Department of Electronic and Telecommunication Engineering
University of Moratuwa, Sri Lanka

EN2160 - Electronic Design Realization

Design Report

Smart Programmable Bench Power Supply

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Abstract

This report presents the design and development of a smart, programmable dual-channel bench power supply, motivated by the essential need for reliable and versatile power sources in electronics prototyping, testing, and debugging environments. While professional-grade power supplies offer excellent performance, they are often prohibitively expensive for students, hobbyists, and small labs. In contrast, affordable commercial options frequently fall short in precision, robustness, and functionality. This project was initiated to bridge that gap by developing a cost-effective power supply with practical features tailored to the needs of its intended users.

To establish user requirements and expectations, a survey was conducted among 18 final-year electronic engineering undergraduates actively engaged in hardware-based academic projects. The survey explored their day-to-day usage of power supplies, challenges faced, and desired features. Insights gathered from this user-centered study were analyzed and translated into preliminary hand-drawn sketches that helped visualize potential interface layouts, output configurations, and interactive elements. Based on this iterative exploration, the product's specifications were defined to address both common use cases and advanced needs, while remaining technically feasible.

The resulting device features two independent output channels with configurable voltage and current limits, designed to support a wide range of lab applications—from powering embedded systems to emulating battery behavior. Emphasis was placed on providing precision control, monitoring, safety, and user-friendly interaction through both a touchscreen interface and PC software.

The development process encompassed all major phases of product engineering: requirements definition, electrical and mechanical design, embedded firmware development, PCB fabrication, and enclosure assembly. The final system is realized through a modular architecture distributed across multiple custom-designed PCBs and integrated into a professionally assembled enclosure.

This report documents the complete development lifecycle—from problem identification and survey-based specification gathering, through concept design and engineering implementation—to the construction and validation of a fully functional programmable bench power supply.

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Chapter 1

Motivation for the Project

In the context of electronics prototyping, testing, and general debugging, a dependable bench power supply is a fundamental piece of equipment. While high-end commercial power supplies—such as those from manufacturers like Keysight—offer excellent performance and reliability, they are often prohibitively expensive for many individuals, students, and smaller laboratories.

Conversely, budget-friendly power supplies available on the market often fall short in terms of quality, accuracy, and consistency, making them unsuitable for more demanding or precision-sensitive tasks. This creates a gap between affordability and performance that is difficult to bridge with off-the-shelf products.

Motivated by this challenge, I decided to design and build a programmable bench power supply that delivers reliable operation and essential functionality at a significantly lower cost compared to premium commercial models. The aim of this project is to offer a practical and accessible solution for those who require a capable power supply for prototyping and testing, without the financial burden of high-end instruments.

This rationale forms the basis for the project title and overall design approach.

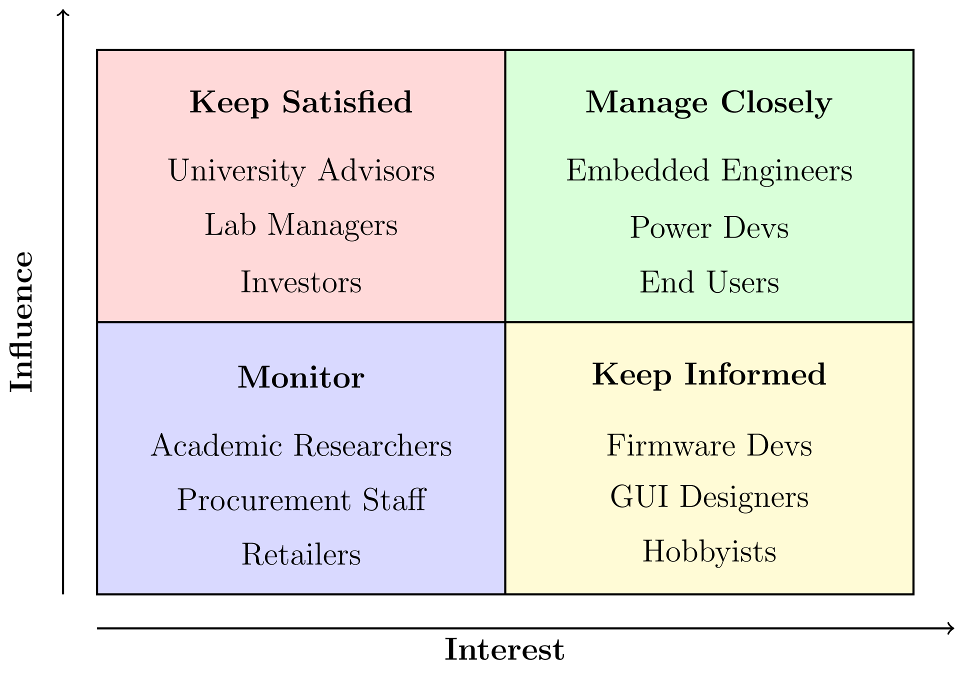
Chapter 2

Stakeholder Mapping

Stakeholder mapping was carried out to identify and prioritize individuals and groups involved in the development of the smart programmable bench power supply. Based on their level of **influence** and **interest**, stakeholders were categorized into four groups:

- **Manage Closely (High Influence, High Interest):**
  Examples: Engineers, Engineering students (end users), academic supervisors, the developer (project owner).
- **Keep Satisfied (High Influence, Low Interest):**
  Examples: University administrators, procurement officers.
- **Keep Informed (Low Influence, High Interest):**
  Examples: Electronics hobbyists, Firmware developers, Windows GUI testers.
- **Monitor (Low Influence, Low Interest):**
  Examples: Academic researchers from unrelated fields, general lab staff.

Stakeholder Matrix



Chapter 3

User Needs Identification Survey

To ensure the design of the programmable bench power supply would address real-world requirements and expectations, a user-centered approach was adopted during the early stages of development. A detailed survey was conducted among 18 electronic engineering undergraduates, all of whom were actively engaged in electronics prototyping, hardware development, or embedded system projects.

The survey was structured using a Google Form and introduced with context on the project motivation: to create a cost-effective yet capable programmable power supply, positioned between premium laboratory-grade equipment like the Keysight E36312A and low-cost, limited-feature models such as the Eventek KPS305D. Respondents were presented with a side-by-side comparison of these reference models to help them make informed decisions during the survey.

The questionnaire explored a wide range of design-related parameters including:

- Preferred number of output channels
- Voltage and current range expectations per channel
- Level of control and independence between outputs
- Essential safety and regulation features (e.g., OVP, OCP, remote sensing)
- Desired voltage and current resolution
- Battery charging and emulation capabilities
- Preferred types of user interfaces (touchscreen, PC control, or both)
- Connectivity requirements (USB, LAN)
- Graphical user interface features (e.g., data logging, graphing, remote control)
- Power consumption monitoring
- Acceptable price ranges
- Primary application areas

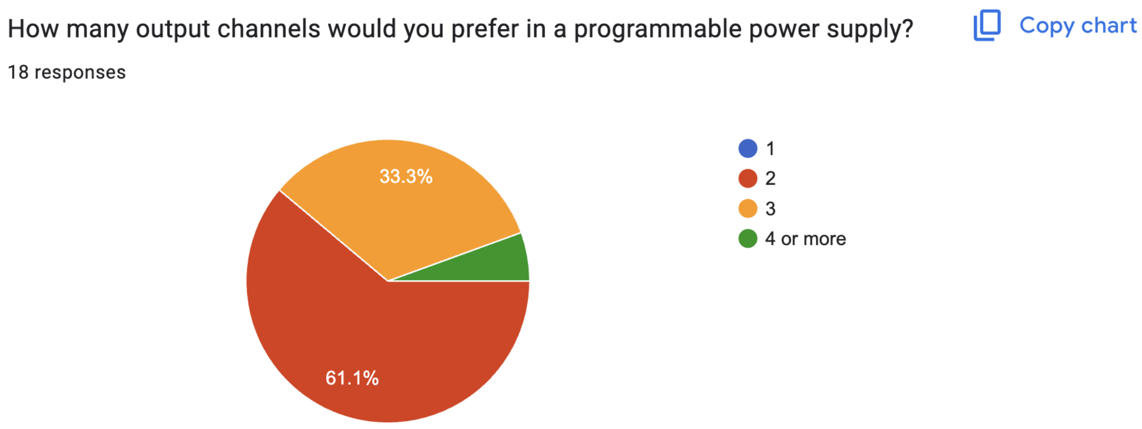


Figure 3.1: Survey - Question 01

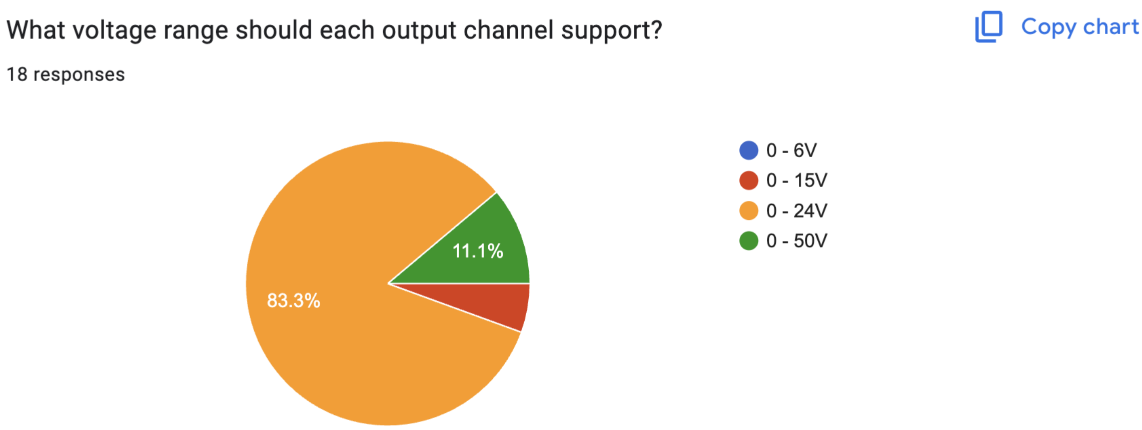


Figure 3.2: Survey - Question 02

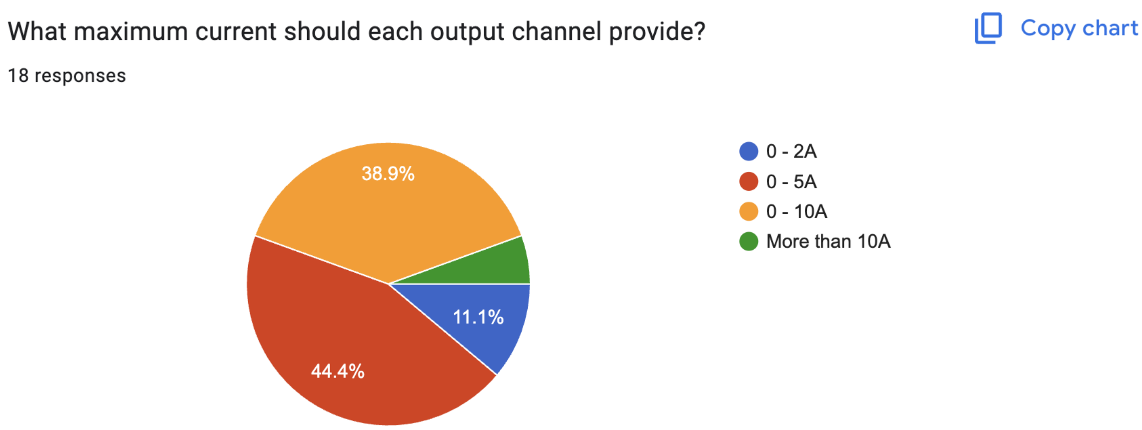


Figure 3.3: Survey - Question 03

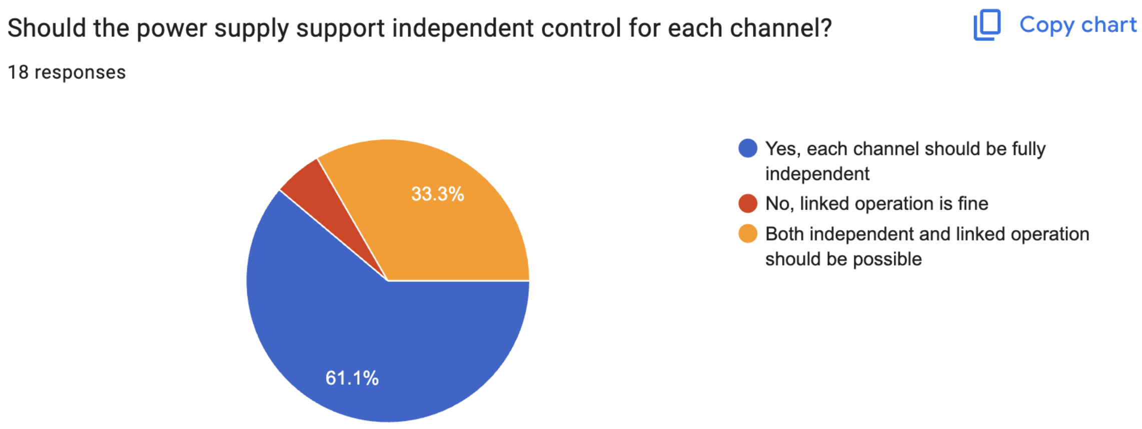


Figure 3.4: Survey - Question 04

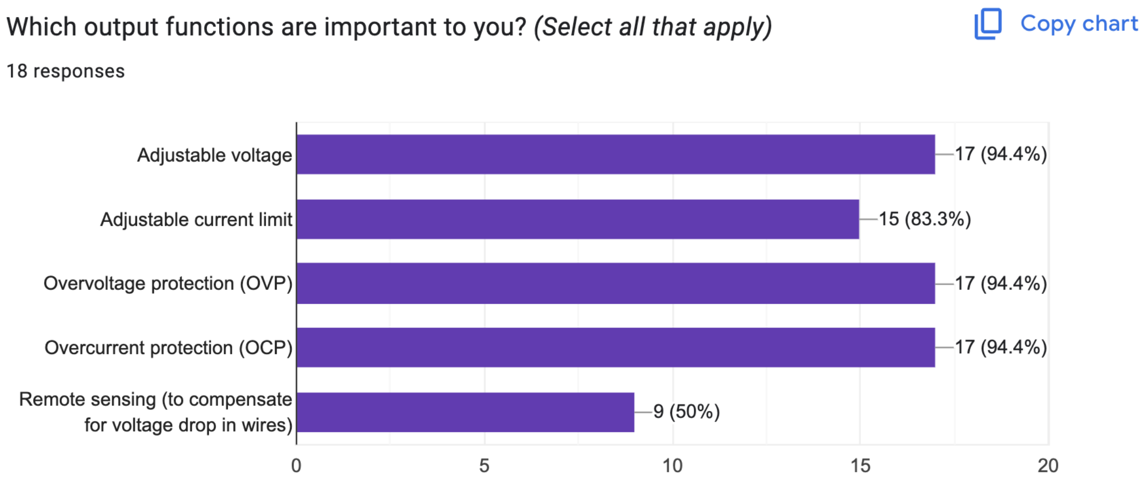


Figure 3.5: Survey - Question 05

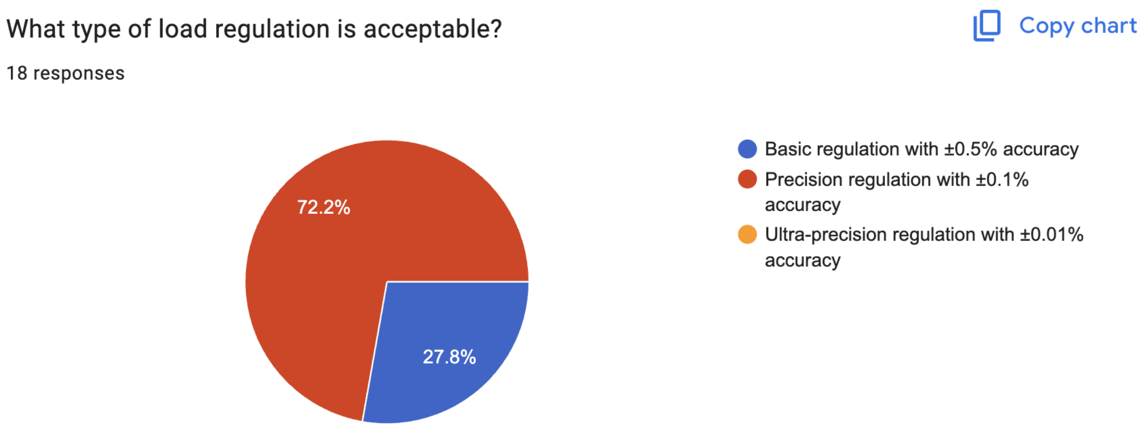


Figure 3.6: Survey - Question 06

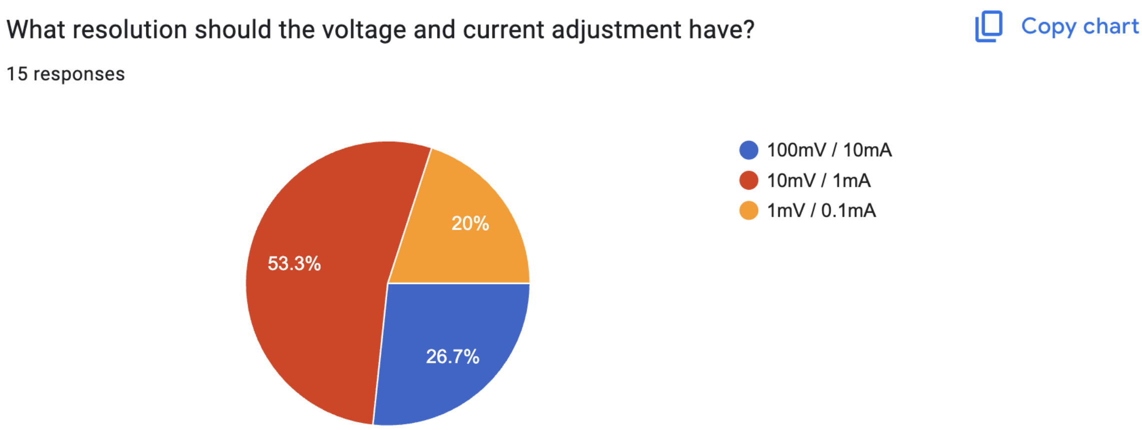


Figure 3.7: Survey - Question 07

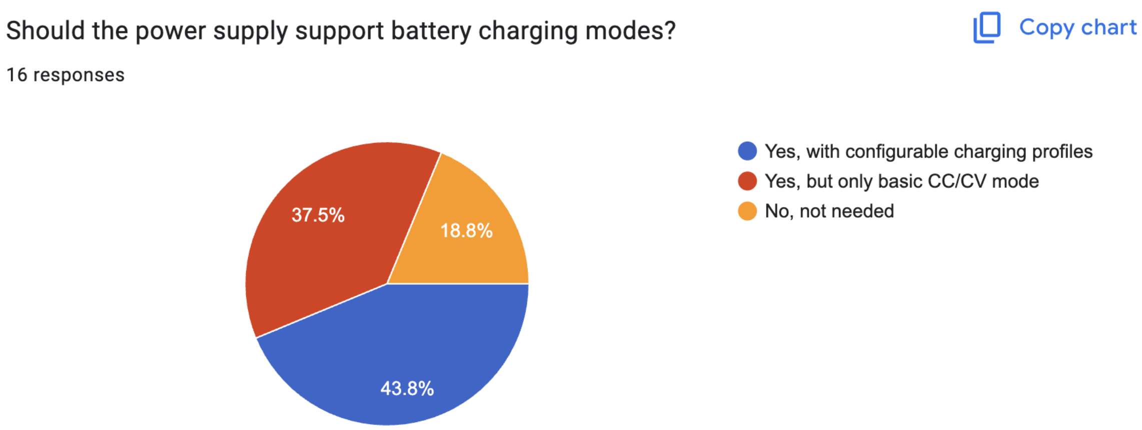


Figure 3.8: Survey - Question 08

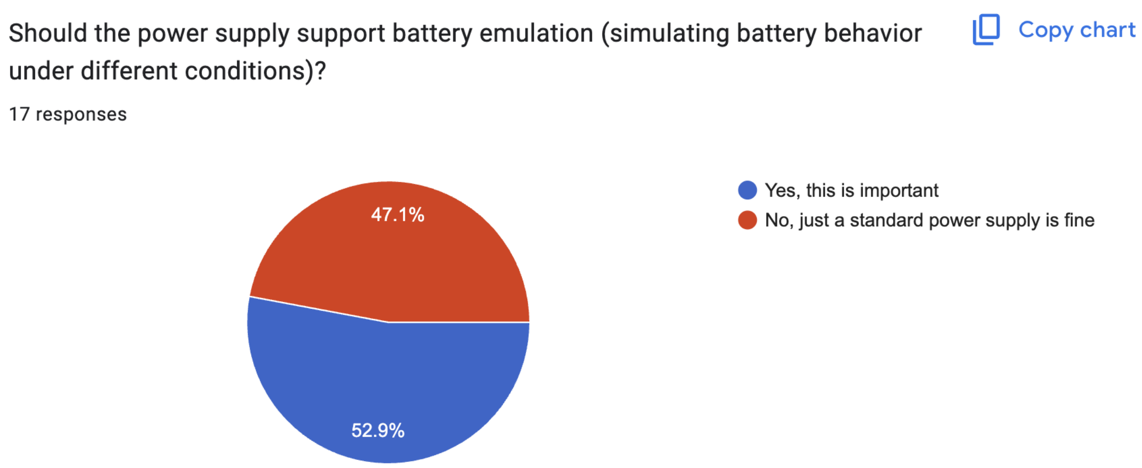


Figure 3.9: Survey - Question 09

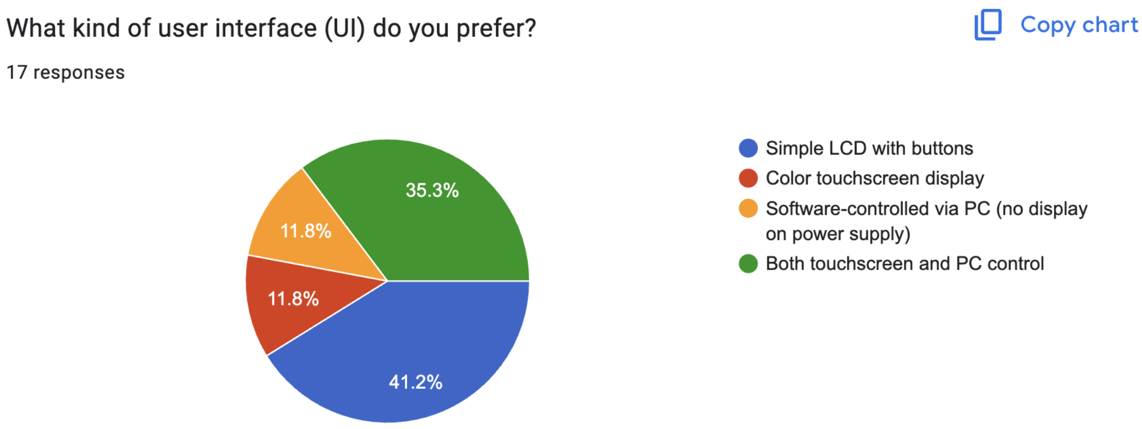


Figure 3.10: Survey - Question 10

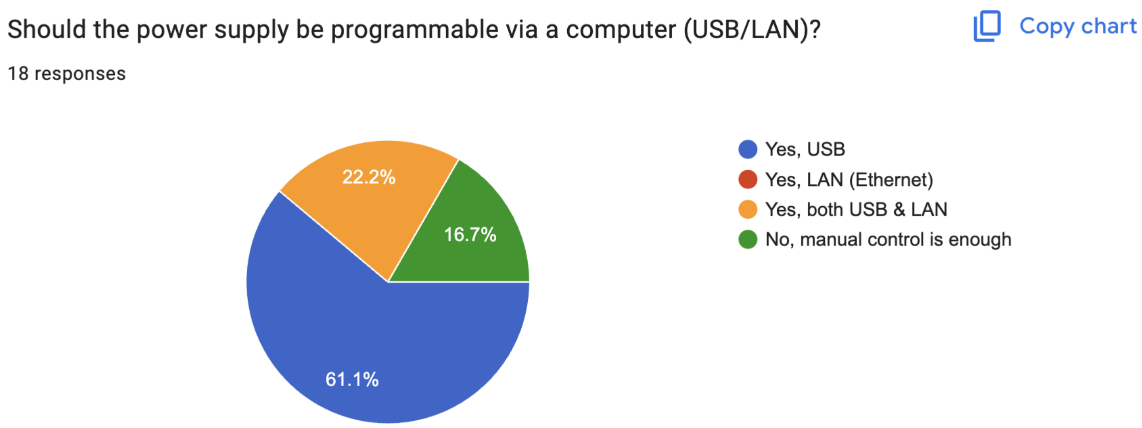


Figure 3.11: Survey - Question 11

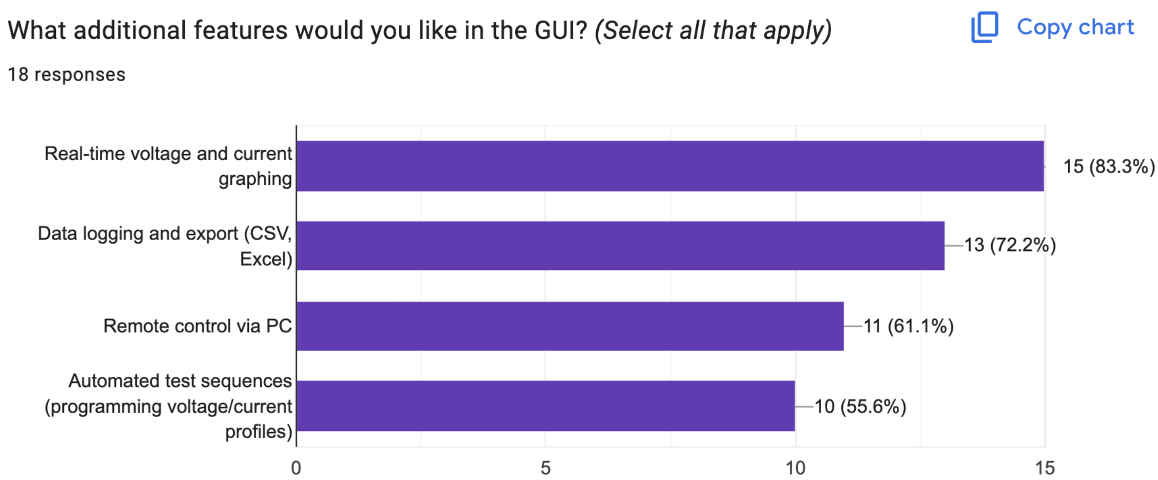


Figure 3.12: Survey - Question 12

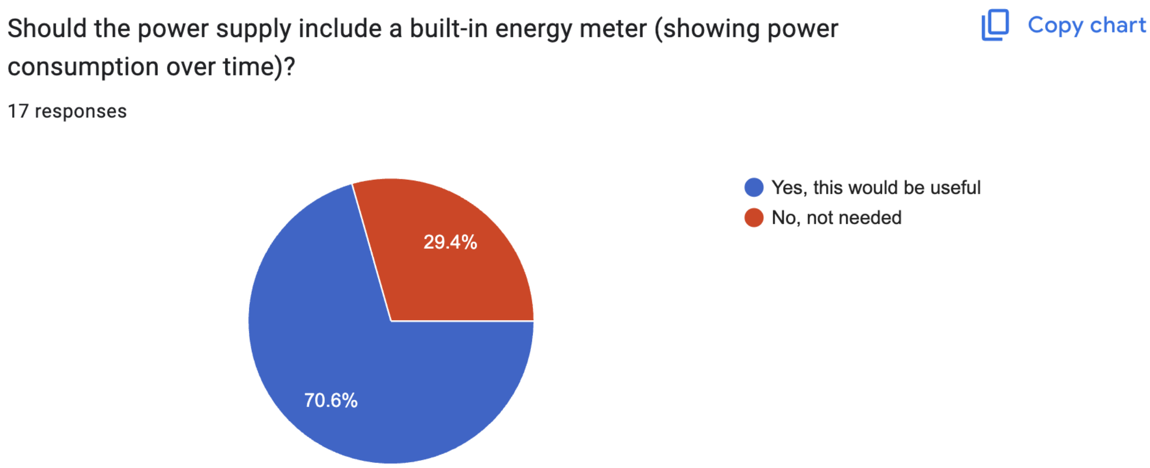


Figure 3.13: Survey - Question 13

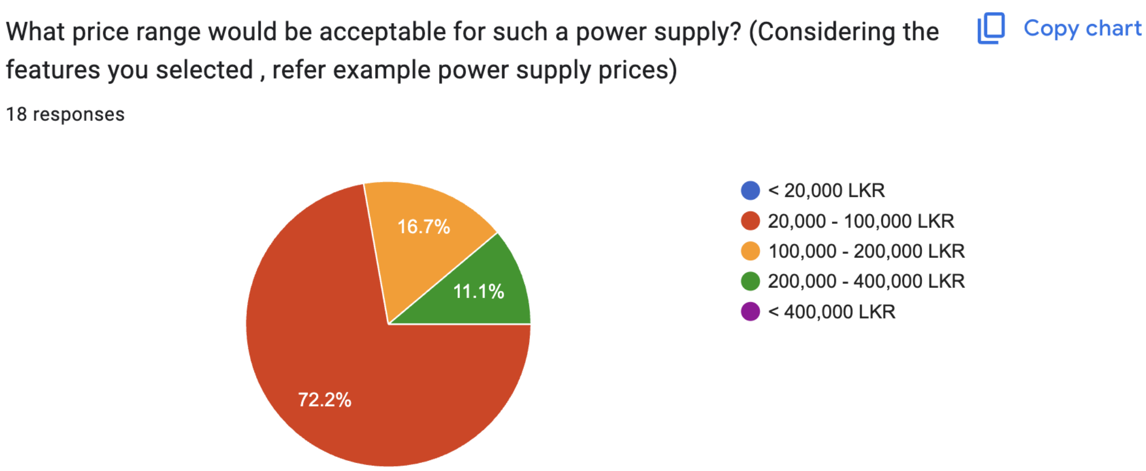


Figure 3.14: Survey - Question 14

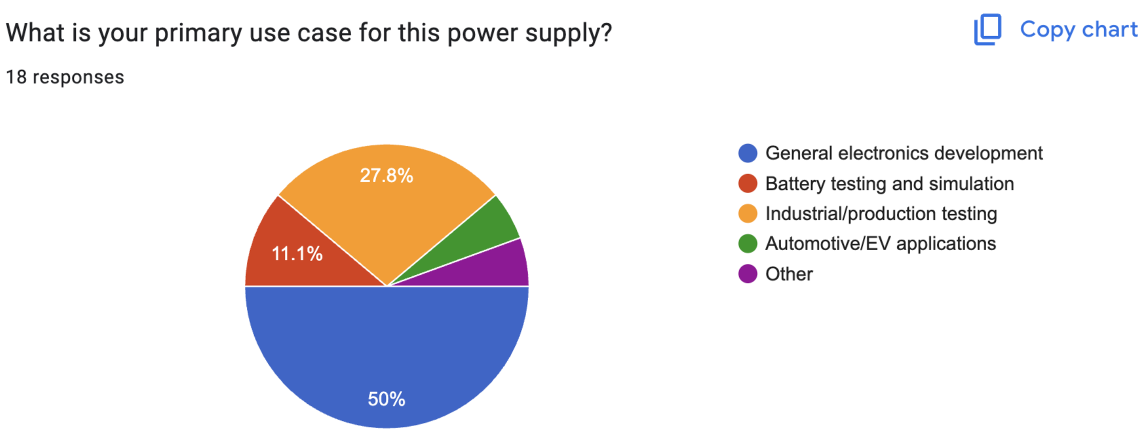


Figure 3.15: Survey - Question 15

Based on the collected user feedback and expectations from the conducted survey, the product specifications of the programmable bench power supply were carefully derived to reflect the most common and critical user requirements. The responses indicated a clear demand for dual-channel operation, fine voltage and current resolution, reliable protection mechanisms, and advanced features such as battery emulation, charging, and GUI-based control.

Using these insights, component selection and system architecture were determined with the goal of achieving a balance between performance, scalability, and cost. Decisions regarding voltage and current ranges, sensing accuracy, user interface design, and communication interfaces were all made in alignment with the survey data. Priority was given to incorporating as many high-impact features as technically and economically feasible within the design constraints.

Additionally, trade-offs between cost and functionality were evaluated to ensure that the resulting power supply would be both affordable and capable, addressing the existing gap between low-cost, limited-functionality devices and premium lab-grade equipment. Special attention was given to scalability and modularity to support future enhancements or customization based on extended use cases.

Through this user-driven approach, the project evolved from abstract requirements into a concrete and technically sound solution that effectively satisfies the needs of the target user group—students, engineers, and hobbyists engaged in electronics prototyping and testing.

Chapter 4

Research on Similar Products

4.1 Keithley 2231A DC Power Supply

The **Keithley 2231A-30-3** is a precision triple-output programmable DC power supply designed for use in electronics development, testing, and automated systems. It offers two isolated 30 V/3 A channels and one 5 V/3 A channel, delivering a total output power of up to 195 W. Each output is independently adjustable, enabling simultaneous powering of analog and digital sections of a circuit or multiple devices under test. The power supply uses linear regulation, ensuring low output ripple and noise, which is essential for sensitive analog and RF circuitry.

Figure 4.1: Keithley 2231A-30-3

Each channel supports precise voltage and current settings with 1 mV and 1 mA resolution and features excellent line and load regulation. The supply is equipped with comprehensive overvoltage (OVP) and overcurrent (OCP) protection, enhancing both user and device safety. Channels 1 and 2 can also be configured in series (up to 60 V) or parallel (up to 6 A), offering flexibility for higher power requirements.

In terms of programmability, the 2231A-30-3 supports remote control via USB and GPIB interfaces, with a fully SCPI-compliant command set. This allows the supply to be integrated into automated test setups and controlled from software platforms such as *LabVIEW*, *MATLAB*, or *Python* via VISA. Users can independently program voltage, current, and protection settings for each channel and monitor output values remotely. Additionally, the power supply features 30 memory slots for saving and recalling configurations, making it ideal for repeated test sequences.

The front panel includes a clear 4-digit display for both voltage and current readings per channel, along with output status indicators. Terminals are available on both the front and rear, allowing flexibility for benchtop or rack-mounted use. The 2231A-30-3 combines compact design, reliable performance, and versatile programmability, making it suitable for research labs, production testing, and educational environments.

4.2 Keysight E36312A DC Power Supply

The **Keysight E36312A** is a high-performance triple-output programmable DC power supply from Keysight's E36300 Series, designed for professional bench and system applications where accuracy, reliability, and ease of use are essential. It offers two isolated 0 V–6 V/5 A channels and one 0 V–25 V/1 A channel, with a total power output of 80 W. Each channel is independently controlled and electrically isolated, making the unit ideal for powering mixed-signal circuits or multiple independent loads.

Figure 4.2: Keysight E36312A

The E36312A delivers very low output ripple and noise thanks to its linear regulation, providing clean and stable power for analog, RF, and precision digital circuits. It features high resolution and accuracy with 1 mV / 0.5 mA programming resolution, and built-in readback capability with 0.03 % + 5 mV voltage and 0.05 % + 250 µA current accuracy, which allows users to verify actual delivered power without needing an external digital multimeter. The supply also supports auto-series and auto-parallel modes for channels 1 and 2, allowing output combinations up to 12 V/5 A (parallel) or 12 V/2.5 A (series), while channel 3 provides higher voltage flexibility.

Programming and remote control are major strengths of the E36312A. It offers LAN (LXI Core), USB, and optional GPIB interfaces, all supporting SCPI and IVI driver compatibility for seamless integration into automated test systems. The power supply allows independent control of each channel's voltage, current, and protection settings, as well as remote enable/disable and real-time monitoring. It includes digital I/O and trigger in/out signals to support synchronized operations with other instruments in a test environment. Additionally, users can save and recall instrument settings via built-in memory, streamlining multi-step testing.

The front panel includes a 4.3 inch color LCD display, offering an intuitive user interface with simultaneous readouts for all three channels, along with soft keys and a rotary knob for fast adjustments. The graphical user interface allows access to advanced features such as output sequencing, data logging, and signal analysis directly from the front panel. These make the E36312A a powerful standalone instrument as well as a capable component in remote-controlled test setups.

Overall, the Keysight E36312A combines excellent output performance, precise programmable control, and a user-friendly interface in a robust, compact form factor. It is well-suited for R&D labs, education, power validation, and functional testing in embedded and mixed-signal design workflows.

4.3 Key Features and Common Specifications of Professional Programmable Power Supplies

Commercial professional DC power supplies are precision instruments designed to deliver stable, accurate, and configurable power to electronic devices under test. These power supplies typically feature multiple isolated outputs, programmable control, and low-noise linear or hybrid regulation to meet the needs of analog, digital, and mixed-signal circuit development.

Key Specifications

– **Output Channels:** Typically 2–3, independently programmable and electrically isolated

– **Voltage Range:** 0–6 V (logic) up to 30 V (analog systems)

– **Current Range:** 0–5 A per channel

– **Power Output:** Ranges from 80 W to over 200 W

– **Resolution:** 1 mV / 0.5–1 mA typical

– **Accuracy:** Voltage ±(0.03–0.05%) + offset; Current ±(0.05–0.1%) + offset

– **Ripple & Noise:** Very low (<5 mVrms), suitable for sensitive analog and RF circuits

Core Features

– **Linear or Linear-Hybrid Regulation:** Ensures clean, noise-free output

– **Series/Parallel Operation:** Combine channels to increase voltage or current

– **Load/Line Regulation:** Excellent regulation under varying conditions

– **SCPI-Compliant Control:** Allows full automation via USB, LAN, or GPIB

– **Readback Support:** Real-time voltage/current feedback for monitoring

– **Memory Functions:** Save and recall setups (common for repeated test cases)

– **Protection Features:** OVP, OCP, thermal protection, foldback options

– **Display:** 4-digit numeric or color LCD with simultaneous multi-channel view

Programmability & Connectivity

– **Interfaces:** USB, LAN (LXI-compliant), GPIB (optional)

– **Software Integration:** Compatible with LabVIEW, Python (via PyVISA), MATLAB, C/C++, and Keysight/Tektronix software suites

– **Remote Programming:** SCPI command sets for scripting and automation

– **Digital I/O or Triggering:** For synchronized or event-driven test setups

Pricing and Services

– **Price Range:** $800 to $2,500 depending on output power, features, and brand

– **Warranty:** 3 years standard, extendable up to 5 years

– **Calibration:** Factory-calibrated; periodic recalibration recommended (1–2 years)

– **Support:** Global technical support, firmware updates, online documentation, and service centers

Typical Applications

– Embedded systems development

– Analog/mixed-signal and RF testing

– Production testing and validation

– Academic teaching and research

– Battery simulation and power profiling for IoT devices

Chapter 5

Product Specifications

Based on a user needs identification survey conducted among 18 electronics engineering undergraduates actively engaged in hardware prototyping, and considering practical feasibility, cost constraints, and component availability, the specifications of the programmable bench power supply were defined to strike a balance between performance, usability, and affordability.

The power supply includes **two independent output channels**, each capable of operating in two configurable modes:

- 24V / 3A Mode
- 6V / 10A Mode

These configurations allow the power supply to support a wide range of test scenarios, from powering low-voltage digital electronics to handling higher-current applications such as motor controllers or battery testing. Each channel supports both **Constant Voltage (CV)** and **Constant Current (CC)** modes, providing flexibility for voltage regulation or current-limited power delivery.

Precision requirements were defined based on survey feedback and technical feasibility:

- **Voltage Resolution:**
  - 5 mV in 6V mode
  - 30 mV in 24V mode
- **Current Resolution:**
  - 1 mA in 3A mode
  - 10 mA in 10A mode

All functions are fully programmable and accessible via a **5-inch color touchscreen** interface. Additionally, a **rotary encoder** is provided for fine manual adjustment, along with **RGB-backlit tactile push buttons** for intuitive navigation and feedback.

Advanced features tailored for modern prototyping and testing environments include:

- **Battery Emulation**: Simulates battery behavior to test battery-powered circuits without using actual batteries.
- **Battery Charging**: Supports user-defined charging profiles for various battery chemistries.

- **Programmable Output Profiles**: Enables creation of automated voltage/current sequences.
- **Data Monitoring & Logging**: Real-time measurement visualization, logging to CSV/Excel, and test report generation.

A dedicated **Windows GUI** communicates with the power supply via **USB** and allows extended control and analysis capabilities, including remote control, profile management, and data export.

The physical user interface and I/O layout are designed for ease of use and professional appearance:

- Two **banana connectors** (positive and ground) per output channel.
- Rear-mounted **cooling fan** for thermal management.
- **Power input**, **USB port**, and **main power switch** positioned at the back for cable organization and safety.

This product offers a comprehensive set of features that fulfill the practical needs and expectations identified in the user survey, making it a highly capable yet cost-effective solution for laboratories, educational institutions, and individual developers.

Chapter 6

Conceptual Design - Enclosure

As part of the front panel interface design, I decided to incorporate a 5-inch touchscreen for interactive control and visualization, alongside a rotary encoder to allow fine adjustment of parameters. For each output channel, two banana connectors are provided to ensure secure and standardized connections. To enhance usability and accessibility, the front panel layout was designed to be clean, organized, and intuitive.

On the rear panel, I included a cooling fan to ensure proper thermal management during high-power operation, along with a 230V AC power inlet and a USB interface for PC communication and software control.

6.1 Initial Sketches

To determine the most ergonomic and visually appealing layout, I created three rough design sketches of the power supply enclosure. These concepts explored different configurations of component placement on both the front and rear panels. The aim was to evaluate and select the best design based on aesthetics, user-friendliness, and practical usability. This iterative sketching process allowed for early identification of spatial and functional considerations, ultimately guiding the final physical design of the unit.

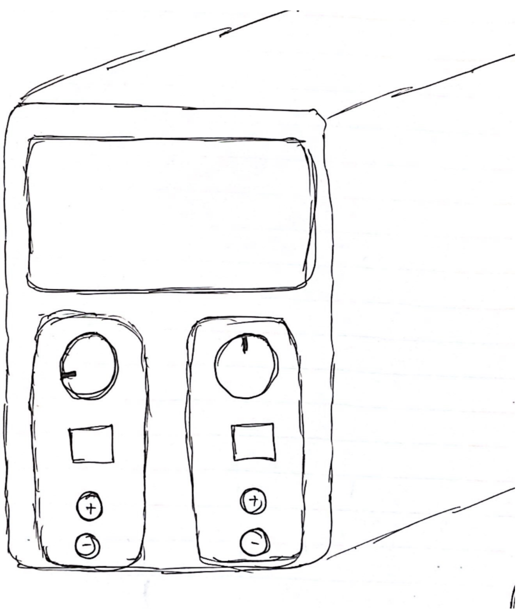


Figure 6.1: Sketch 01 - Front View

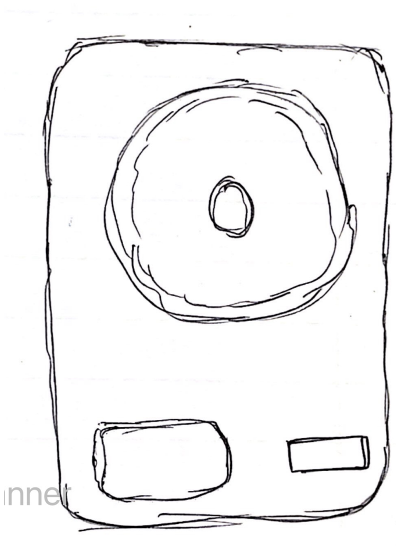


Figure 6.2: Sketch 01 - Back View

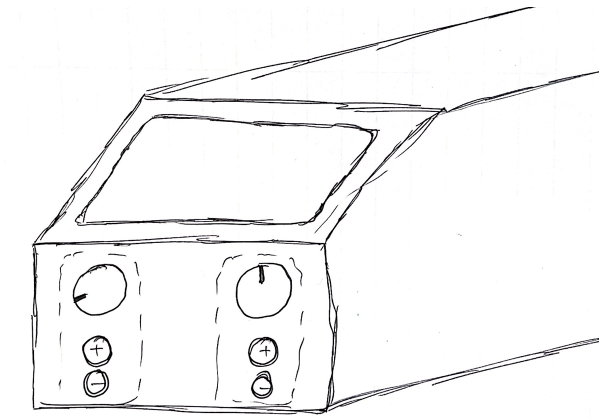


Figure 6.3: Sketch 02 - Front View

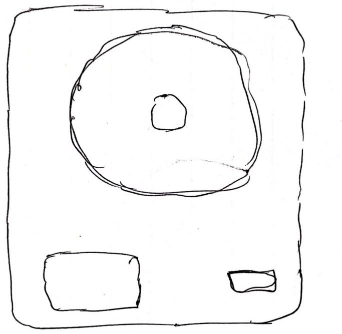


Figure 6.4: Sketch 02 - Back View

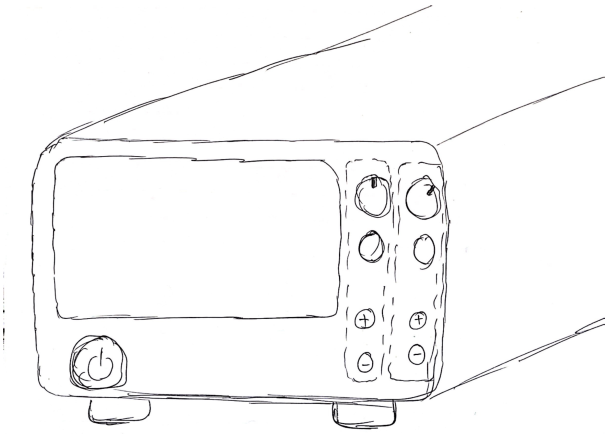


Figure 6.5: Sketch 03 - Front View

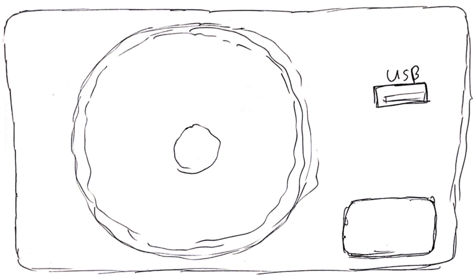


Figure 6.6: Sketch 03 - Back View

6.2 Refined Design

Selection Criteria

- Professional Appearance
- User Accessibility
- Functional Layout (Touchscreen, Rotary Encoder, Connectors)
- Interface Organization and Workflow
- Compactness and Aesthetics
- Suitability for Lab/Educational Use
- Ease of Assembly and Serviceability

Design Comparison Table

Criteria	**Sketch 01**	**Sketch 02**	**Sketch 03**
Professional Appearance	6/10	7/10	**9/10**
User Accessibility	5/10	7/10	**9/10**
Functional Component Layout	6/10	6/10	**9/10**
Interface Organization & Workflow	5/10	7/10	**10/10**
Compactness & Aesthetic Form Factor	7/10	6/10	**9/10**
Suitability for Educational/Professional Use	6/10	7/10	**9/10**
Ease of Assembly & Serviceability	7/10	6/10	**8/10**
Total Score	**42/70**	**46/70**	**63/70**

Table 6.1: Comparison of Sketch Concepts for Front Panel Design

Sketch 03 was selected as the final layout due to its high scores across all key criteria. It features a professional and compact design, intuitive control and interface layout, and is well-suited for both educational and professional laboratory environments.

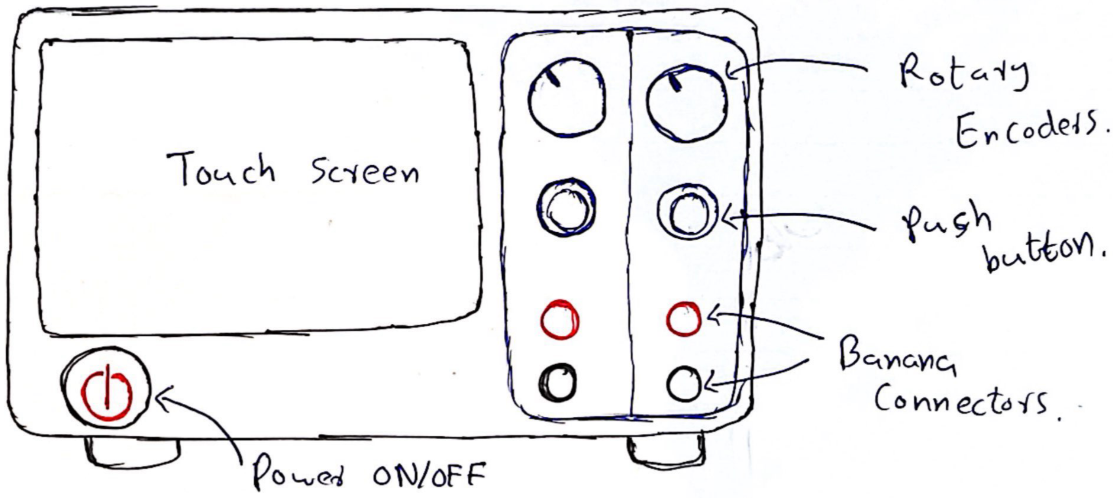


Figure 6.7: Refined Design - Front View

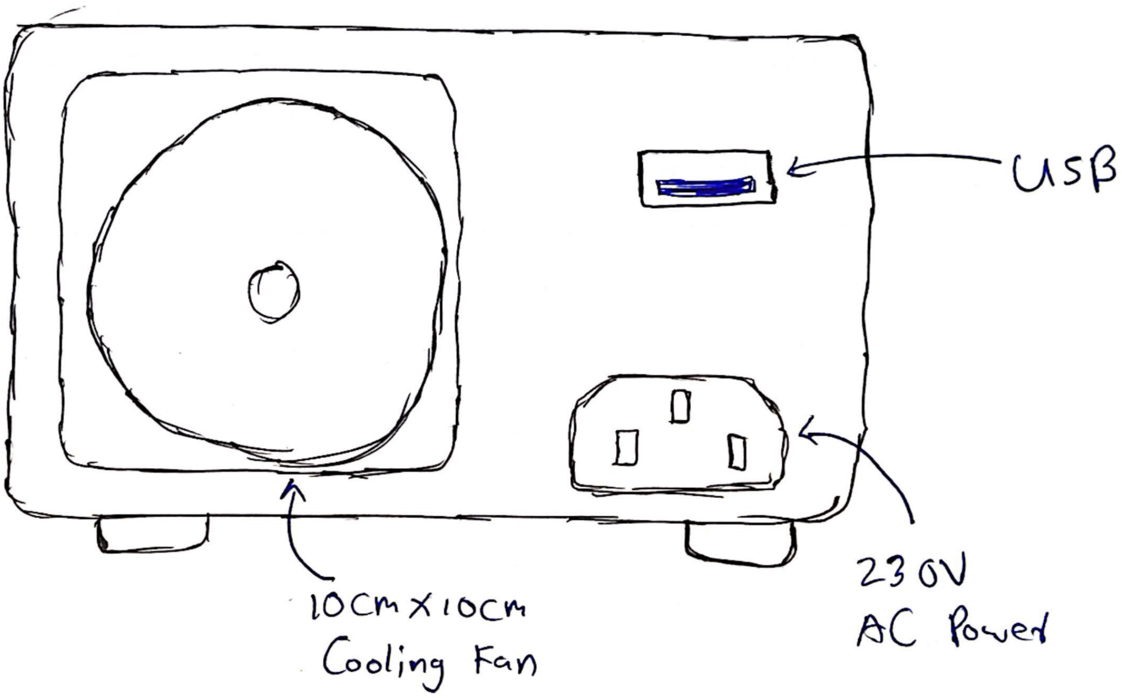


Figure 6.8: Refined Design - Rear View

Chapter 7

Conceptual Design - Circuit

7.1 Descriptions of Circuit Conceptual Design Options

Design 1: Single All-in-One PCB

A single PCB that integrates all subsystems—AC rectification, voltage regulation, control microcontroller, user interface (touchscreen, encoder), and output channels. The transformer, user interface, and power stages are all directly mounted or connected to this single board.

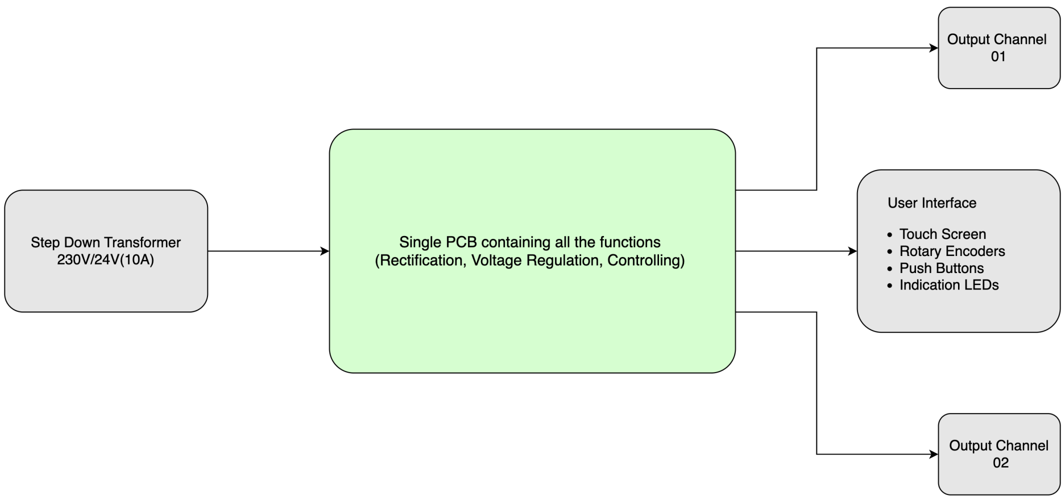


Figure 7.1: Circuit Conceptual Design 01

Pros:

- Lowest initial component cost
- Simplified wiring
- Compact footprint

Cons:

- High EMI risk due to mixed signal/power zones
- Poor modularity
- Difficult to debug and repair
- Limited thermal dissipation control

Design 2: Two-PCB Split (Power + Control)

This design separates the system into two boards:

- **Power PCB:** Handles high-current power paths, AC rectification, and voltage regulation.
- **Controller PCB:** Hosts the microcontroller and digital interface circuitry, powered via the Power PCB and connected through a signal harness.

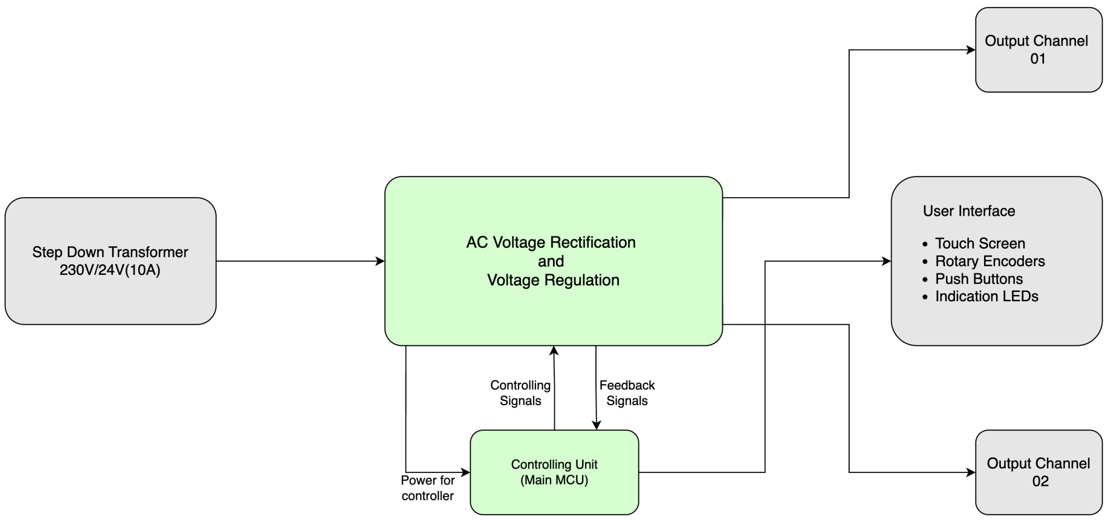


Figure 7.2: Circuit Conceptual Design 02

Pros:

- Better EMI control
- Improved development flow
- Physical isolation between control and power domains

Cons:

- Slightly higher manufacturing and assembly complexity
- Limited modularity compared to more segmented designs

Design 3: Three-PCB Modular Design

This design divides the system into three distinct functional blocks:

- **Controller PCB:** Manages user interface and communication tasks
- **Power Stage 1 PCB:** Performs AC rectification, smoothing, and first-stage buck regulation
- **Power Stage 2 PCB:** Contains the linear regulation stage, voltage/current sensing, and protection circuitry

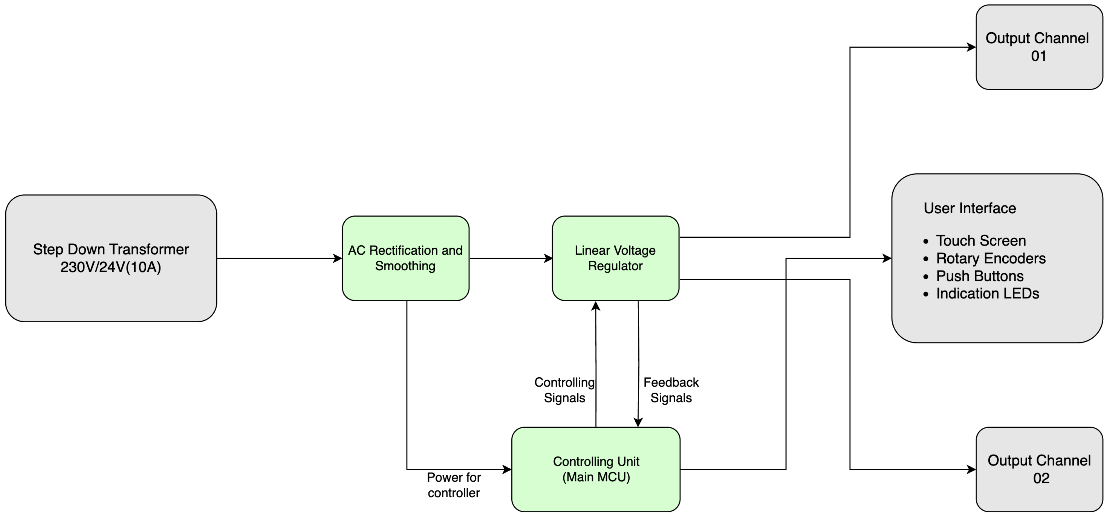


Figure 7.3: Circuit Conceptual Design 03

Pros:

- Better thermal and EMI isolation
- Improved serviceability and modularity
- Easier testing and debugging

Cons:

- Increased overall cost
- Higher interconnect complexity

Design 4: Improved Three-PCB with External BJT

This version builds on Design 3 by placing the linear regulator's power BJT on a separate, connectorized sub-module attached to a dedicated external heatsink.

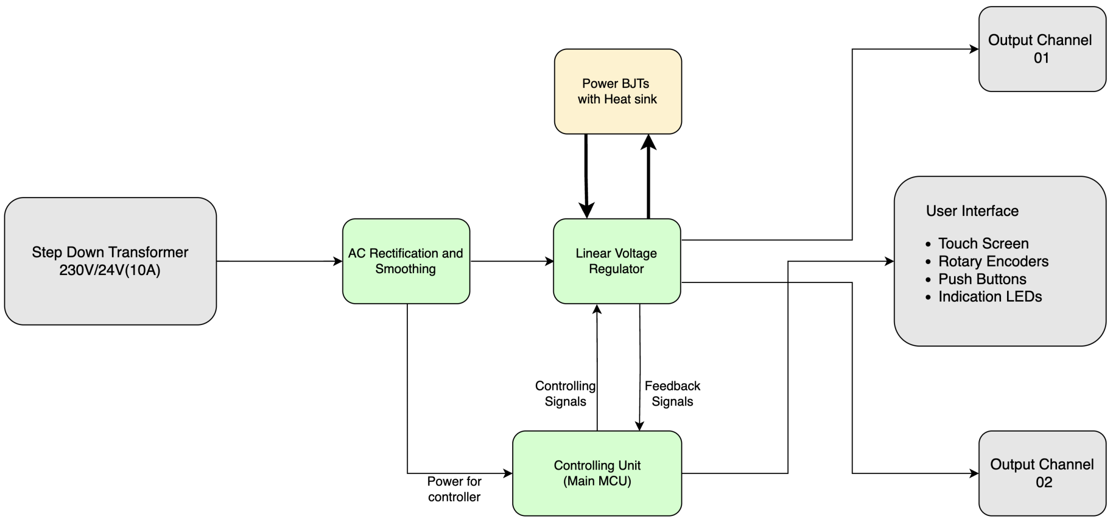


Figure 7.4: Circuit Conceptual Design 04

Pros:

- Best thermal management
- Easiest to repair/replace power devices
- Excellent EMI and noise control
- Professional-grade modularity

Cons:

- Slightly higher mechanical and connector cost

Criteria	**Design 1**	**Design 2**	**Design 3**	**Design 4**
Cost Efficiency	4	6	7	8
Complexity	3	4	6	7
EMI Performance	3	5	6	7
Thermal Management	4	5	6	7
Debuggability	3	4	6	7
Repairability	3	4	6	8
Modularity	2	4	6	8
Mechanical Integration	6	5	4	3
Signal Integrity	3	5	6	7
Heat Dissipation Capability	3	5	6	8
Interconnect Complexity	2	4	6	6
Ease of Manufacturing	7	6	5	4
Maintenance Over Lifecycle	3	4	6	8
Upgrade Flexibility	2	3	6	7
Total Score (/140)	**48**	**65**	**86**	**99**

Table 7.1: Vertical Comparison of Four Conceptual Power Supply PCB Designs

Based on the comprehensive comparison across key criteria such as cost efficiency, modularity, thermal management, EMI performance, repairability, and upgrade flexibility, Design 4 demonstrates the highest overall score and offers the most balanced trade-off between performance, maintainability, and professional implementation. Therefore, Design 4 is selected as the final PCB architecture for the power supply system.

Chapter 8

Methodology

The development of the dual-channel programmable bench power supply was accomplished through a structured engineering design methodology encompassing power architecture definition, functional hardware partitioning, analog and digital control loop design, firmware development, component evaluation and selection, PCB layout and design, and user interface implementation. Each functional block of the system was independently designed, validated, and then systematically integrated to ensure modularity, maintainability, and performance consistency across the entire system.

The hardware design begins with the AC-DC front-end, where a 230V AC mains input is stepped down using a center-tapped transformer. Only the outer terminals of the transformer are utilized, delivering approximately 24V RMS. This AC voltage is rectified using a bridge rectifier and filtered with a bank of large electrolytic capacitors to produce a smoothed DC bus. This bus serves as the primary power source for the two output channels of the power supply.

Each output channel includes its own independent power regulation path, composed of a high-efficiency DC-DC buck converter followed by a high-current linear regulation stage. The dual-stage regulation approach was chosen to strike a balance between efficiency and output noise performance. The buck converter handles the coarse voltage conversion with high efficiency, while the linear regulator refines the output by significantly reducing ripple and switching artifacts, achieving low-noise, high-precision power delivery.

To enable programmability and real-time control, a central microcontroller interfaces with each regulation path via digital-to-analog converters (DACs), digital potentiometers, and analog feedback loops. The system continuously monitors voltage and current through dedicated precision measurement ICs, allowing it to operate in either constant voltage (CV) or constant current (CC) mode. Additionally, programmable gain control in the voltage driver stage and selectable shunt resistors in the current path enable dual-range operation for both voltage and current outputs.

The programmability is realized through firmware running on the microcontroller, which manages the closed-loop control algorithms, switching logic, protection features, and user interaction. A touchscreen interface provides on-device control, while a Windows-based GUI enables advanced operations such as battery charging, emulation, and automated test procedures. This comprehensive hardware-software integration enables the power supply to meet diverse application requirements with precision, flexibility, and user-friendly control.

8.1 Hardware

The programmable bench power supply consists of several key components designed to ensure high performance, reliability, and user-friendly operation. At its core is a step-down transformer rated for 230V AC to 24V DC at 10A, which serves as the primary power source for the entire system. The hardware architecture includes five custom-designed PCBs, organized into three main types: two Power Distributor PCBs, two Output Interface PCBs (one for each output channel), and a single Controller Unit PCB that centrally manages system control, regulation, monitoring, and communication.

Each output channel has its own dedicated Power Distributor and Output Interface PCB to facilitate isolated regulation and measurement, while the Controller Unit interfaces with all channels and orchestrates real-time control logic. The user interface is built around a 5-inch touchscreen display and is complemented by rotary encoders, push buttons, and a buzzer for intuitive user interaction and status alerts.

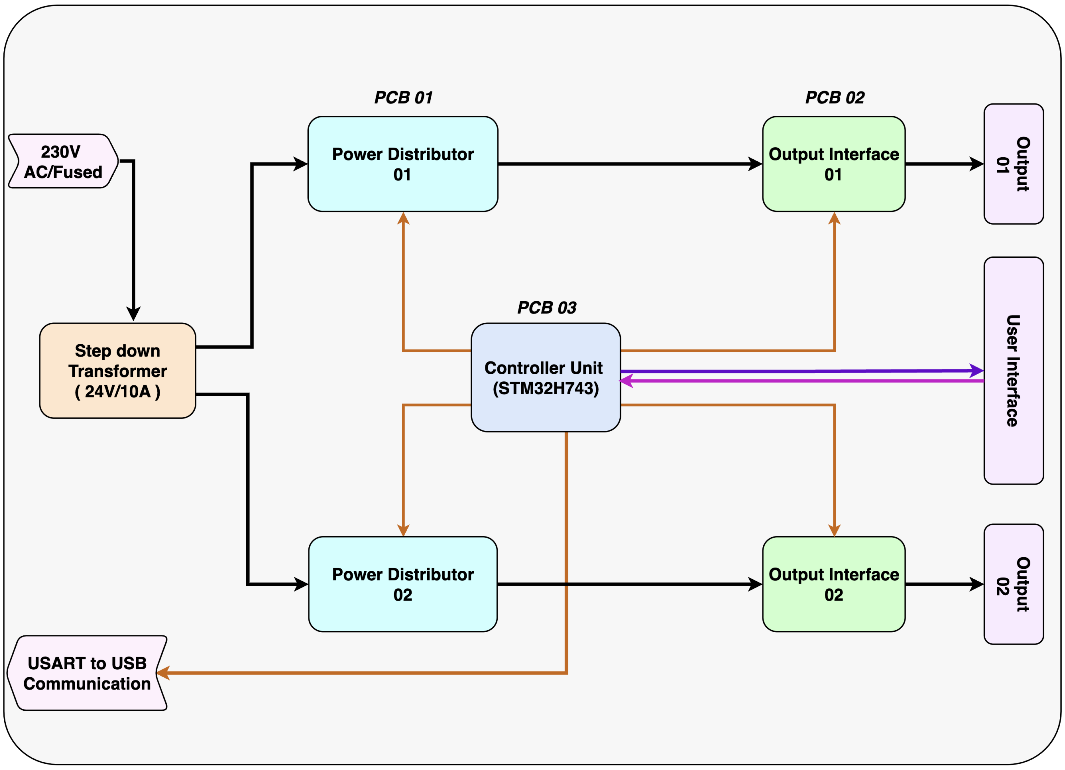


Figure 8.1: Hardware Architecture Block Diagram

To maintain thermal stability during high-load operation, the system is equipped with two active cooling fans positioned to cool critical power components and heat sinks. Additionally, the system features PC connectivity via a USB-to-UART converter, allowing seamless communication with a Windows-based graphical user interface for remote control, monitoring, and advanced functionalities such as battery simulation and charging profiles.

8.1.1 PCB 01 - Power Distributor Circuit

The Power Distributor PCB is designed as the primary power processing and distribution stage for each output channel of the programmable bench power supply. There are two identical Power Distributor PCBs, one for each channel, responsible for converting raw rectified DC voltage into a digitally adjustable intermediate voltage using high-efficiency buck converters. These PCBs also provide the auxiliary power rails required by the control electronics and other low-power subsystems.

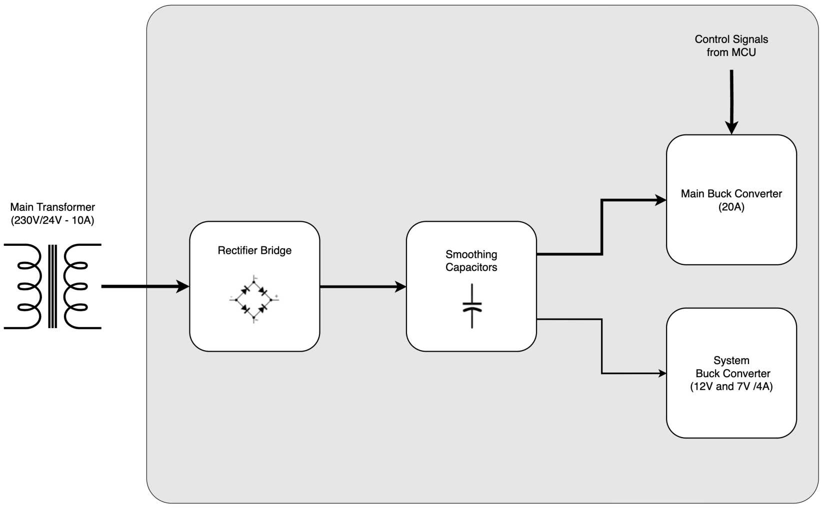


Figure 8.2: Power Distributor PCB - Block Diagram

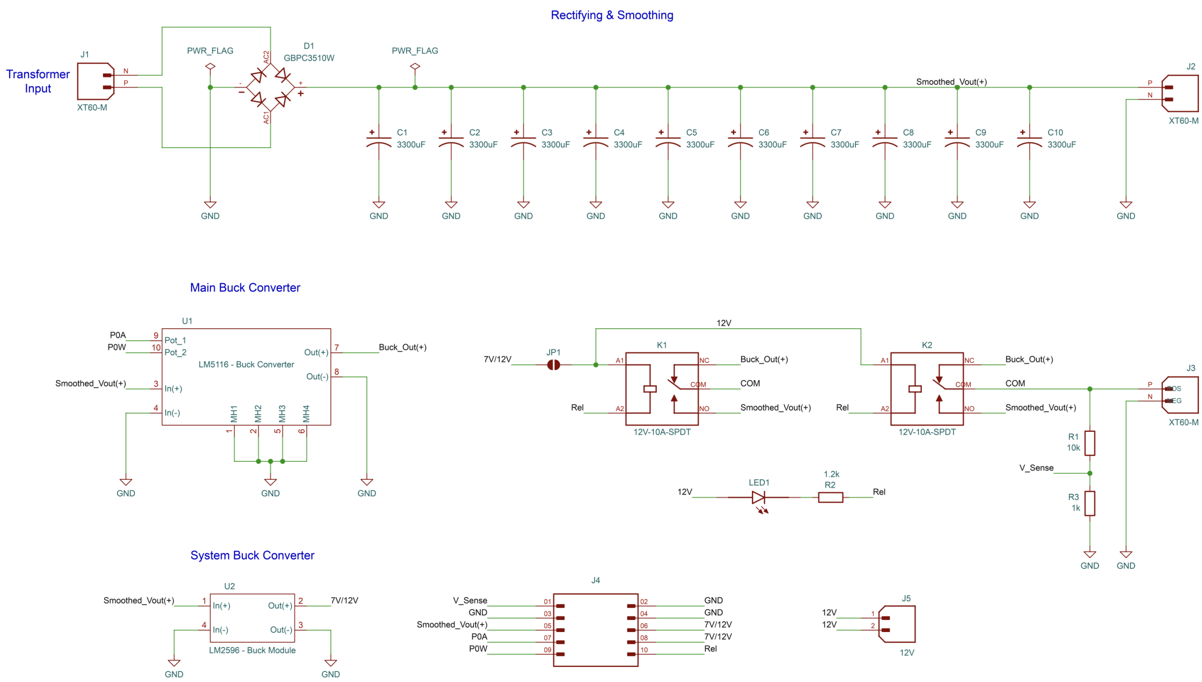


Figure 8.3: Power Distributor PCB - Schematic

AC to DC Conversion Analysis

The AC to DC conversion stage of the programmable bench power supply begins with stepping down the 230V AC mains input using a transformer, followed by rectification, filtering, and regulation. This section presents detailed calculations of voltage levels, power dissipation, and ripple characteristics.

Transformer Output

A 230V AC to 12-0-12V, 10A center-tapped transformer is used. The center tap is unused, effectively producing a 24V RMS secondary.

$$V_{\text{peak}} = V_{\text{RMS}} \times \sqrt{2} = 24 \times 1.414 = 33.94\,\text{V} \tag{8.1}$$

Bridge Rectifier Voltage Drop and Output Voltage

The bridge rectifier used is the C3510W [1], with a forward voltage drop of 1.1V per diode. Since two diodes conduct in each half-cycle:

$$V_{\text{drop}} = 2 \times 1.1 = 2.2\,\text{V} \tag{8.2}$$

$$V_{\text{DC, peak}} = V_{\text{peak}} - V_{\text{drop}} = 33.94 - 2.2 = 31.74\,\text{V} \tag{8.3}$$

Power Dissipation in Rectifier

At full load of 10A, power dissipation in the bridge is:

$$P_{\text{rectifier}} = V_{\text{drop}} \times I = 2.2 \times 10 = 22\,\text{W} \tag{8.4}$$

Filtering and Ripple Calculation

The smoothing stage consists of 10 electrolytic capacitors, each 3300μF, yielding:

$$C_{\text{total}} = 10 \times 3300\,\mu\text{F} = 33000\,\mu\text{F} = 0.033\,\text{F} \tag{8.5}$$

Ripple voltage for a full-wave rectifier at 100 Hz is given by:

$$V_{\text{ripple}} = \frac{I}{f \cdot C} = \frac{10}{100 \times 0.033} = 3.03\,\text{V} \tag{8.6}$$

DC Output Range After Filtering

The DC bus voltage will fluctuate between:

$$V_{\text{min}} = 31.74 - 3.03 = 28.71\,\text{V} \tag{8.7}$$

$$V_{\text{max}} = 31.74\,\text{V} \tag{8.8}$$

Summary Table

Table 8.1: AC-DC Stage Summary

Parameter	**Value**
Transformer Secondary RMS	24 V AC
Transformer Secondary Peak	33.94 V
Bridge Rectifier Drop	2.2 V
DC Bus Peak Voltage	31.74 V
DC Bus Min Voltage @ 10A	28.71 V
Ripple Voltage (P-P)	3.03 V
Filter Capacitance	33000 μF
Load Current	10 A
Bridge Rectifier Power Dissipation	22 W

Power Distributor PCB Functional Description

The **Power Distributor PCB** plays a central role in regulating and distributing power within the dual-channel programmable bench power supply. It integrates both the main high-current DC-DC power conversion stage and the auxiliary power supplies required by the internal system.

At the heart of this PCB is **U1** [2], a 20A-rated buck converter module that steps down the high-voltage DC bus (derived from the AC mains) to a programmable DC output. The output voltage of U1 is controlled digitally via programmable potentiometers, enabling software-defined output regulation.

To support high-output voltage operation, two relays, **K1** and **K2**, are connected in parallel with the buck converter. Controlled by the microcontroller, these relays bypass the buck converter and feed the rectified DC voltage directly to the downstream linear regulation stage, minimizing voltage drop and improving efficiency.

To monitor the buck converter's output voltage, a resistor divider network composed of **R1 (10 kΩ)** and **R2 (1 kΩ)** is used. This scales the voltage down by a factor of 11, ensuring that even the maximum output voltage (up to 30 V) is safely reduced to below 3.3 V—suitable for the microcontroller's ADC input.

Additionally, the PCB includes **U2** [3], a compact buck converter dedicated to generating two internal supply rails: **12 V and 7 V**. These regulated outputs are used to power various internal subsystems, including the controller unit, relay drivers, analog front-end circuits, and display interfaces.

All connections between the Power Distributor PCB and the Controller Unit are routed through a connector interface. This includes the **12 V and 7 V outputs**, **GND**, **V_Sense** (the scaled-down voltage from the resistor divider), **Rel** (the digital control signal for toggling K1/K2 relays), and **POW/POA** (the control lines for adjusting the digital potentiometers).

Overall, the Power Distributor PCB combines high-efficiency conversion, bypass flexibility, and intelligent voltage monitoring to support the power supply's programmable output functionality and reliable internal operation.

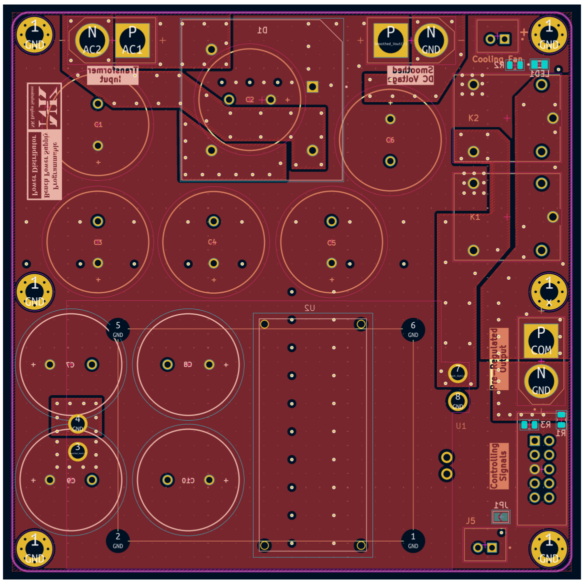


Figure 8.4: Power Distributor PCB Layout - Top Layer

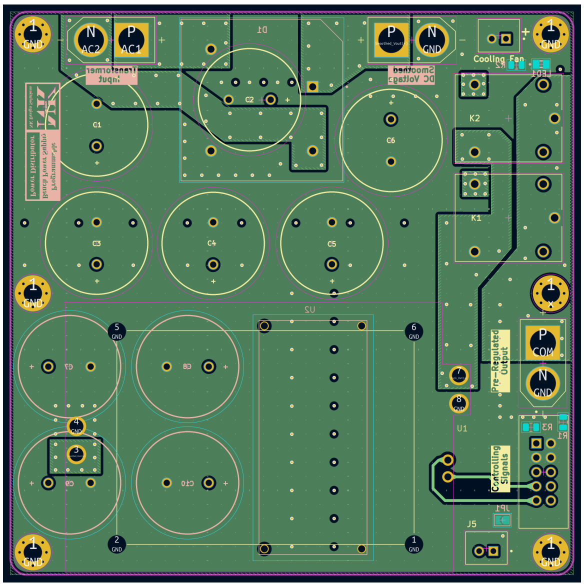


Figure 8.5: Power Distributor PCB Layout - Top Inner Layer

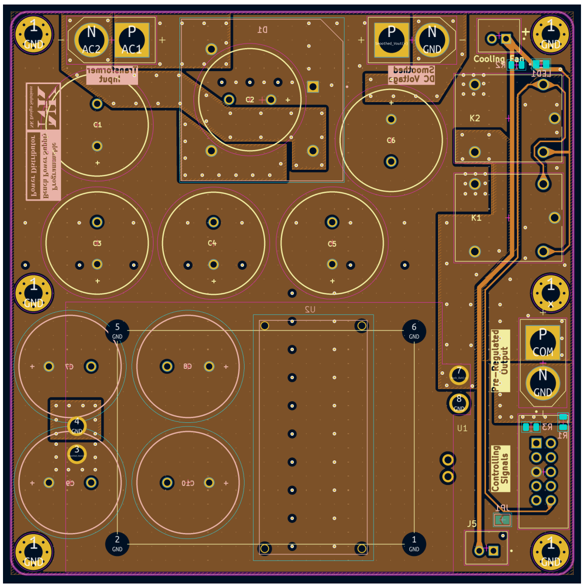


Figure 8.6: Power Distributor PCB Layout - Bottom Inner Layer

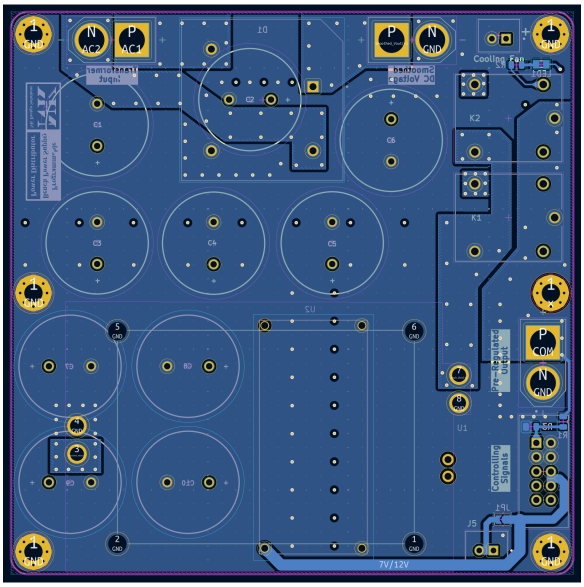


Figure 8.7: Power Distributor PCB Layout - Bottom Layer

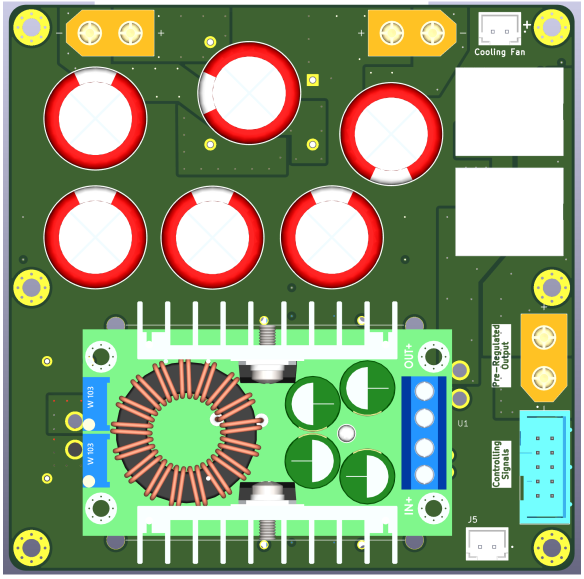


Figure 8.8: Power Distributor PCB 3D View - Top View

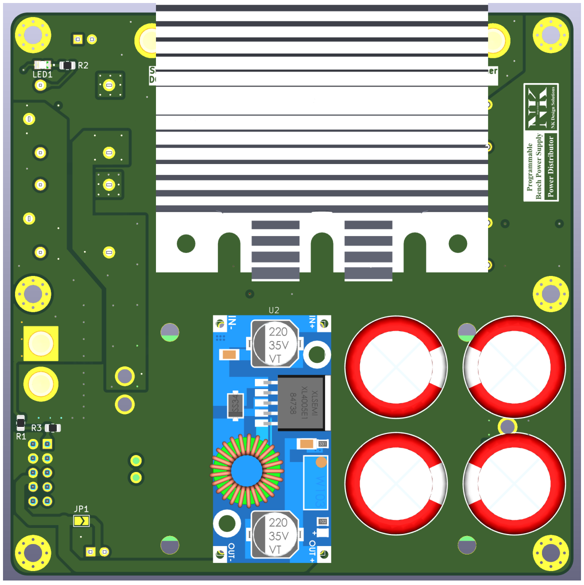


Figure 8.9: Power Distributor PCB 3D View - Bottom View

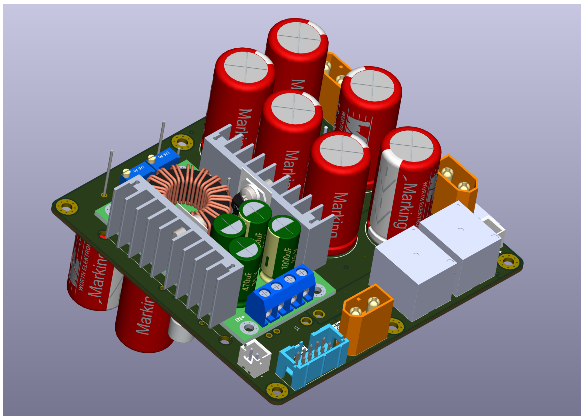


Figure 8.10: Power Distributor PCB 3D View - Side View 01

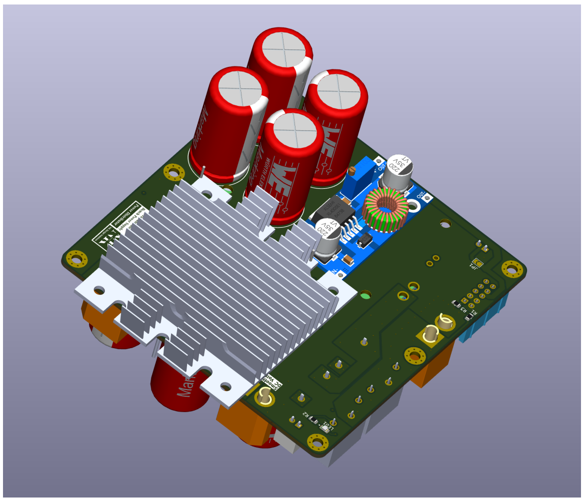


Figure 8.11: Power Distributor PCB 3D View - Side View 02

8.1.2 PCB 02 - Output Interface Circuit

The **Output Interface PCB** is a critical subsystem in each output channel of the programmable bench power supply, providing final-stage conditioning, linear regulation, monitoring, and noise suppression. Each of the two output channels in the system is supported by a dedicated Output Interface PCB, precise control, and modularity.

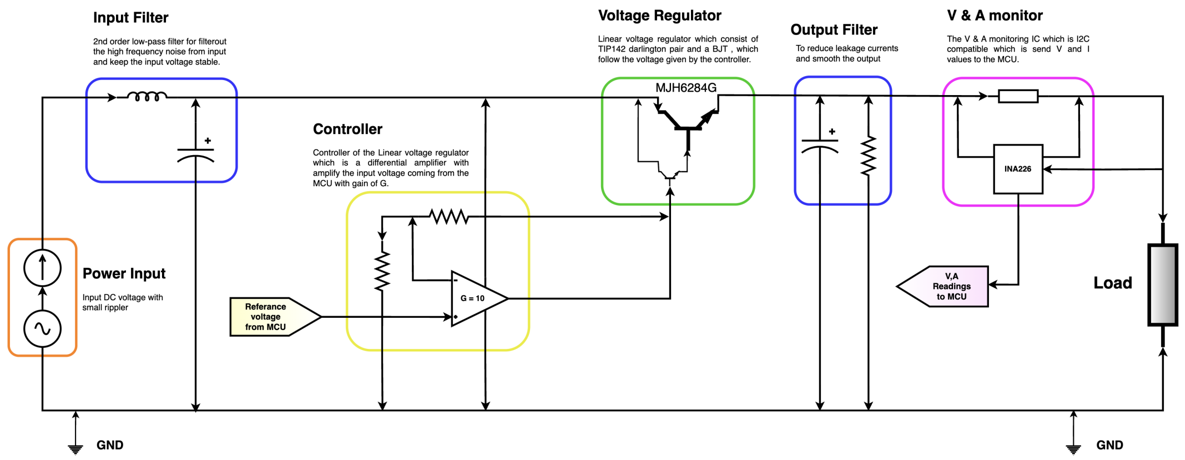


Figure 8.12: Output Interface PCB - Block Diagram

The input to the Output Interface PCB receives the regulated voltage from the Power Distributor PCB. To minimize residual switching noise and high-frequency artifacts from the buck stage, the input stage incorporates an **LC low-pass filter** designed for high current handling. This passive filtering improves voltage stability and ensures the output is suitable for powering sensitive electronic circuits.

Following the filter, the main regulation is performed by a **discrete linear regulator stage** using a high-current NPN BJT (MJH6284G) operating in emitter-follower configuration. The transistor is driven by a **non-inverting op-amp-based driver circuit**. The op-amp receives a reference voltage from a DAC output of the main controller and provides the necessary base current to the BJT to regulate the output voltage precisely. This linear stage operates in conjunction with firmware-based PID control, allowing real-time adjustment of the output voltage.

At the output terminal, a small **output ripple filter** is used, consisting of a **200 nF capacitor in parallel with a 20 kΩ resistor**. This network effectively attenuates minor voltage ripples and suppresses leakage currents, maintaining a clean DC output even under light or no-load conditions.

For output monitoring, both **voltage and current sensing** are handled by the **INA226 power monitoring IC**. The INA226 directly interfaces with the main microcontroller, digitizing voltage and current measurements. It uses the I^2C interface for communication with the microcontroller, providing real-time voltage and current data for dynamic regulation and protection functions. The voltage is sensed across a precision shunt resistor, and the current is monitored through the low-side path, both of which are directly monitored by the INA226.

This configuration enables each output to operate in constant voltage (CV) or constant current (CC) mode with high accuracy and stability. The Output Interface PCB thus plays a key role in delivering clean, programmable, and precisely monitored power to the load.

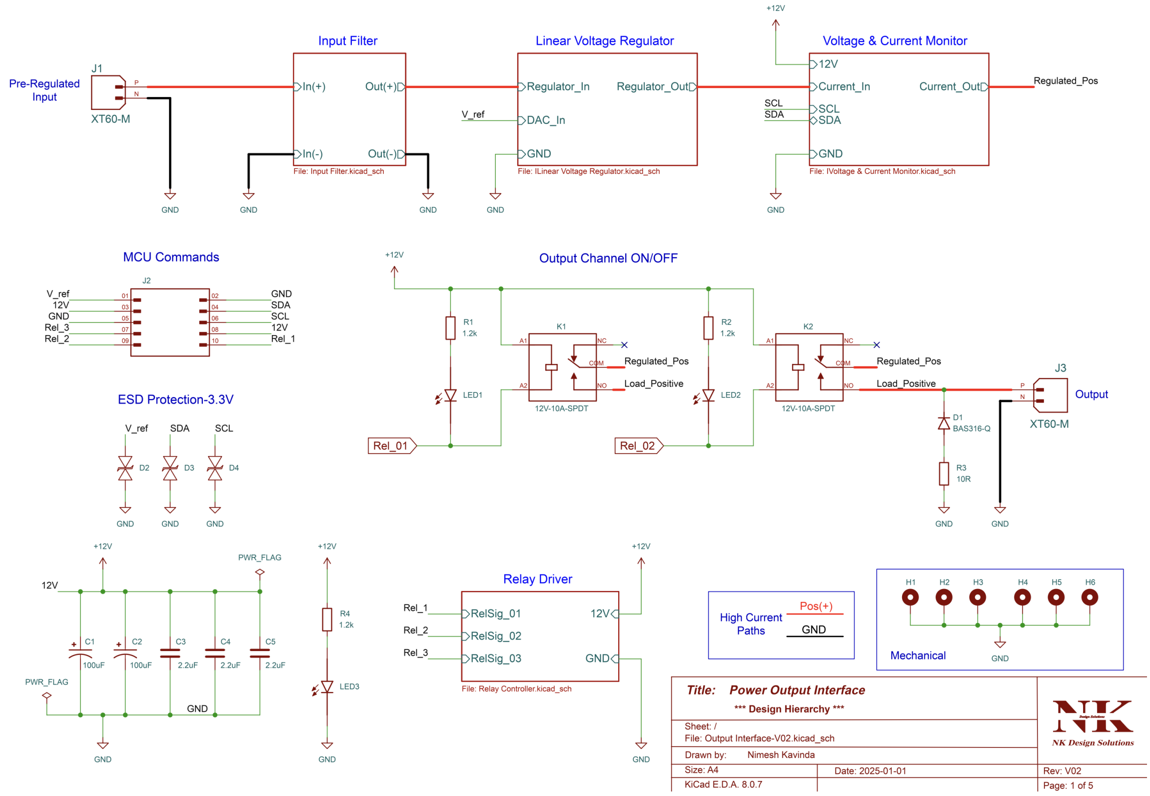


Figure 8.13: Output Interface Schematic - Hierarchical Design

This is the hierarchical design schematic of the **Output Interface** module. Connector **J1** receives the **pre-regulated voltage** from the main **buck converter** located on the **Power Distributor PCB**. The key functional blocks included in the schematic are the **input filter**, **linear voltage regulator**, and **voltage and current monitoring** section.

The **J2** connector interfaces with the **Controller Unit**, providing the following:

- A regulated **12 V power rail**
- A **reference voltage** from a DAC
- **I^{2}C communication lines** for the **INA226** voltage and current monitoring IC
- **Three digital control signals** for relay operation

The **J3** connector serves as the **power output** to the external load. Relays **K1** and **K2** are connected in **parallel** to increase the output current capacity and are used to switch the load **ON or OFF** under controller command.

Capacitors **C1 to C5** are **smoothing capacitors** placed on the 12 V power rail to filter voltage ripple and ensure stable operation. This 12 V supply is sourced from the Controller Unit.

A dedicated **relay driver block** is implemented to drive the relay coils using the digital control signals provided by the Controller Unit.

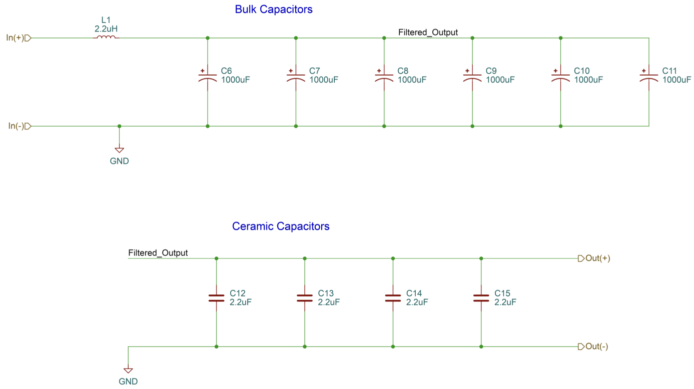


Figure 8.14: Output Interface Schematic - Second order Low pass Filter

In the schematic, a **second-order low-pass filter** is implemented, consisting of a 20 A rated power inductor and a combination of capacitors: 6000 µF / 50 V electrolytic capacitors and 2.2 µF ceramic capacitors. The filter is designed to suppress high-frequency noise present in the DC output of a power supply or converter stage. The large electrolytic capacitor provides substantial charge storage to maintain voltage stability, while the smaller ceramic capacitor ensures effective high-frequency decoupling due to its low equivalent series resistance (ESR) and inductance.

To evaluate the performance of this filter, a **MATLAB simulation** was performed. A noisy voltage signal was used as the input to model a typical output from a switching regulator. The filter's output was then analyzed, demonstrating significant attenuation of high-frequency components and a much cleaner DC voltage. This confirms the filter's effectiveness in smoothing transient spikes and reducing ripple, thereby ensuring a stable output suitable for sensitive analog or digital circuitry.

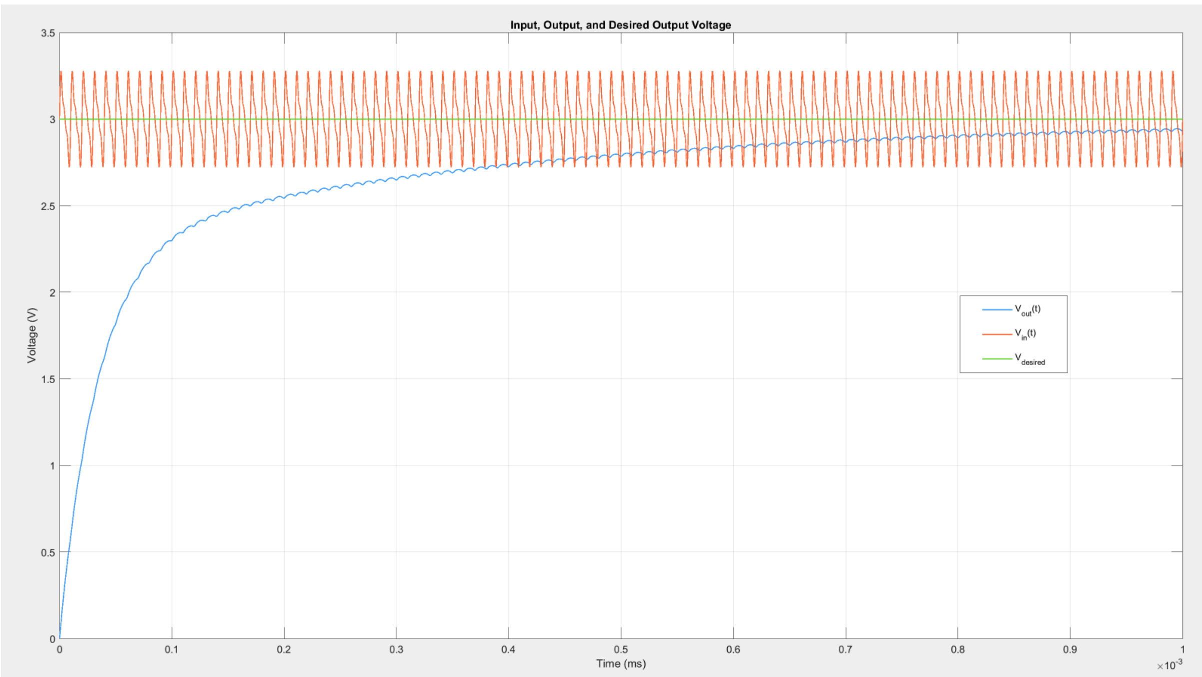


Figure 8.15: LPF Simulation Transient Analysis - 0 to ms

```matlab
% /////    Low Pass Filter for Output Side of the Buck Converter   ///// %

%%%%%%%%%%%%%%%%%%%%%%%%%  Component Parameters  %%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%   Inductor  %%%%
L = 2.20e-6;                                 %  Inductance (H)
R_L =  0.02 ;                                %  Series Resistance of Inductor (Ohm)

%%%%   Capacitors  %%%%
C = 6*1000e-6 + 4*2.2e-6;                    %  Capacitance (F)
R_C = 0.05 ;                                 %  Series Resistance of Capacitor (Ohm)

%%%%  Connected Load  %%%%
Load = 10 ;                                  % Load Resistance

% Input Signal Parameters
Set_DC_Voltage = 3;                          % Set Output DC voltage Value
Noise_freq = 100e3;                          % Noise frequency in hertz
Noise_max_Voltage = 200;                     % Maximum noise voltage in milivolt

% Time interval of the Graphs
Start_time = 20;                             % Start Time in miliseconds
End_time = 20.1;                             % End Time in miliseconds
Resolution = 100000;                         % Samples per milisecond
```

Figure 8.16: Matlab Code - Parameters

```matlab
% Define Time-t and s-laplace
syms s t;

% Define input voltage in time-domain
V_In_t =  Set_DC_Voltage  + (Noise_max_Voltage/1000)*sin(2*pi*Noise_freq*t)
                          + (Noise_max_Voltage/2000)*sin(4*pi*Noise_freq*t)
                          + (Noise_max_Voltage/4000)*sin(6*pi*Noise_freq*t);

% Get laplace of V_In
V_In_S = laplace(V_In_t , t, s);

% Transfer Function
Z_L_S =  R_L +  (s * L)  ;
Z_C_S = R_C + (1/(s * C)) ;
Z_LOAD_S = Load ;

H_S = ( (Z_C_S * Z_LOAD_S)/(Z_C_S + Z_LOAD_S) )  /  ( ((Z_C_S * Z_LOAD_S)/(Z_C_S + Z_LOAD_S)) + Z_L_S) ;

V_Out_S   = V_In_S * H_S ;

% Get the inverse laplace of V_Out
V_Out_t = ilaplace(V_Out_S, s, t);

t = Start_time/1000:1/(Resolution*1e3):End_time/1000;        % Define range of time

V_Out_numeric = matlabFunction(V_Out_t);                     % Convert to numeric function
V_In_numeric = matlabFunction(V_In_t);                       % Convert to numeric function

Vt_Out = V_Out_numeric(t);
Vt_In = V_In_numeric(t);
V_Desired = Set_DC_Voltage + t*0;

plot(t, Vt_Out, t, Vt_In, t, V_Desired);
xlabel('Time (ms)');
ylabel('Voltage (V)');
legend('V_{out}(t)', 'V_{in}(t)', 'V_{desired}');
title('Input, Output, and Desired Output Voltage');
grid on;
```

Figure 8.17: Matlab Code - Equations

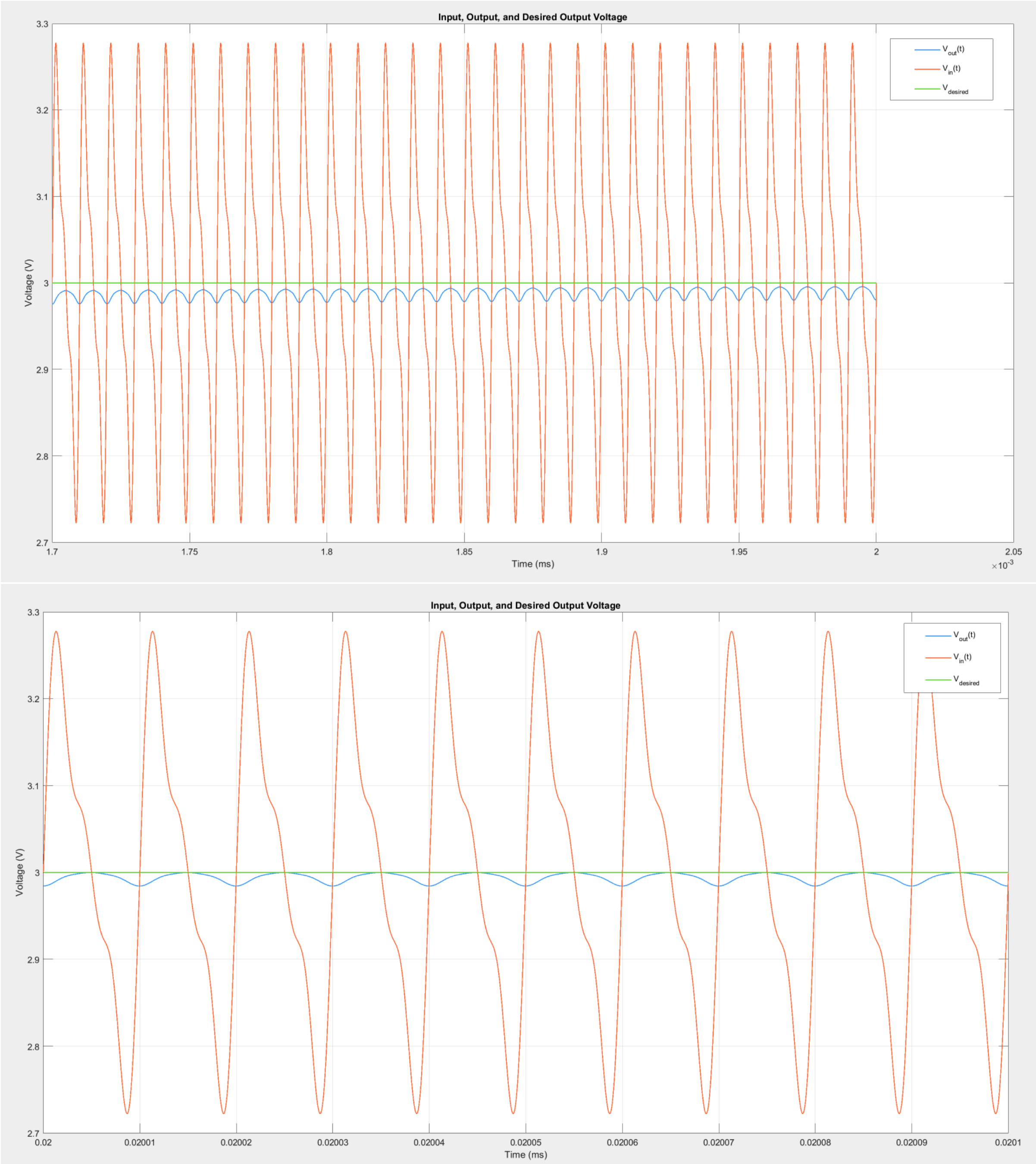


Figure 8.18: LPF Simulation Transient Analysis - Output Voltage , Input Voltage and Desired Voltage

The output low-pass filter is modeled as a second-order passive LC network comprising a series inductor and a parallel capacitor-load branch. The inductor, with an inductance of 2.2 µH and a series resistance of 20 mΩ, introduces frequency-dependent impedance that blocks high-frequency components. The output capacitance, totaling approximately 6009 µF (from multiple electrolytic and ceramic capacitors in parallel), smoothens voltage fluctuations and is modeled with a series resistance of 50 mΩ to account for equivalent series resistance (ESR).

The input voltage is defined as a composite of a 3 V DC value and superimposed sinusoidal disturbances at 100 kHz, 200 kHz, and 300 kHz, simulating switching noise typically present in buck converter outputs. These are added as harmonic sine functions with progressively decreasing amplitudes (200 mV, 100 mV, and 50 mV, respectively).

The analysis proceeds by expressing the total input voltage in the Laplace domain, then formulating the filter's transfer function $H(s)$ using impedance relations. The inductor impedance is $Z_L(s) = R_L + sL$, while the output branch impedance is the parallel combination of the capacitor impedance $Z_C(s) = R_C + \frac{1}{sC}$ and the resistive load $R_{\text{load}} = 10\ \Omega$. The total transfer function becomes:

$$H(s) = \frac{Z_C(s) \parallel R_{\text{load}}}{Z_C(s) \parallel R_{\text{load}} + Z_L(s)}$$

This transfer function is then multiplied with the Laplace-transformed input voltage to derive the output voltage in the Laplace domain. The final time-domain expression of the output voltage is obtained by taking the inverse Laplace transform of the resulting expression. This output is evaluated over a short time window to assess the filter's effectiveness in attenuating the AC noise components, confirming that the output closely follows the desired 3 V DC level with minimal ripple.

Linear Voltage Regulation

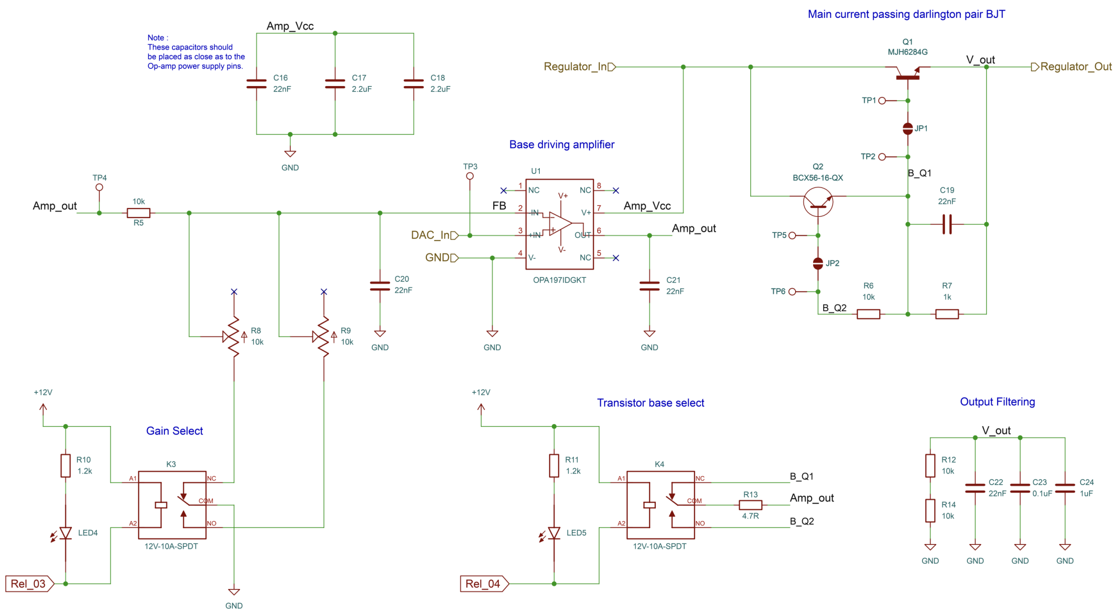


Figure 8.19: Output Interface Schematic - Linear Voltage Regulator

In the linear voltage regulator schematic, **Q1 (MJH6284G)** [4]serves as the main pass transistor responsible for regulating the output voltage by dropping the excess input voltage. Since the regulator must support output currents up to 10 A continuously, the power BJT was selected with careful consideration of its maximum collector current rating, power dissipation, thermal resistance, current gain (h_{FE}), and Safe Operating Area (SOA) characteristics. The MJH6284G was chosen due to its high current handling capability, TO-247 package for better thermal management, and robust SOA at elevated voltages and currents, making it ideal for linear mode operation in a programmable power supply.

To ensure that Q1 receives sufficient base current, especially under high-load conditions, a secondary BJT, **Q2 (BCX56-16-QX)** [5], is used as a base driver. This BJT was selected based on its high current gain, fast switching capability, low saturation voltage, and good thermal stability. These features make it suitable for driving high-current BJTs like MJH6284G with minimal base drive limitations. Its SOT-89 package also offers a compact form factor with acceptable thermal performance for this role.

The control signal is provided by **U1**, a non-inverting operational amplifier that regulates the output voltage based on a programmable reference from the DAC output of the MCU. In this design, the **OPA197** [6]op-amp is used. The OPA197 was selected due to its precision characteristics, including ultra-low input offset voltage (as low as $25\,\mu$V), low offset drift, and rail-to-rail output, which are essential for accurate and consistent voltage regulation. Its high common-mode rejection and wide supply voltage range (4.5 V to 36 V) make it suitable for single-supply operation in power management applications. Moreover, its output drive capability is adequate to source base current directly for Q1 during light load, or via Q2 under heavier load.

The gain of the amplifier stage is configured using a feedback network consisting of resistors **R8** and **R9**, while **R2** is a selectable resistor that can be toggled in or out via relay **K3**. This arrangement enables programmable gain control to accommodate different output voltage modes (e.g., 0–6 V or 0–24 V). The use of the relay and selectable resistors offers flexibility in response to mode switching controlled by the firmware.

Additionally, relay **K4** is used to bypass the base driver transistor Q2 during low current operation. This feature enhances output voltage precision by eliminating the base-emitter drop of Q2 when it is unnecessary. During low load conditions, the op-amp output is directly connected to the base of Q1, resulting in improved linearity and tighter regulation.

This integrated design strategy ensures that each active component is optimally chosen based on the electrical and thermal demands of the circuit. The result is a stable, efficient, and programmable linear regulator capable of meeting the high-performance requirements of the bench power supply.

Key Requirements for Component Selection

- Accurate voltage regulation across multiple output ranges (e.g., 0–6 V and 0–24 V).
- Continuous current output capability up to 10 A.
- Fast transient response with minimal output ripple.
- Thermally safe operation within SOA constraints.
- Compact design using readily available, cost-effective components.

Parameter	**MJH6284G**	**TIP142**	**BDW93C**	**MJ11015**
Collector Current (Ic max)	20 A	10 A	12 A	30 A
Collector-Emitter Voltage (V_{CEO})	100 V	100 V	100 V	120 V
DC Gain (hFE) @ Ic=5A	750	1000	750	1000
Power Dissipation (Ptot)	160 W	125 W	90 W	200 W
$V_{CE(sat)}$ @ Ic=10A	2 V	2.5 V	2 V	2 V
Package	TO-247	TO-218	TO-220	TO-3
Cost (approx.)	\$5.07	\$2.20	\$1.45	\$6.50
Parameter Evaluation (Marks out of 10)				
Collector Current Capability	9	6	7	10
Voltage Rating	8	8	8	9
Current Gain	8	10	8	10
Thermal Power Handling	9	8	6	10
Saturation Voltage	8	6	8	8
Cost	8	9	10	2
Total Score (out of 60)	**50**	47	47	49

Table 8.2: Comparison of Darlington Power BJTs for Output Linear Regulation Stage

Parameter	**BCX56-16-QX**	**BC817-40**	**2N2222A**	**MPSA06**
Max Collector Current (Ic)	1.5 A	0.5 A	0.8 A	0.5 A
DC Gain (hFE @ 500mA)	100–250	160–400	75–300	100
Power Dissipation (Ptot)	830 mW	625 mW	500 mW	625 mW
$V_{CE(sat)}$ @ Ic=500mA	0.5 V	0.6 V	1.0 V	0.3 V
Package	SOT-89	SOT-23	TO-18	TO-92
Cost (approx.)	\$0.28	\$0.10	\$0.15	\$0.09
Parameter Evaluation (Marks out of 10)				
Ic Capability	10	6	7	6
Current Gain	8	9	7	6
Power Dissipation	9	7	6	7
Saturation Voltage	7	6	3	9
Footprint / Package Practicality	9	10	5	6
Cost	7	9	8	10
Total Score (out of 60)	**50**	47	36	44

Table 8.3: Comparison of Medium Current BJTs for Op-Amp to Darlington Base Drive Buffer

Electrical Characteristics Comparison				
Parameter	**OPA197 (DGKT)**	**TLV2371**	**LM358**	**OPA2333**
Supply Voltage Range (V)	± 2.25 to ± 18	2.7 to 16	3 to 32	1.8 to 5.5
Output Current Drive (mA)	65	60	40	10
Input Offset Voltage (µV)	25	1500	3000	10
Slew Rate (V/µs)	20	3	0.3	0.3
Gain Bandwidth (MHz)	10	3	1.1	0.35
Package Type	VSSOP-8	SOT-23-5	SOIC-8	VSSOP-8
Cost (approx.)	$1.50	$0.60	$0.20	$2.76
Parameter Evaluation (Marks out of 10)				
Metric	**OPA197**	**TLV2371**	**LM358**	**OPA2333**
Output Drive Capability	10	9	6	2
Low Offset Voltage	9	3	1	10
Slew Rate	10	5	2	2
Gain Bandwidth	9	6	3	1
Voltage Range Flexibility	9	8	8	5
Cost	7	8	10	4
Total Score (out of 60)	**54**	39	30	24

Table 8.4: Technical Comparison of Op-Amps for Base Drive Application

All active components were analyzed and rated based on these requirements. Power BJTs were compared on their collector current, power dissipation, current gain, and SOA. The OPA197 op-amp was chosen after evaluating various candidates on output swing, input offset voltage, bandwidth, and load drive capability. Driver BJTs were examined for gain, saturation performance, and switching speed. The detailed selection tables summarize these results and guided the final component choices for the regulator design.

Voltage and Current Measuring with INA226

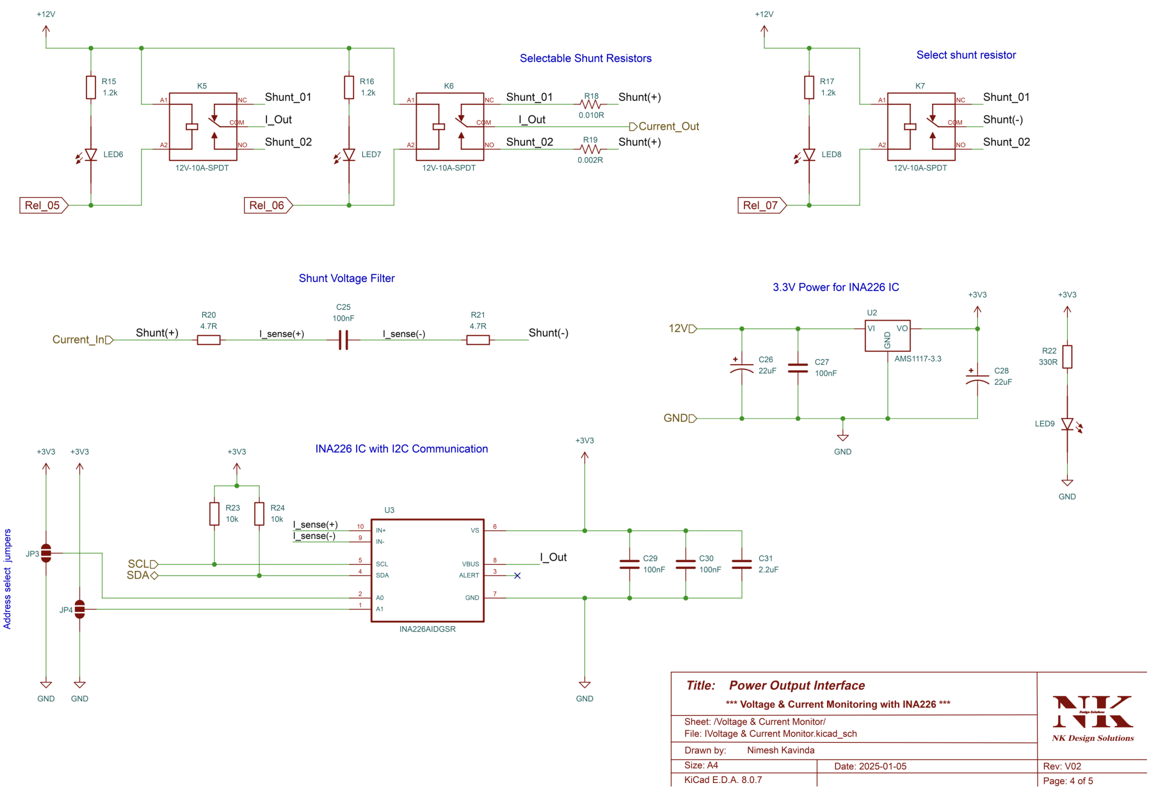


Figure 8.20: Output Interface Schematic - Voltage and Current Measuring with INA226

In the current and voltage sensing stage of the design, the **INA226** [7] (U3) is employed as the primary measurement IC. It is a high-precision digital power monitor with an I^2C interface, capable of measuring both shunt voltage and bus voltage, and reporting calculated current and power values to the microcontroller. The device is powered by a dedicated 3.3 V regulator, **U2 (AMS1117-3.3)**, rather than relying on the MCU supply rail. This approach helps to minimize digital noise coupling and improves the measurement accuracy, especially under varying load conditions.

To support a wide dynamic current measurement range, two shunt resistors are connected in parallel and selected via **K5** and **K6**, which are relays controlled by the MCU. Depending on the current demand, the MCU activates one of the relays to switch in the appropriate shunt resistor with optimized resistance for accurate measurement and minimal power loss. This technique allows the system to balance between resolution at low currents and thermal performance at high currents.

Additionally, relay **K7** is used to switch the voltage sensing path corresponding to the selected shunt resistor. This ensures that the INA226 always receives the correct differential input from the active current sensing path, maintaining measurement integrity regardless of the selected range.

To select the most suitable current and voltage monitoring IC for this application, several candidates were evaluated based on criteria such as input voltage range, current sensing capability, resolution, interface protocol, power consumption, and cost. The **INA226** was ultimately chosen for its integrated power calculation functionality, high-resolution ADC, wide input common-mode voltage range, and reliable I^{2}C communication. The results of this evaluation are summarized in the following comparison table.

Parameter	**INA226**	**INA219**	**MAX34407**
Max Sense Voltage	36 V	26 V	26 V
Max Measurable Current	36 A	12 A	10 A
Voltage Measurement Range	0–36 V	0–26 V	0–26 V
Shunt Resistance Range	0.1–2 Ω	0.1–1 Ω	0.001–2 Ω
Voltage Accuracy	0.05%	0.1%	0.05%
Current Accuracy	0.1%	0.1%	0.05%
Interface	I^{2}C	I^{2}C	I^{2}C
Supply Voltage	2.7–5.5 V	2.7–5.5 V	2.7–5.5 V
Temp. Range	–40°C to +125°C	–40°C to +125°C	–40°C to +125°C
Package	SOIC-8	SOIC-8	TSSOP-14
Cost (approx.)	$2.31	$2.03	$10.49
Evaluation Scores (Out of 10)			
Current Measurement	9	6	7
Voltage Range	9	8	8
Accuracy	9	7	9
Shunt Flexibility	8	7	9
Temperature/Supply	10	10	10
Cost	8	9	2
Total Score (Out of 60)	**53**	47	45

Table 8.5: Feature and Performance Comparison of Current/Voltage Monitoring ICs

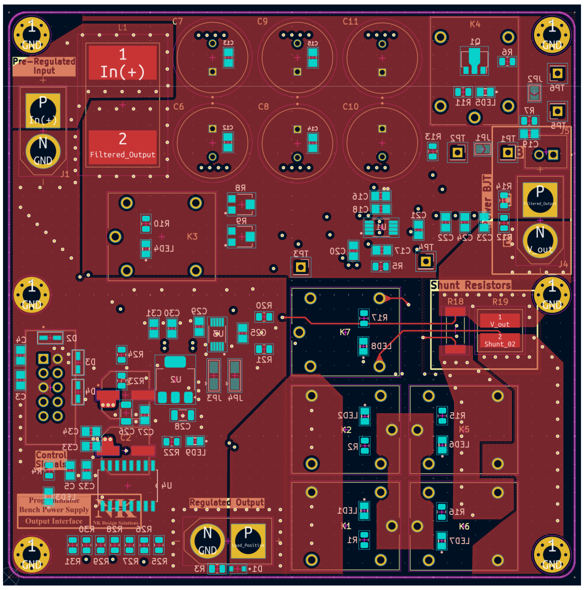


Figure 8.21: Output Interface PCB Layout - Top Layer

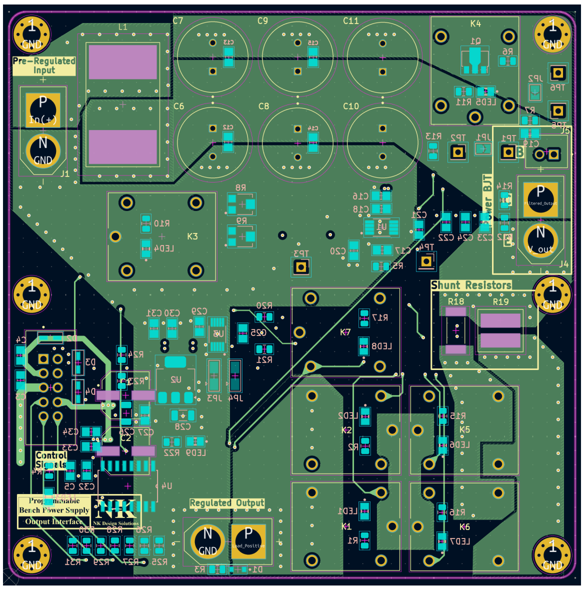


Figure 8.22: Output Interface PCB Layout - Top Inner Layer

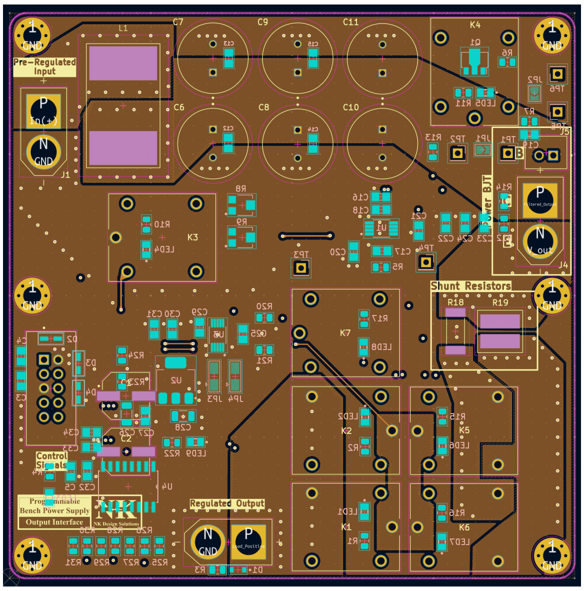


Figure 8.23: Output Interface PCB Layout - Bottom Inner Layer

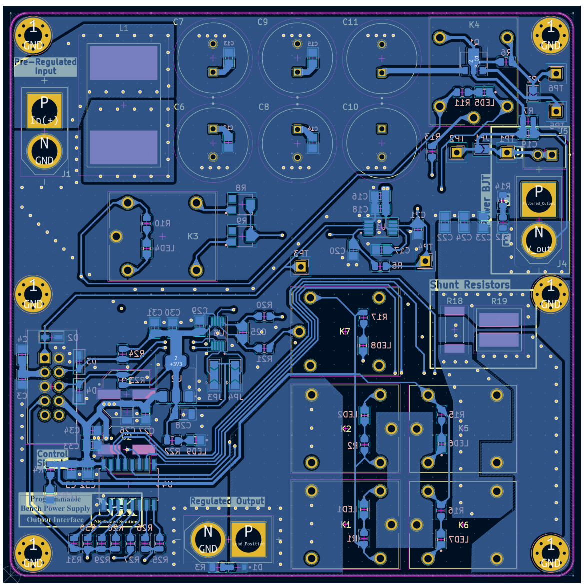


Figure 8.24: Output Interface PCB Layout - Bottom Layer

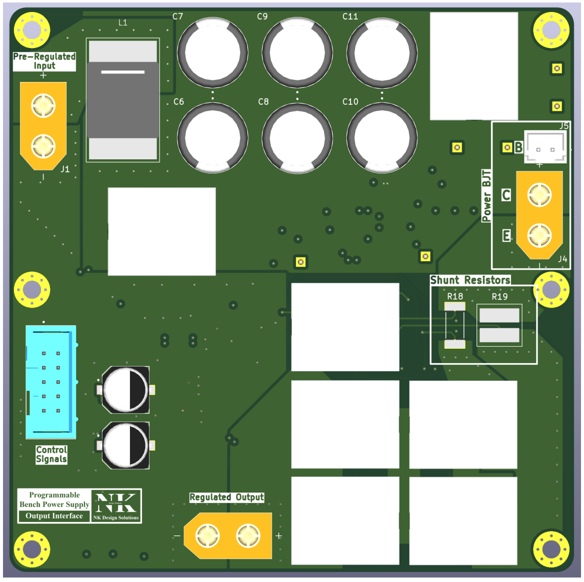


Figure 8.25: Output Interface PCB 3D View - Top View

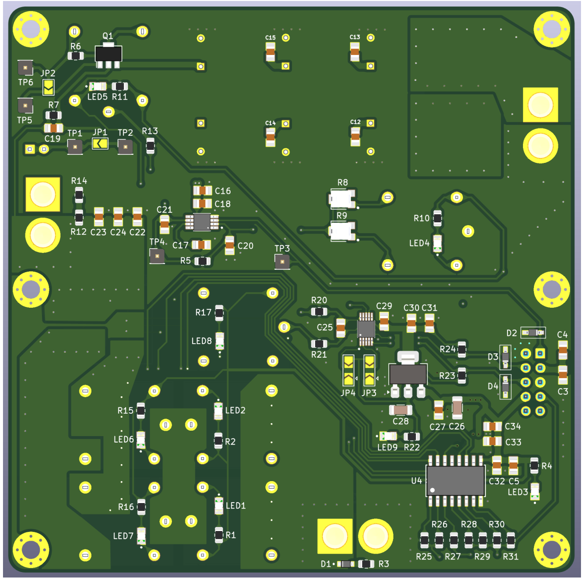


Figure 8.26: Output Interface PCB 3D View - Bottom View

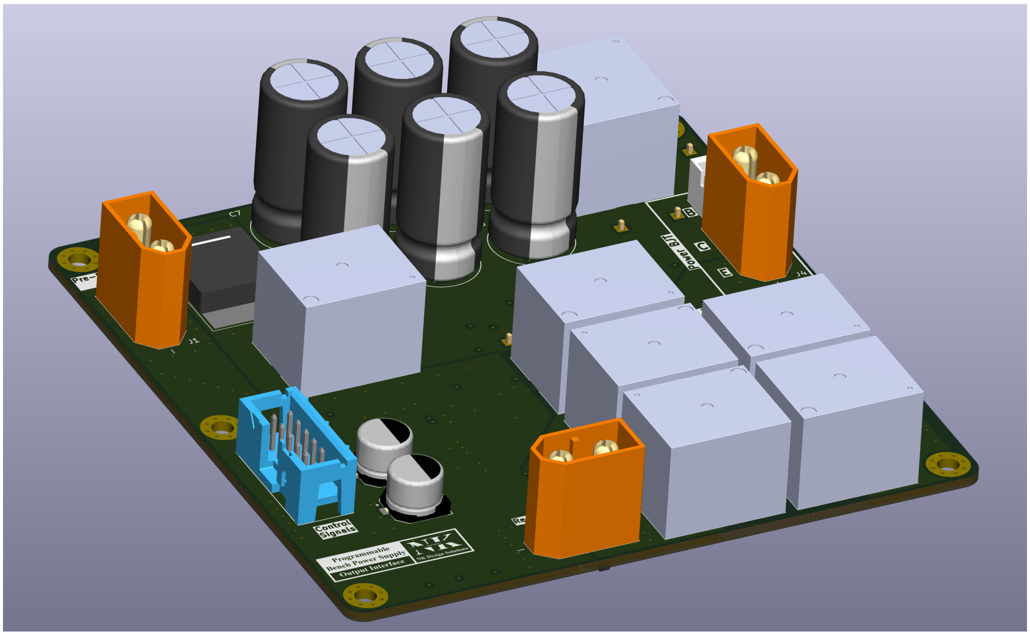


Figure 8.27: Output Interface PCB 3D View - Side View

8.1.3 PCB 03 - Controller Unit

The Controller Unit PCB acts as the central control platform for the programmable bench power supply system. It integrates all critical peripherals, connectors, regulators, and communication lines required for seamless operation. At the heart of this unit is the **STM32H743 development board**, which is chosen for its high-performance processing, extensive peripheral support, and native USB interface.

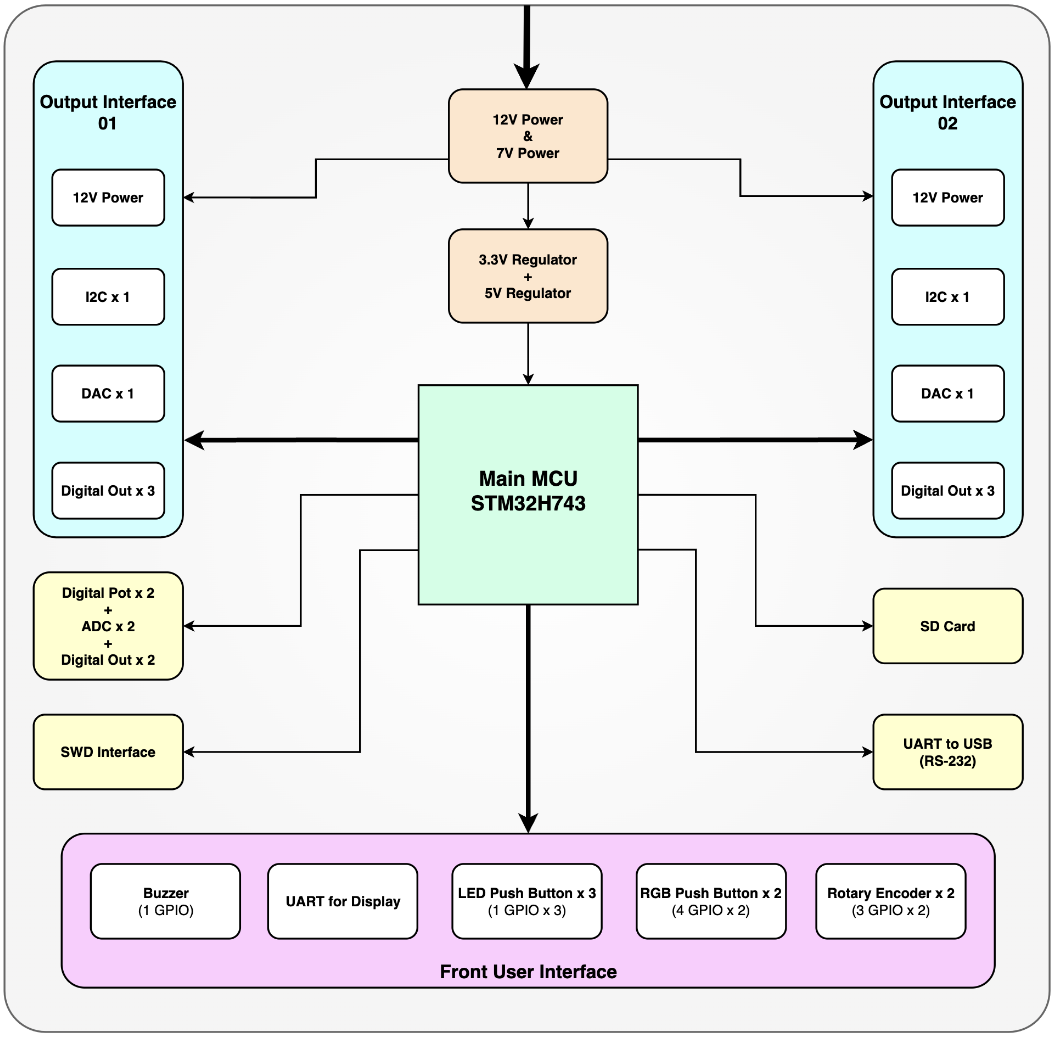


Figure 8.28: Controller Unit PCB - Block Diagram

Powering the controller board is achieved by deriving a regulated 5 V rail from an incoming 7 V power line, which originates from the Power Distributor Board. A dedicated 5 V Low Dropout (LDO) regulator is used to ensure a clean and stable supply to the development board, protecting the system from transients and supply ripple.

Each Output Interface Module connected to the system is provisioned with one I^2C line for sensor or peripheral communication, one DAC channel for analog control, three digital output lines to drive relays or switches, and a 12 V power rail for higher voltage components. These outputs allow the microcontroller to configure and manage each channel independently.

The Power Distributor Boards receive one ADC input for voltage or current monitoring, one digital output line for switching or control purposes, and an SPI connection for communicating with a digital potentiometer. This setup allows dynamic feedback control and precise adjustment of regulation parameters.

To power the touchscreen display, another 5 V LDO is deployed, drawing its input from the same 7 V rail. This isolation ensures that the touch interface receives a stable voltage source, free from noise generated by the digital logic of the microcontroller. Communication with the touchscreen is established via a dedicated UART line, isolating it from other peripheral buses for increased reliability.

Approximately 20 general-purpose I/O (GPIO) lines from the STM32H743 are allocated for auxiliary functionalities such as user interaction and status indication. These include connections for a buzzer, rotary encoders, push buttons, RGB LEDs, and standard indicator LEDs, providing a rich human-machine interface.

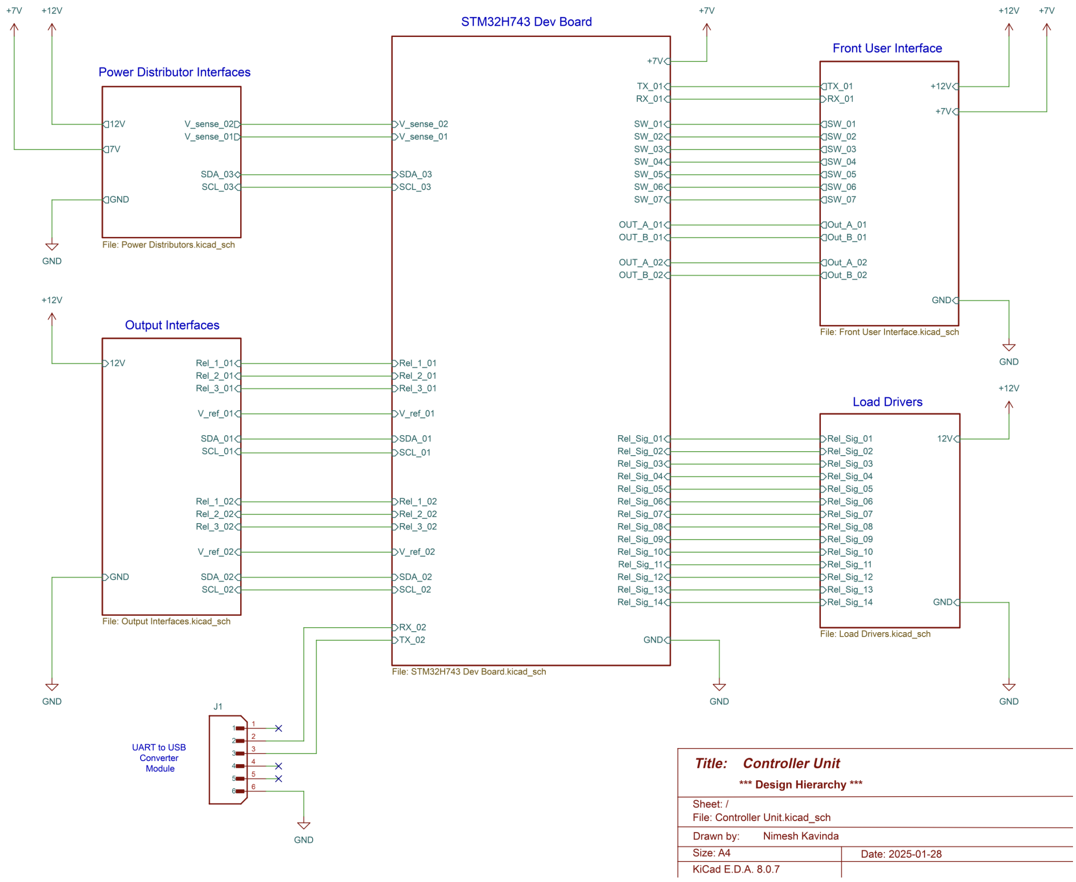


Figure 8.29: Controller Unit Schematic - Design hierarchy

The design also directly utilizes the built-in SWD (Serial Wire Debug) and SD card interfaces available on the development board. These features support efficient firmware debugging and enable onboard data logging, respectively. Additionally, the STM32H743's built-in USB peripheral is employed to communicate with a PC, supporting USB CDC for virtual COM port operation or other custom USB protocols as required.

This architecture ensures reliable operation and provides flexibility in expansion, making it well-suited for a high-performance programmable power supply with advanced control, feedback, and user interaction capabilities.

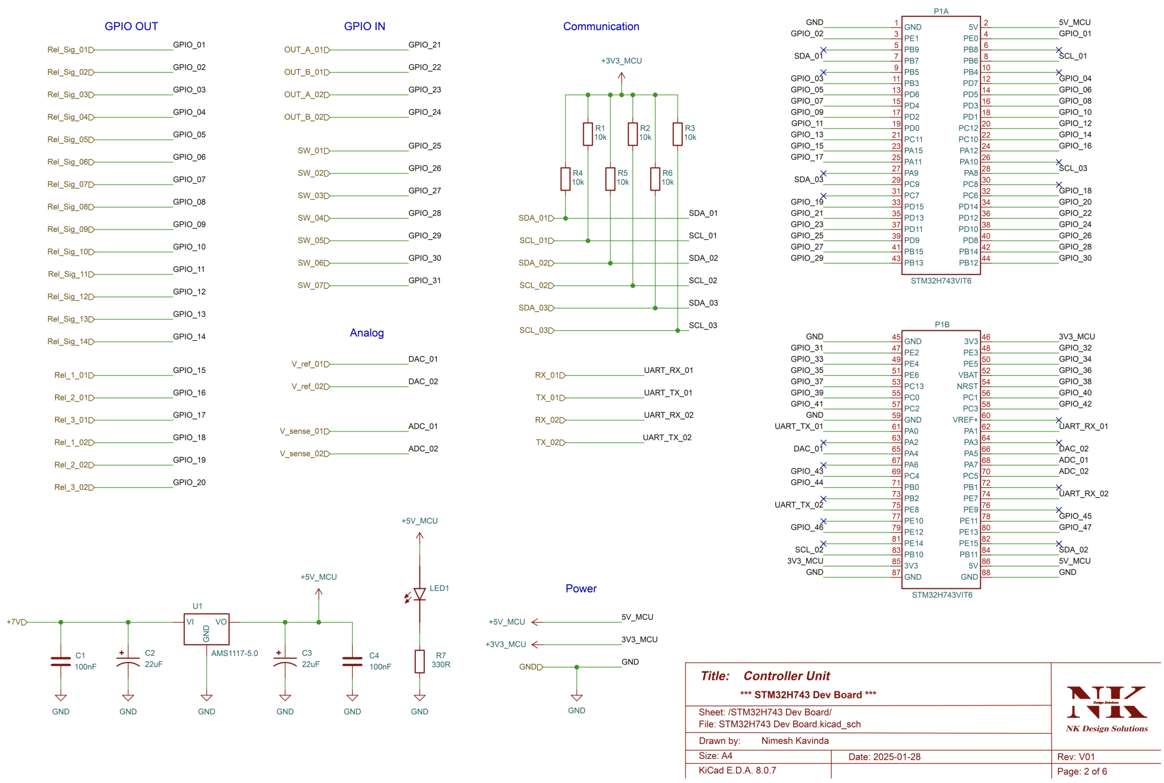


Figure 8.30: Controller Unit Schematic - STM32H743 Dev Board and Peripherals

This schematic illustrates how the peripherals are interfaced with the STM32H743 development board. The power for the development board is supplied through a dedicated 5 V Low Dropout (LDO) regulator, denoted as **U1**, which derives its input from a 7 V rail coming from the Power Distributor Board. This regulator ensures stable and noise-free power delivery to the digital core of the system.

To ensure reliable I^{2}C communication, pull-up resistors **R1–R6** are used on the SDA and SCL lines of the multiple I^{2}C buses. These resistors are carefully selected in value to balance the trade-off between speed and signal integrity, depending on the total bus capacitance and desired I^{2}C clock rate.

In selecting the main microcontroller unit (MCU) for this project, several STM32 families and variants were considered. The decision was based on a detailed comparison of processing performance, peripheral availability, memory size, ADC/DAC resolution and speed, communication interfaces (I^{2}C, SPI, UART, USB, CAN), and real-time control features. The system also required a fast internal clock, multiple high-resolution timers, and support for high-speed USB communication with a host PC.

Based on these requirements, the **STM32H743** [8]MCU was selected as the central controller. It features a high-performance ARM Cortex-M7 core running at up to 480 MHz, ample Flash and RAM, multiple high-speed ADCs and DACs, and extensive peripheral support including I^{2}C, SPI, UART, CAN-FD, USB OTG, and more. Its high-speed operation and large number of GPIOs made it ideal for managing the multiple Output Interface Boards, Power Distributor Boards, analog feedback systems, and user interface modules such as the touchscreen.

The following table presents a comparative analysis of various STM32 microcontrollers.

Parameter	**STM32H743**	**STM32F411**	**STM32F103**
Core Architecture	Cortex-M7	Cortex-M4	Cortex-M3
Max CPU Clock Speed	480 MHz	100 MHz	72 MHz
Flash Memory	2 MB	512 KB	128 KB
RAM	1 MB	128 KB	20 KB
I/O Pins	168	51	37
ADC Channels	24	16	10
DAC Channels	2	1	1
SPI Interfaces	6	4	3
I2C Interfaces	3	2	2
UART Interfaces	4	3	1
USB Support	USB FS	USB FS	No USB
DMA Channels	16	7	7
Operating Voltage	1.8 V to 3.6 V	2.0 V to 3.6 V	2.0 V to 3.6 V
Cost (approx.)	$9.50	$5.00	$2.00
Evaluation Scores (Out of 10)			
Core Architecture	10	7	5
Max CPU Clock Speed	10	6	4
Flash Memory	10	7	3
RAM	10	5	2
I/O Pins	10	6	4
ADC Channels	10	8	6
DAC Channels	10	6	6
SPI Interfaces	10	7	6
I2C Interfaces	10	8	6
UART Interfaces	10	8	4
USB Support	8	8	0
DMA Channels	10	7	7
Operating Voltage	8	8	8
Cost	5	8	10
Total Score	**129**	**89**	**67**

Table 8.6: Feature and Performance Comparison of STM32H743, STM32F411, and STM32F103 based on PS project requirements

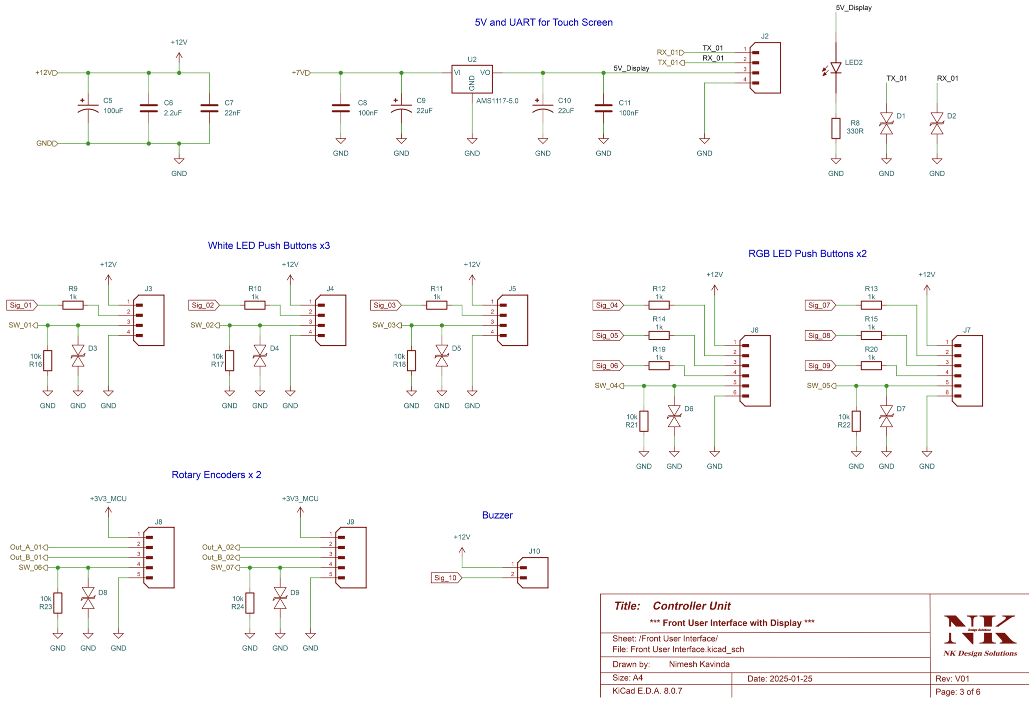


Figure 8.31: Controller Unit Schematic - User Interface Connectors

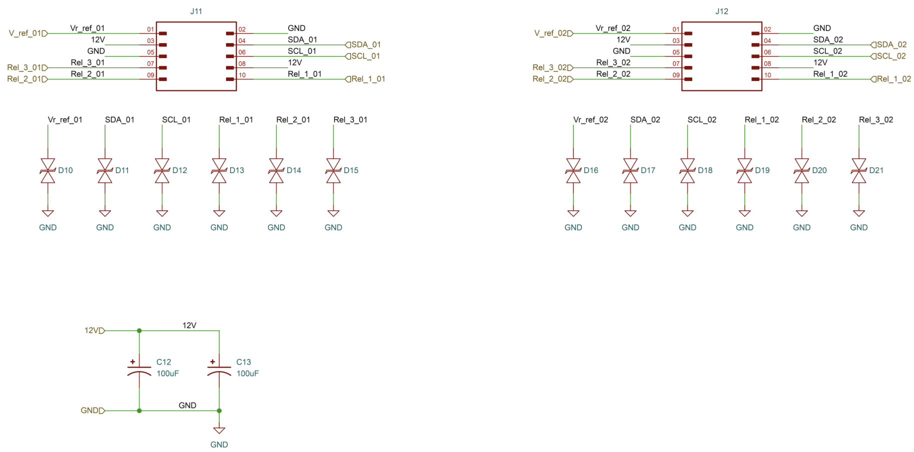


Figure 8.32: Controller Unit Schematic - Output Interface Connectors

The two schematics shown above illustrate the output connector configurations for both the User Interface and the Output Interface. In these designs, Electrostatic Discharge (ESD) protection is implemented using **TVS (Transient Voltage Suppression) diodes** to safeguard sensitive components from high-voltage transients that may occur due to human handling or external disturbances. Since these interfaces are directly accessible and frequently interacted with during normal operation, robust ESD protection is essential to ensure system stability and prevent potential damage. The TVS diodes are strategically placed at signal and power lines exposed to the external environment, where they provide fast clamping action and divert surge currents away from critical circuitry. This design approach significantly enhances the long-term reliability and durability of the system under real-world conditions.

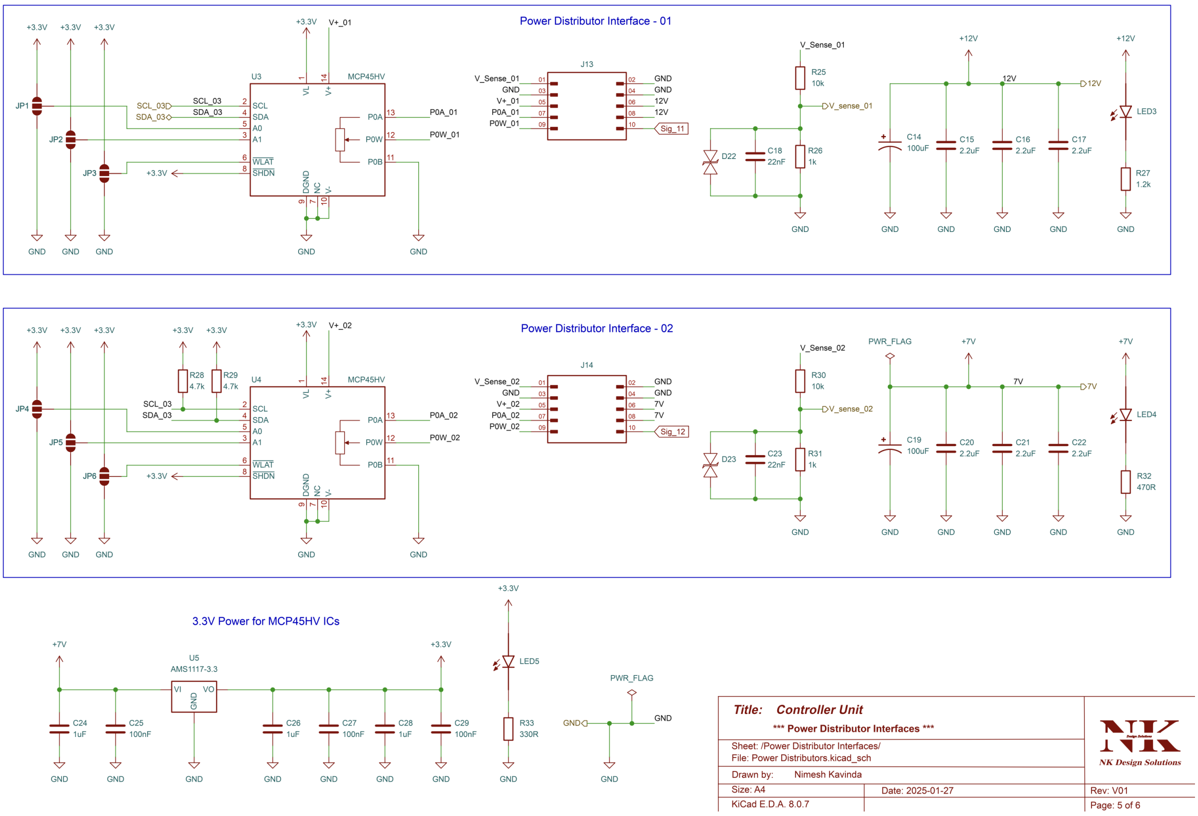


Figure 8.33: Controller Unit Schematic - Power Distributor PCB Interfaces

This schematic shows the connector configuration for the Power Distributor PCB. To enable digitally adjustable output for the main buck converters, **MCP45HV** [9]digital potentiometers are used. These are controlled by the MCU to set reference voltages, allowing precise and programmable voltage regulation.

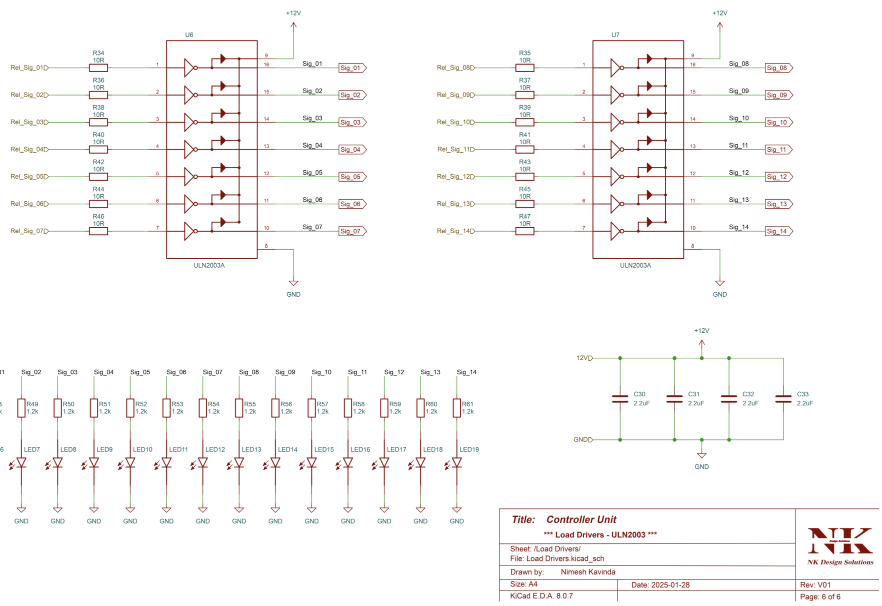


Figure 8.34: Controller Unit Schematic - Load Drivers / ULN2003A

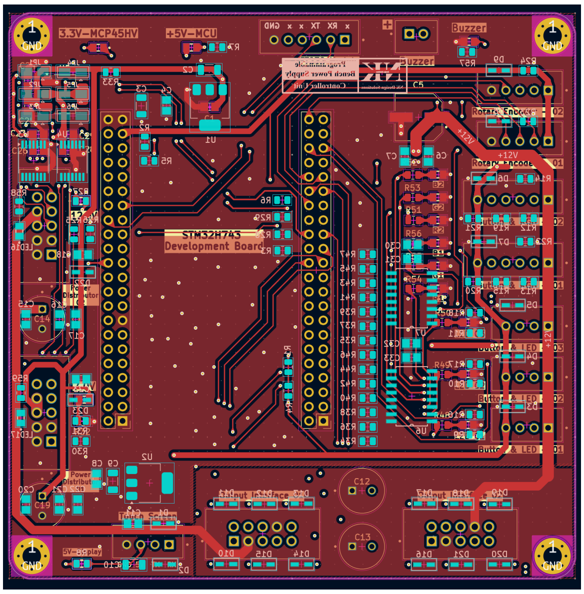


Figure 8.35: Controller Unit PCB Layout - Top Layer

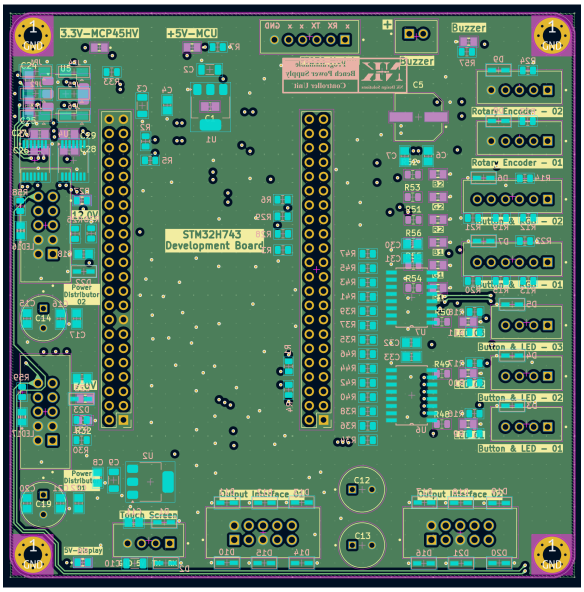


Figure 8.36: Controller Unit PCB Layout - Top Inner Layer

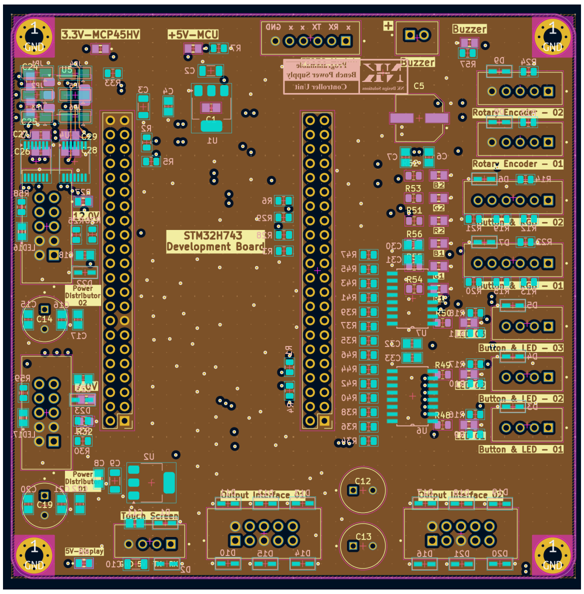


Figure 8.37: Controller Unit PCB Layout - Bottom Inner Layer

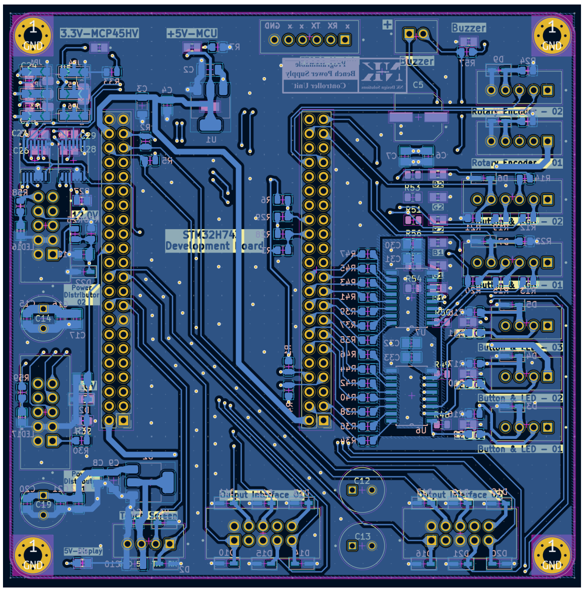


Figure 8.38: Controller Unit PCB Layout - Bottom Layer

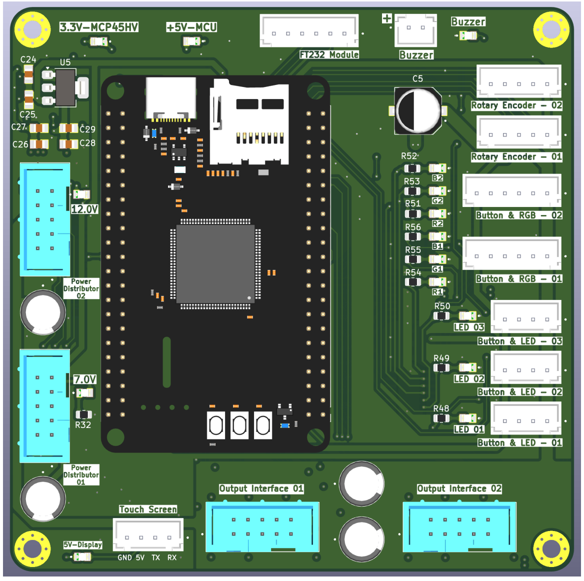


Figure 8.39: Controller Unit PCB 3D View - Top View

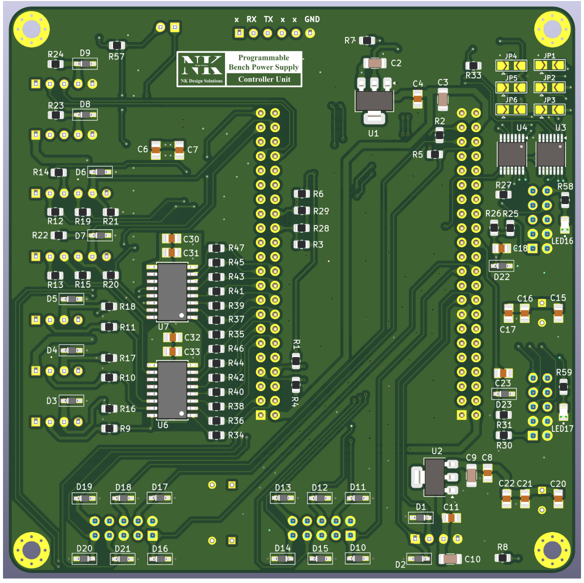


Figure 8.40: Controller Unit PCB 3D View - Bottom View

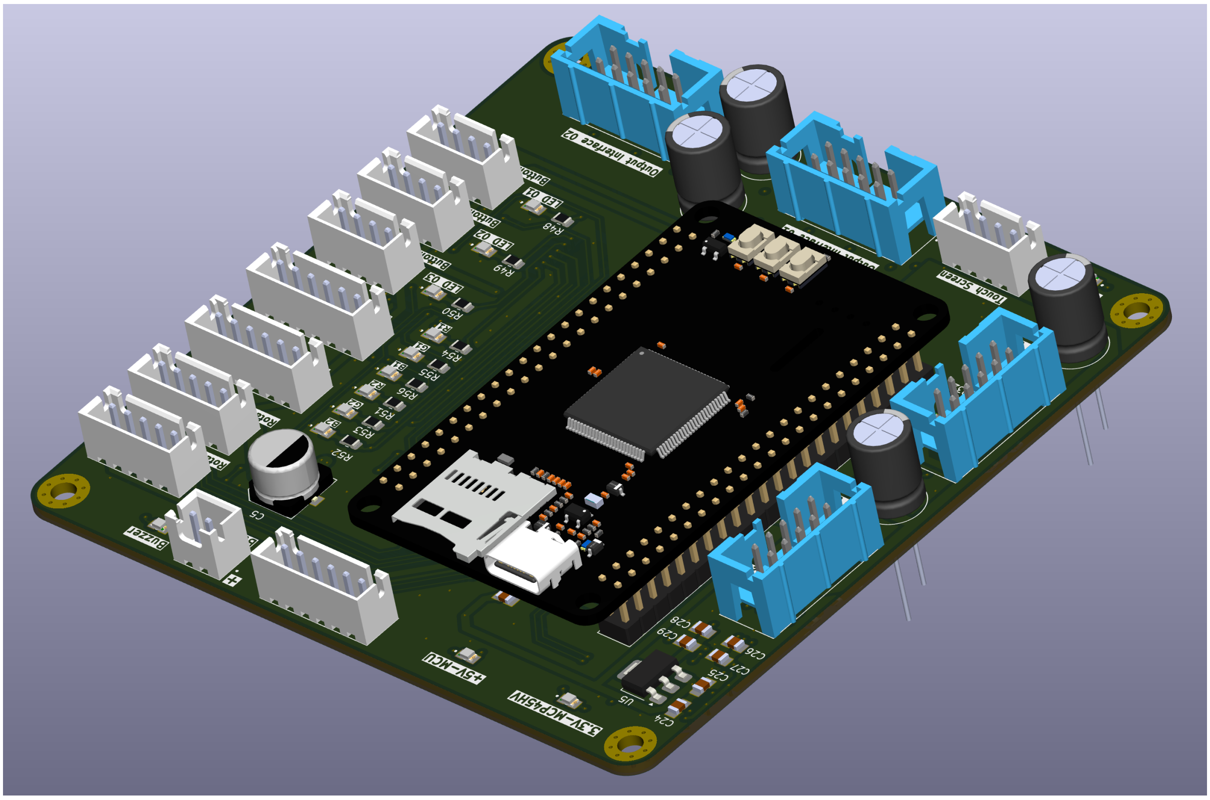


Figure 8.41: Controller Unit PCB 3D View - Side View

Chapter 9

Enclosure & Hardware Arrangement

The enclosure used for the programmable bench power supply is a pre-made iron chassis, selected for its mechanical strength and EMI shielding capabilities. Both the front and rear panels of the enclosure are made of plastic, making them suitable for precise cutouts and hardware mounting via laser cutting. This hybrid construction ensures both durability and ease of customization.

Figure 9.1: Metal Enclosure - Internal View

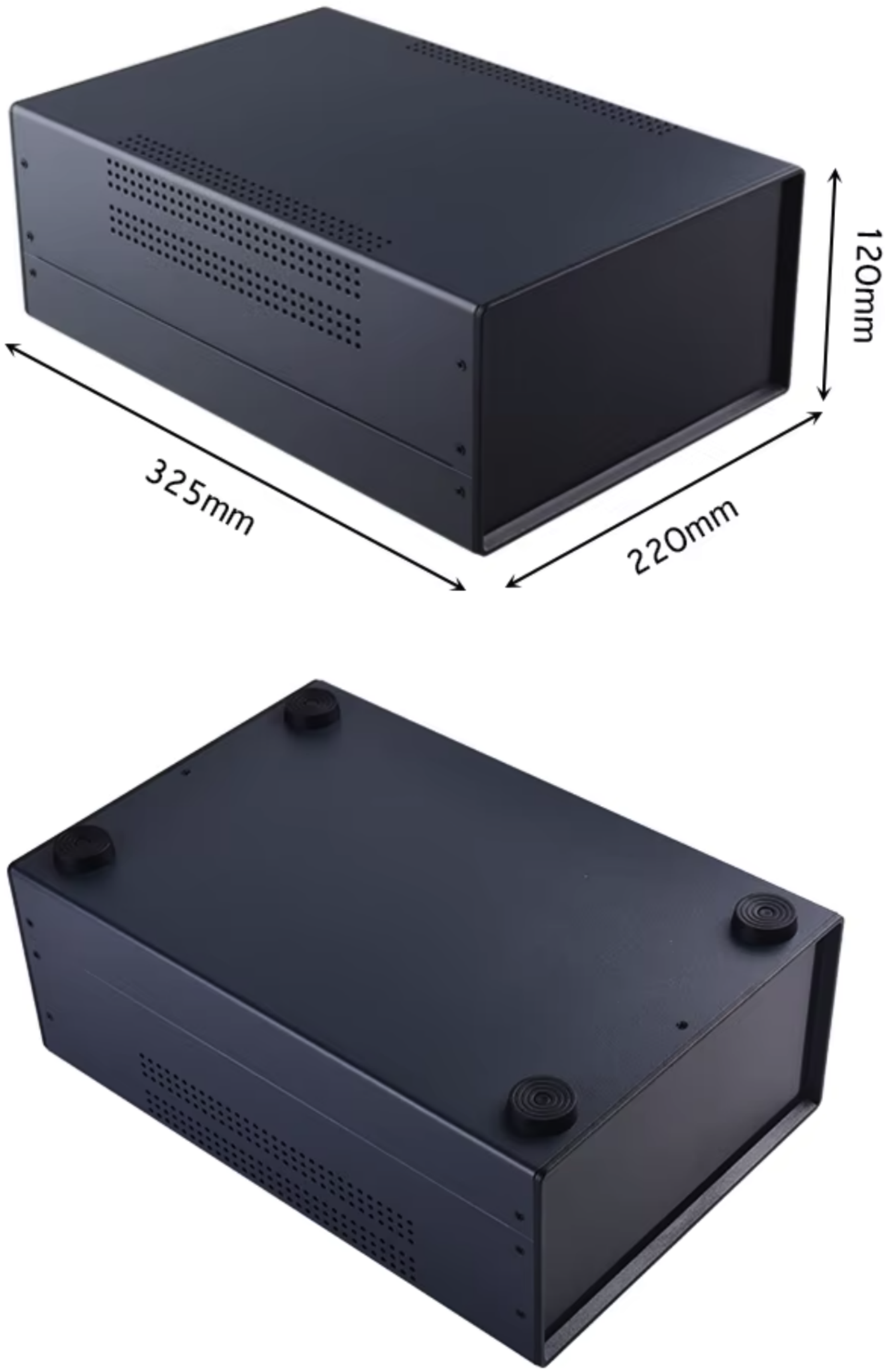


Figure 9.2: Metal Enclosure - Front and Rear View

On the front panel, the user interface is designed to provide intuitive and comprehensive control for each output channel. Each of the two output channels features a capacitive touch screen for real-time display and control, a rotary encoder for manual parameter adjustment, two banana connectors for output terminals (positive and ground), and an RGB push-button that serves both as a channel status indicator and a function switch. Additionally, a main power ON/OFF push-button is mounted on the front for overall system control.

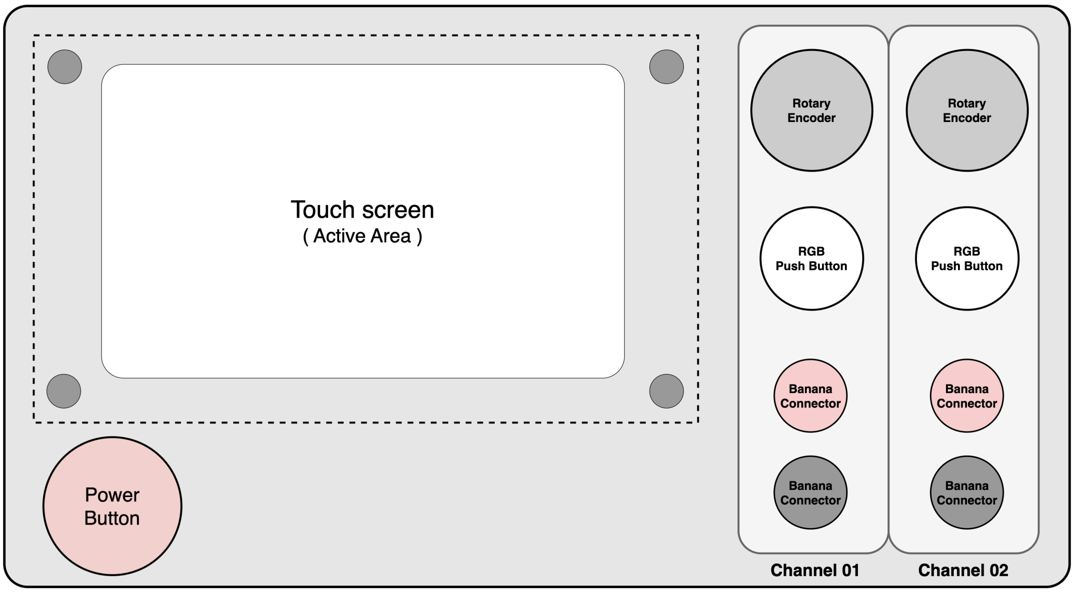


Figure 9.3: Hardware & Module Arrangement - Frount View

The rear panel is designed for power input and cooling. It includes a 230,VAC mains power input connector for supplying the internal power distribution circuitry, a USB port for PC communication or firmware updates, and a cooling fan to ensure thermal stability during high current operation. Proper ventilation holes are provided around the fan area to facilitate adequate airflow and heat dissipation.

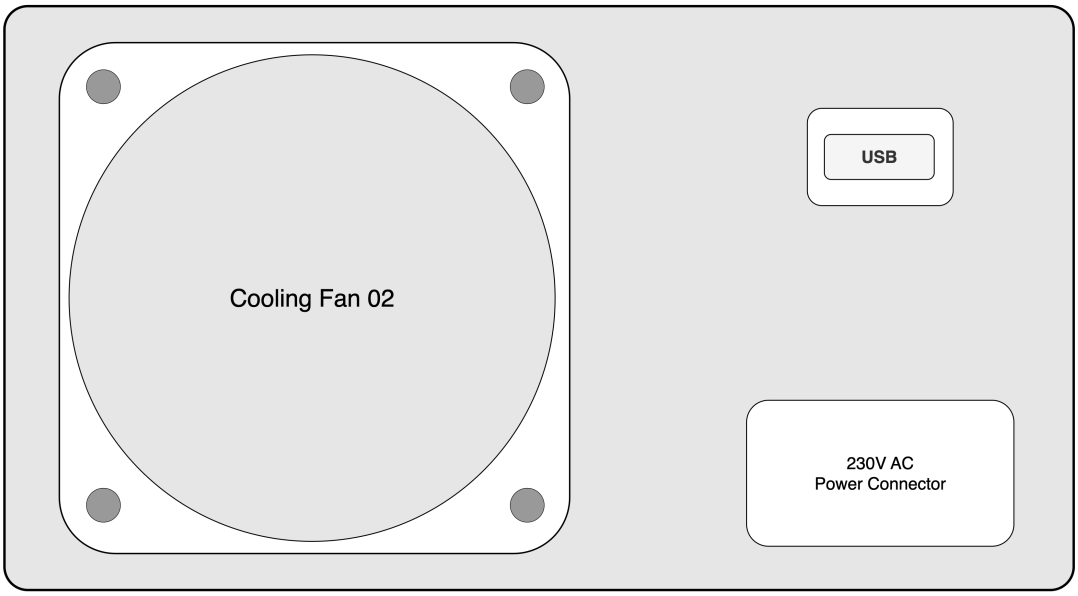


Figure 9.4: Hardware & Module Arrangement - Back View

To assemble the system, the plastic front and back panels are laser-cut precisely according to the hardware dimensions, ensuring accurate placement and a clean finish. For mounting internal components such as the controller PCB, power distributor board, transformer, heatsinks, and other modules, the metal enclosure is drilled at the appropriate points. These components are then securely fastened using screws and nuts, ensuring mechanical robustness and proper alignment. This approach allows efficient assembly while providing flexibility for maintenance and potential future upgrades.

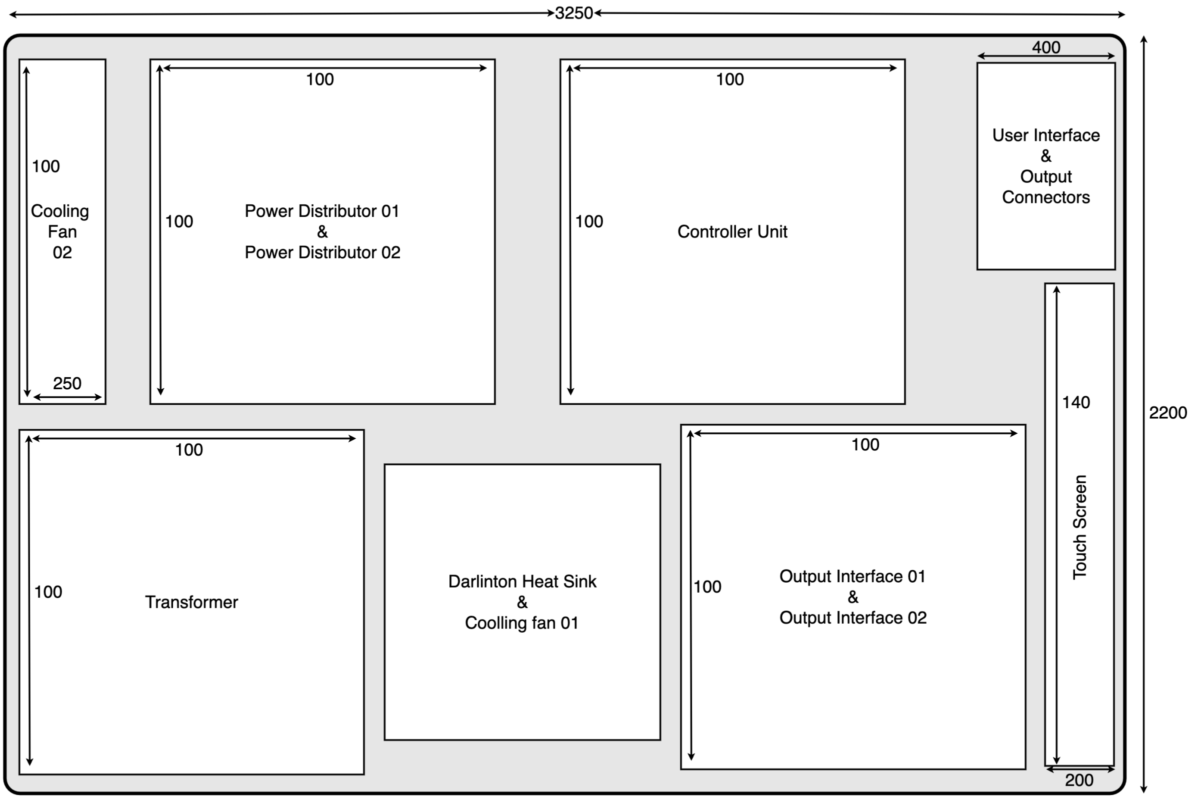


Figure 9.5: Hardware & Module Arrangement - Top View

Chapter 10

Tests and Results

Chapter 11

Discussion

Chapter 12

Conclusion

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