consistency and Reliability**: Using a standard value like 5 nF ensures consistency in performance and reliability across different units of the converter, making the design robust and predictable.

A.1.8. The Input Voltage Divider (R_{en1} and R_{en2})

Importance and Function: The input voltage divider, composed of resistors R_{en1} and R_{en2}, is used to set the Undervoltage lockout (UVLO) thresholds for the buck converter. This ensures the converter operates within a specified input voltage range, preventing it from functioning at too low an input voltage, which could lead to instability or malfunction. Setting appropriate start (V_{START}) and stop (V_{STOP}) voltages safeguards both the converter and the load from improper voltage conditions [79].

UVLO Thresholds:

- V_{START}: This is the input voltage at which the converter begins operating. Let's set V_{START} = 18V.
- V_{STOP}: This is the input voltage at which the converter stops operating to protect itself and the load. Let's set V_{STOP} = 17V.

Why 3 µA: The 3 µA value used in the calculations comes from the typical internal pull-up current of the EN (Enable) pin of the TPS54331, as specified in the datasheet. This current is used to develop the voltage across the input voltage divider.

Calculations: To determine R_{en1} and R_{en2} for the given V_{START} and V_{STOP} values, we use the following formulas:

$$R_{en1} = \frac{V_{START} - V_{STOP}}{3\mu A} \tag{A.12}$$

Calculate R_{en1}:

$$R_{en1} = \frac{18V - 17V}{3\mu A} = \frac{1V}{3\mu A} = 333.33k\Omega \tag{A.13}$$

Using R_{en1} to calculate R_{en2}:

$$R_{en2} = \frac{V_{EN} \times R_{en1}}{V_{STOP} - V_{EN}} \tag{A.14}$$

Where V_{EN} is equal to 1.25V:

$$R_{en2} = \frac{1.25V \times 332k\Omega}{17V - 1.25V} = \frac{415k\Omega}{15.75V} \approx 26.35k\Omega \tag{A.15}$$

Reasoning of the Values:

- **Accurate UVLO Setting:** By selecting R_{en1} and R_{en2} based on the given V_{START} and V_{STOP}, we ensure the converter starts and stops at the appropriate input voltages, protecting the system from operating under unstable conditions.
- **Standard Resistor Values:** Choosing standard resistor values (332 kΩ and 26.1 kΩ) simplifies the design and ensures the availability and reliability of the components.
- **Stable Operation:** Using these resistor values ensures that the voltage at the EN pin accurately reflects the input voltage thresholds, providing stable and predictable operation of the UVLO function.

The input voltage divider resistors, R_{en1} and R_{en2}, are chosen to set the UVLO thresholds at 18V (V_{START}) and 17V (V_{STOP}). The use of 3 µA comes from the internal pull-up current of the EN pin in the TPS54331 datasheet [79]. Calculated values of 332 kΩ for R_{en1} and 26.1 kΩ for R_{en2} ensure accurate and reliable UVLO functionality, protecting the buck converter and load from improper voltage conditions and ensuring stable operation.

A.1.9. Diode (D1)

Importance and Function: The catch diode provides a path for the inductor current when the high-side MOSFET is off, preventing negative voltage spikes and ensuring continuous current flow. It is crucial for protecting the converter from voltage spikes and ensuring efficient energy transfer. The diode must handle the output current and withstand the reverse voltage, ensuring reliable operation under various load conditions.

Selection Reason: The selected diode is the B340A, with the following characteristics:

- Forward Voltage: 0.5V
- Reverse Voltage: 40V
- Forward Current: 3A

The B340A diode is chosen for its low forward voltage drop, which improves efficiency, and its ability to handle the required current and voltage ratings. Its robust design ensures reliable operation in the converter, making it a suitable choice for this application.

B Appendix

B.1. State of the art

Table B.1: Detailed descriptions of components used in different products of the USB-C charger stations.

Component	Description
Overvoltage Protection	Protects the device from excessive voltage which can cause damage.
Zener Diode	A semiconductor device that allows current to flow in the forward direction like a typical diode but also in the reverse direction if the voltage exceeds a certain value, called the breakdown voltage. This property makes it useful for voltage regulation and protection.
TVS Diode	A Transient Voltage Suppression diode designed to protect electronic circuits from transient voltage spikes, such as those caused by lightning or other high-voltage surges. It responds quickly to clamp the voltage to a safe level, thereby protecting the circuit components.
Film capacitors	These capacitors use a thin plastic film as the dielectric and are known for their stability, reliability, and low inductance. They are used in various applications for filtering, coupling, and decoupling because they can handle high current pulses and provide excellent temperature stability.
Optocoupler (EL1019)	An electronic component that transfers electrical signals between two isolated circuits using light. It typically consists of an LED that emits light in response to an electrical input and a photodetector that receives the light and converts it back into an electrical signal, ensuring isolation.
Synchronous rectifier controller (TEA1995)	This controller is used to manage synchronous rectifiers, which are more efficient than traditional diodes in converting AC to DC. By reducing the losses associated with diode rectification, it improves the overall efficiency of power supplies, especially in high-current applications.
Primary controller (XPDS2201)	This component manages the main operational functions of a power supply, including regulation, control, and protection mechanisms such as overvoltage, overcurrent, and thermal management. It ensures the power supply operates efficiently and safely under various conditions.
Overcurrent Protection	A safety feature that prevents damage by interrupting the power supply if the current exceeds a safe level. This is crucial for preventing overheating and potential fires.

Component	Description
Fuse	A safety device that protects electrical circuits by melting and breaking the connection if the current flowing through it exceeds a certain level. This prevents excessive current from damaging the circuit or causing a fire.
Current Sense Resistors	Resistors that are specifically designed to measure the amount of current flowing through a circuit. They provide a voltage drop proportional to the current, which can be monitored to detect overcurrent conditions and initiate protective actions.
Primary controller (XPDS2201)	In addition to its other functions, this controller monitors the current flow and can shut down the power supply or reduce the current if it detects levels that are too high, thereby providing protection against overcurrent situations.
Electrostatic Discharge	Protection mechanisms designed to safeguard electronic circuits from the sudden and momentary electric currents caused by electrostatic discharge (ESD), which can occur when electronic devices come into contact with charged objects.
ESD Protection Diodes	These diodes are used to protect sensitive electronic components from electrostatic discharge. They work by clamping the voltage to a safe level and dissipating the energy from an ESD event, preventing it from damaging the circuit.
TVS Diode	Similar to their role in overvoltage protection, TVS diodes also protect against electrostatic discharges by clamping high-voltage spikes and providing a path to ground for the excess energy, thus protecting the circuit components.
Overheating Protection	A feature that prevents electronic devices from overheating by monitoring temperatures and taking action to reduce or shut off power if temperatures exceed safe levels.
Thermal pad	A heat-conductive pad placed between components and heatsinks to improve thermal transfer. It helps in efficiently dissipating heat away from critical components to prevent overheating and ensure reliable operation.
Primary controller (XPDS2201)	This controller also includes thermal management features that monitor the temperature of the power supply components. If it detects excessive temperatures, it can reduce the power output or shut down the supply to prevent damage.
Synchronous rectifier controller (TEA1995)	Besides improving efficiency, this controller also helps in managing heat dissipation by optimizing the operation of synchronous rectifiers, which produce less heat compared to traditional diodes, thus contributing to overall thermal management.
Thermistors	Temperature-sensitive resistors used to monitor and control the temperature within the device. They change resistance with temperature changes and can trigger cooling mechanisms or shut down the system to prevent overheating.
Electromagnetic Interference	Measures and components used to reduce or eliminate interference from external electromagnetic fields, which can cause electronic devices to malfunction or perform poorly.
Common mode choke	An inductive component are used to filter out common-mode noise, which is interference that appears equally on both lines of a two-wire system. It works by presenting high impedance to the noise frequencies, thereby attenuating them and allowing the desired signals to pass through.

Component	Description
Ferrite Beads	Passive electronic components are used to suppress high-frequency noise in electronic circuits. They act as low-pass filters, blocking high-frequency noise while allowing lower-frequency signals to pass, thus reducing electromagnetic interference.
EMI Mitigation Techniques (Buck-Converter)	The EMI suppression in the TPS54331 buck converter minimizes electromagnetic interference through fixed frequency PWM control, an integrated bootstrap diode, and frequency reduction during startup and overcurrent conditions, ensuring stable performance and reduced noise.

B.2. Table for Electrical Safety

Table B.2: Effects of Electrical Shock as a Function of Current [11]

Current (mA)	Effect
1	Threshold of sensation
5	Maximum harmless current
10-20	Onset of sustained muscular contraction; cannot let go for duration of shock; contraction of chest muscles may stop breathing during shock. This is specifically for AC currents due to their natural frequency.
50	Onset of pain
100-300+	Ventricular fibrillation possible; often fatal. This is specifically for AC currents due to their natural frequency
300	Onset of burns depending on the concentration of current
6000 (6 A)	Onset of sustained ventricular contraction and respiratory paralysis; both cease when shock ends; heartbeat may return to normal; used to defibrillate the heart. This is specifically for AC currents due to their natural frequency

Table B.3: Consequences of Electrical Hazards [11]

Consequence	Description
Thermal hazards	Excessive heat development due to electric current can cause fire or melting.
Shock hazards	Range from mild shocks to cardiac arrest.
Muscle contractions	Can lead to involuntary movements or the inability to release the electrical source.
Ventricular fibrillation	Heartbeat becomes irregular; fatal if not treated.
Burns	Can occur at high current strengths.
Microshock	Small currents can be dangerous, especially during medical procedures that break the skin barrier.

B.3. Table For Design Process

Table B.4: Components for Overcurrent Protection in Electronic Devices

Type	Description	Advantage	Disadvantage	Cost (Euro)
PTC [78] [77]	Resistor that increases resistance with rising temperature. Made from ceramic or polymer. And a resettable fuses.	Reusable, automatically resets after cooling.	Higher resistance during normal operation. Slow response time (seconds to minutes).	0.20 - 5.00
PPTC [30]	Polymeric PTC resettable fuses. Polymer material with conductive particles changes resistance with temperature.	Reusable, automatically resets after cooling. Flexible for low currents.	Limited to lower currents (up to 2A). Higher resistance during normal operation.	0.20 - 5.00
Fuses [54]	Melting fuses that break the circuit when current is too high.	Simple and inexpensive. Reliable with clear fault indication.	Must be replaced after activation.	0.10 - 1.00
Circuit breakers [60]	Electromechanical switches that break the circuit when overloaded.	Reusable, easy to reset, adjustable trip points.	More expensive than fuses. Larger physical size.	5.00 - 50.00
eFuse[54]	Solid-state switches that electronically monitor and interrupt circuits.	Fast response, precise control, integrated monitoring features.	Can be expensive and generate heat.	10.00 - 100.00

Table B.5: ESD Protection Components

Type	Description	Advantage	Disadvantage	Cost (Euro)
TVS Diodes [72] [18]	Protect circuits by clamping voltage spikes to a safe level and absorbing and dissipating static discharges.	Fast response time, high reliability.	Limited energy absorption capacity.	0.20 - 5.00
ESD Suppressors (Polymer)[25] [4] [65] [91]	Protect against electrostatic discharge (ESD) events.	Fast response, good for high-speed data lines.	Limited energy absorption.	0.20 - 5.00
Zener Diodes [51] [10]	Allow current to flow in reverse when a specific voltage is exceeded.	Precise voltage clamping.	Lower energy absorption compared to MOVs.	0.10 - 1.00
Varistors (MOV) [76]	Change resistance with applied voltage, clamping transient overvoltages.	High energy absorption, inexpensive.	Degrades over time with repeated use.	0.10 - 2.00

Table B.6: Fuse Selection Criteria for Input

Action	Details	Selection Fuse: TR-3216FF15-R [15]
Nominal Current I_{op}	The maximum current that normally flows through the circuit without issues.	I_{op} = 15A
Choose the Type of Fuse	• Time-delay fuse: For high inrush currents (motors, transformers) • Fast-acting fuse: For sensitive electronics	Fast-acting fuse
Calculate the Rated Current of the Fuse	Use 110% of the calculated current: $I_{\text{fuse}} = 1.10 \times I_{\text{load}}$	$I_{\text{fuse}} = 16.5$A
Check the Rated Voltage	The fuse must have a rated voltage equal to or higher than the circuit voltage	Rated voltage of at least 20V
Cost		0.99€

Table B.7: TVS Diode Selection Criteria for Input

Selection Criteria	Details/Description	Selected TVS: SMBJ20CA [14]
Working Voltage (V_w)	The maximum continuous operating voltage of the TVS diode. It should be slightly above the maximum operating voltage of the USB-C interface.	20V
Breakdown Voltage (V_{br})	The voltage at which the TVS diode starts to conduct and shunt excess energy. It should be higher than the working voltage but low enough to protect against overvoltage.	24V
Clamping Voltage (V_{clamp})	The maximum voltage the TVS diode will allow before it fully clamps the voltage to protect the circuit.	29.4V at I_{pp} (Peak Pulse Current)
ESD Protection	The level of protection against electrostatic discharge as defined by the IEC 61000-4-2 standard. Level 2 is chosen for adequate protection in consumer environments.	Level 2 (±4kV contact, ±8kV air)
Polarity	Unidirectional or bidirectional, depending on the nature of the signal and the requirement for protection in both directions.	Bidirectional
Cost		0.34€

Table B.8: Comparison of Stepdown Converters

Stepdowm converter	LMR51430 [32]	LM2596 [31]	TLVM13630 [34]	TPS54331 [79]	LM7805 [21]
Type	Buck converter	Buck converter	Buck converter	Buck converter	Linear voltage Regulator
Efficiency	Up to 85%	Up to 80%	Up to 90%	Up to 90%	Typically around 50%
Switching Frequency	400 kHz to 2.2 MHz	150 kHz	400 kHz to 2.2 MHz	100 kHz to 2.5 MHz	N/A
Size	9 mm²	100 mm²	30 mm²	20 mm²	150 mm²
Thermal Management	Operating Temperature up to 125°C	Thermal Resistance 15°C/W to 25°C/W	Thermal Vias; Copper Pour	Thermal Conductivity; Heat Spreaders	Thermal Resistance 10°C/W to 15°C/W
Cost	~€1.35	€1.80 - 4.50	~€2.70	~€1.35	€0.45 - 0.90
Application Suitability	Ideal for compact and efficient designs	Suitable for robust designs with space	Best for high-current, compact designs	Suitable for high-efficiency applications	Suitable for low-current, simple designs with fixed output

Table B.9: Causes and Descriptions of ESD Events

Cause	Description
Static Charge Buildup	When a USB-C cable is plugged in and out repeatedly, friction between the cable and the port can generate static electricity. This is particularly true for different materials used in the construction of the cable and the port. When the built-up static charge finds a path to a conductive material, such as the internal circuitry of a charging station or a connected device, it can result in an ESD event. This sudden discharge can damage sensitive electronic components [66].
Body Movement	When two different charged objects come into contact and then separate, electrons can transfer from one material to the other. This causes an imbalance of electrical charges, leading to static electricity. A common example is getting statically charged while walking on a carpet or due to synthetic clothing. When a statically charged person touches a conductive object, the accumulated charge can quickly transfer to that object, resulting in an ESD event [55].
Environmental Conditions	Dry environments promote the buildup of static electricity because low humidity levels reduce the likelihood of natural discharge of accumulated charges. This makes it easier for objects and people to become statically charged, increasing the frequency of ESD events [55].

Table B.10: Description of Power Supply and Safety Components

Modules	Description
Adapter Lenovo [40]	Provides the main power to the system, delivering 300 watts of power at 20 volts and 15 amps, ensuring sufficient power for all connected devices.
Safety & Power Module	Serves as the central point for power distribution with key safety features such as overcurrent protection, overvoltage protection, and short circuit protection. Regulates and distributes power to the touchscreen, MCU, and PD modules.
Touchscreen [52]	Functions as the user interface for the system, receiving regulated and protected power through the protection circuit post-buck converter. Ensures stable and safe power supply for reliable operation.
MCU [73]	Acts as the central processing unit, receiving regulated and protected power through the protection circuit post-buck converter. Ensures stable power supply for correct operation and overall system functionality.
6 PD-Modules [19]	Power Delivery modules managing power supply for connected devices. Requires regulated power for efficient and safe operation.
Stepdown Converter [31]	Steps down the voltage from the adapter to suitable levels required by downstream components. Ensures the power supplied matches the voltage requirements of sensitive devices like the touchscreen and MCU.
Protection Circuits	Placed between the buck converter and each sensitive device (Touchscreen and MCU). Provides additional layers of protection to prevent damage due to electrical faults or surges, ensuring localized protection and enhancing safety.

Table B.11: Selection of PPTC Fuse for Touchscreen Application

Parameter	Description	Touchscreen Values	Selected PPTC: Littelfuse 1812L050 [20]
Nominal Current I_{op}	The maximum current that normally flows through the circuit without issues.	0.5 A	0.5 A
Trip Current I_{trip}	The current at which the fuse must trip to protect the circuit.	0.55 A (10% above nominal current)	1.0 A
Maximum Voltage V_{max}	The maximum voltage the fuse can safely operate under.	5 V	6 V
Ambient Temperature T_{op}	The temperature at which the PPTC fuse will operate.	-20°C to 70°C	-40°C to 85°C
Cost			0.84€

Table B.12: Selection Criteria and Details for the TVS Diode of MCU & Touchscreen

Selection Criteria	Details/Description	Selected TVS: SMAJ5.0CA [47]
Working Voltage (V_w)	The maximum continuous operating voltage of the TVS diode. It should be slightly above the normal operating voltage of the MCU & Touchscreen.	5V
Breakdown Voltage (V_{br})	The voltage at which the TVS diode starts to conduct and shunt excess energy. It should be higher than the working voltage but low enough to protect against overvoltage.	6.4V (minimum), 7.0V (maximum)
Clamping Voltage (V_{clamp})	The maximum voltage the TVS diode will allow before it fully clamps the voltage to protect the circuit.	9.2V at I_{pp} (Peak Pulse Current)
ESD Protection	The level of protection against electrostatic discharge as defined by the IEC 61000-4-2 standard. Level 2 is chosen for adequate protection in consumer environments.	Level 2 (±4kV contact, ±4kV air)
Peak Pulse Power (P_{ppm})	The maximum power the TVS diode can dissipate in a short pulse, which should be sufficient for expected transient events.	400W (typical for SMAJ series)
Polarity	Unidirectional or bidirectional, depending on the nature of the signal and the requirement for protection in both directions.	Bidirectional
Cost		0.37€

Table B.13: Selection of PPTC Fuse for MCU Circuit

Parameter	Description	MCU Values	Selected PPTC: Littelfuse 1206L016 [41]
Nominal Current I_{op}	The maximum current that normally flows through the circuit without issues.	0.15 A	0.15 A
Trip Current I_{trip}	The current at which the fuse must trip to protect the circuit.	0.165 A (10% above nominal current)	0.37 A
Maximum Voltage V_{max}	The maximum voltage the fuse can safely operate under.	5 V	30 V
Ambient Temperature T_{op}	The temperature at which the PPTC fuse will operate.	-40°C to 125°C	-40°C to 85°C
Cost			0.45€

Table B.14: Comparison of Conformal Coatings

Criteria	**Acrylic Coating** [2] [81]	**Polyurethane Coating** [43] [81]	**Silicone Coating** [13] [81]
Protection	Good electrical insulation, protection against moisture and dust	Excellent protection against moisture, chemicals, and fungi, good mechanical strength	Resistant to high temperatures, flexibility at low temperatures, good moisture protection
Application	Consumer electronics, industrial electronics	Industrial, automotive, and military applications	Aerospace, military, and industrial applications
Advantages	Easy to apply and remove, cost-effective	Excellent moisture and chemical resistance, mechanically strong	Resistant to extreme temperatures, flexible, excellent moisture resistance
Disadvantages	Less resistant to solvents, lower chemical resistance	Difficult to remove, can be more expensive	Higher cost, can be difficult to apply
Examples	HumiSeal 1B31 [28]	MG Chemicals 4223F	Dow Corning 1-2577
Application Methods	Spray, dip, brush	Spray, dip	Spray, brush
Drying and Curing Time	Fast drying, usually within a few hours	Longer drying time, can take several hours to a day	Longer drying time, depending on ambient temperature and humidity

C

Appendix

C.1. Simulation Graphs

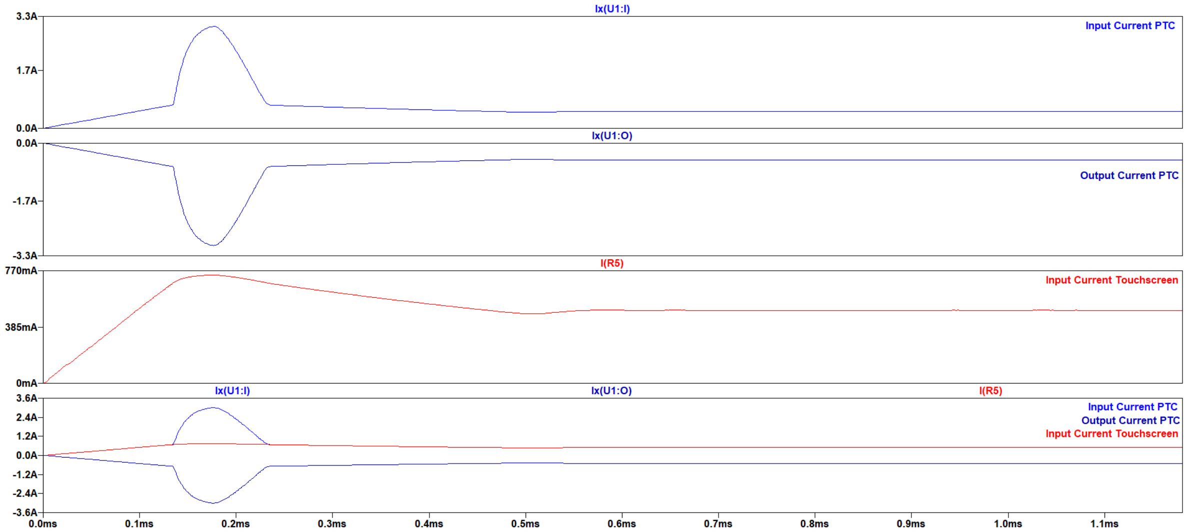


Figure C.1: Touchscreen OCP

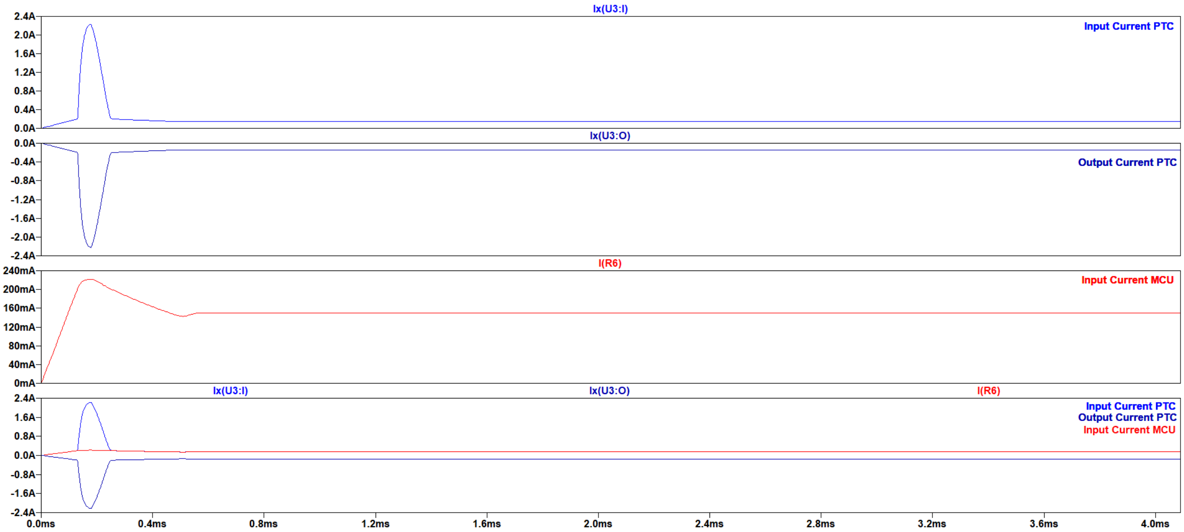


Figure C.2: MCU OCP