

Department of Electronic and Telecommunication Engineering

University of Moratuwa

EN2160 - Electronic Design Realization



Variable Frequency Drive for AC Motors

Design Methodology

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1 Introduction

Variable Frequency Drives (VFDs) for AC motors play a pivotal role in modern industrial applications, offering precise control over motor speed and enhancing energy efficiency. These systems employ sophisticated electronic circuits to regulate the frequency and voltage supplied to the motor, allowing for seamless adjustment of motor speed according to the application requirements.

2 VFD Manufacturers

Here is a brief overview of four major VFD manufacturers:

1. Gozuk (Chinese Company)

Specifications:

- Model -GK3000-2S0004
- Capacity -0.5 hp (0.4 kW)
- Rated Current -3 A
- Input Voltage -220 240V AC Single Phase
- Input Frequency -50Hz /60 Hz
- Output Voltage -3 phase AC
- Output Frequency -0.00 400 Hz

We have included a collection of helpful links and informative PDFs for further clarifications.

- [Seller Link](#)
- [Quick Setup Manual](#)
- [User Manual](#)
- [YouTube Installation Video](#)

2. ABB (Asea Brown Boveri):

ABB is a multinational corporation headquartered in Switzerland, specializing in robotics, power, heavy electrical equipment, and automation technology areas. Their VFD product line includes a wide range of drives suitable for various applications, from simple to complex industrial processes.

ABB -ACS880 Series:

- Model: ACS880-01
- Capacity: Ranges from 0.55 kW to 3200 kW
- Rated Current: Varies based on the specific model within the ACS880-01 series
- Input Voltage: 208 to 690 VAC, three-phase
- Input Frequency: 50/60 Hz
- Output Voltage: 0 to Input Voltage
- Output Frequency: 0 to 500 Hz

- Features: The ACS880 series offers high-performance motor control and advanced safety features. It is suitable for various applications, including pumps, fans, conveyors, and compressors. It supports various communication protocols for seamless integration into automation systems.

3. Siemens:

Siemens is a German conglomerate company headquartered in Berlin and Munich, operating in various sectors including industry, energy, healthcare, and infrastructure. Siemens offers a comprehensive portfolio of VFDs under the SINAMICS brand, catering to different industries and applications.

Siemens -SINAMICS G120 Series:

- Model: SINAMICS G120P
- Capacity: Ranges from 0.55 kW to 250 kW
- Rated Current: Varies based on the specific model within the SINAMICS G120 series
- Input Voltage: 380 to 480 VAC, three-phase
- Input Frequency: 50/60 Hz
- Output Voltage: 0 to Input Voltage
- Output Frequency: 0 to 650 Hz
- Features: The SINAMICS G120 series offers versatile drive solutions with high power density and efficiency. It features built-in safety functions, modular design, and a wide range of communication options. Suitable for various applications, including pumps, fans, compressors, and conveyor systems.

4. Danfoss:

Danfoss is a Danish multinational corporation, specializing in the research, development, and production of mechanical and electronic components for several industries. Their VFD products are known for their energy efficiency, reliability, and advanced control features, suitable for various HVAC, water, and industrial applications.

Danfoss -VLT AutomationDrive FC 302:Model:

- Model: VLT AutomationDrive FC 302
- Capacity: Ranges from 0.25 kW to 1400 kW
- Rated Current: Varies based on the specific model within the VLT AutomationDrive FC 302 series
- Input Voltage: 200 to 240 VAC or 380 to 500 VAC, three-phase
- Input Frequency: 50/60 Hz
- Output Voltage: 0 to Input Voltage
- Output Frequency: 0 to 500 Hz
- Features: The VLT AutomationDrive FC 302 offers precise and efficient motor control with adaptive features for optimal energy savings. It supports a wide range of motor types and communication protocols, making it suitable for various industrial applications, including pumps, fans, compressors, and extruders.

3 Research Publications

- Design and Implementation of a Variable Frequency Drive for Three Phase Induction Motor Using Arduino
 - This research is about an Arduino based V/f drive for a three phase induction motor using single phase supply. It discusses controlling a three phase induction motor with a single phase supply. The hardware involves a rectifier, inverter, and DC link. The software uses timers on the Arduino microcontroller to generate the switching pulses. The authors achieved simulation results with validation from a hardware setup.
- A Novel Intelligent Power Module (IPM) for High Power Density and High Efficiency Applications
 - This research paper is about a new technology for building power modules. It discusses how thermal engineering is important for these modules. The article introduces a copper bonded metal substrate (CBM) that can be used to build power modules. This CBM technology avoids using adhesives, which can cause problems. The CBM substrate has good thermal and electrical properties. This makes it a good choice for building power modules.
- Application Of AC Induction Motors with VARIABLE FREQUENCY DRIVES
 - This is an article about applying AC induction motors with variable frequency drives. It discusses what VFDs are and how they are used. They are used to control the speed of AC induction motors. This can result in energy savings. VFDs can also provide soft starts and high torque. When specifying a motor for use with a VFD, the load type, speed range, overload requirements, and VFD bypass requirement must allbe considered.
- Research to study Variable Frequency Drive and its Energy Savings
 - This is a research paperabout variable frequency drives (VFDs). It discusses what VFDs are and how they work. VFDs are used to control the speed of AC motors by changing the voltage and frequency of the power supplied to the motor [1]. This can lead to significant energy savings. The article also discusses some of the challenges of using VFDs, such as harmonics distortion.

4 Stakeholder Map

Creating a stakeholder map for a Variable Frequency Drive (VFD) for AC motors involves identifying the key individuals or groups affected by or involved in the use, implementation, or maintenance of the VFD system.

1. Team
2. Supervisor
3. End Users/Operators:
 - Those who operate the machinery or equipment powered by the VFD.
 - Their concerns might include ease of use, reliability, and performance.
4. Maintenance Technicians:
 - Those responsible for the upkeep and repair of the VFD system.
 - Concerns may revolve around maintenance schedules, troubleshooting, and spare parts availability.

5. Electrical Engineers:

- Professionals involved in the design, installation, and integration of the VFD into the electrical system.
- They may focus on technical specifications, compatibility, and safety standards

6. Manufacturers/Suppliers:

- Companies that produce or supply VFD equipment.
- Concerns include product quality, availability, and customer support.

7. Regulatory Bodies:

- Government agencies or industry organizations responsible for setting standards and regulations related to VFDs and electrical equipment.
- Their concerns may involve compliance with safety, environmental, and efficiency regulations

8. Environmental Agencies:

- Organizations concerned with the environmental impact of VFDs, such as energy efficiency and emissions.
- Their concerns might involve compliance with energy efficiency standards and reducing electrical waste.

9. Financial Stakeholders:

- Investors, shareholders, or financial institutions that have a personal stake in the successful deployment or operation of VFD systems
- Their concerns may include return on investment, cost-effectiveness, and financial risk.

10. Community/Public:

- Residents or community groups living near facilities that use VFDs
- Concerns may include noise pollution, environmental impact, and safety.

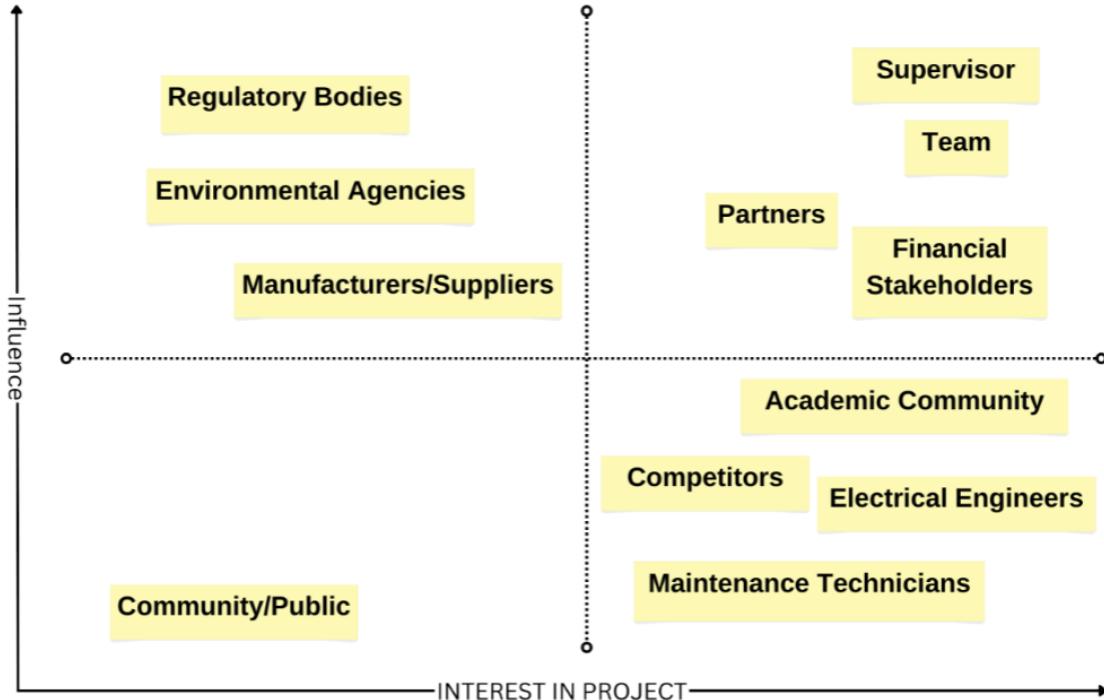


Figure 1: Stakeholder map

5 Need List

1. Components: Consider designing essential components such as AC/DC power supply, rectifiers (diodes or bridge rectifiers), DC bus with capacitors and inductors, inverters with IGBTs or MOSFETs, microcontroller or DSP for control, sensors for monitoring, feedback and protection systems, EMI and harmonic filters, user interface, and cooling enclosure.
2. Software: Develop firmware with advanced control algorithms, create user interface software for easy parameter setting and monitoring, and implement communication protocols like Modbus, CAN, or Ethernet.
3. Design and Development Tools: Use EDA tools for schematic capture and PCB design, simulate circuits with SPICE and MATLAB/Simulink, and validate designs using development boards and test instruments.
4. Testing and Validation: Set up a dedicated test bench for motor configuration, ensuring safety with proper protective gear.
5. Documentation
6. Project Management: Plan the project timelines meticulously, setting achievable milestones and budgeting wisely to ensure smooth execution.

6 Planned Steps

Project Definition and Scope:

- Clearly define the objectives of the project, including the design and implementation of a Variable-Frequency Drive (VFD) for a three-phase induction motor using a single-phase power supply.
- Determine the functionalities and features the VFD should include.

Research and Background Study:

- Review the referencing sources to understand the principles of VFD operation, the role of the Atmega328p microcontroller, and the usage of Intelligent Power Modules (IPMs).
- Gain insights into the theory behind PWM generation, motor control techniques, and safety considerations.

Component Selection:

- Select appropriate components based on the project requirements and budget constraints.
- Choose an Atmega328p microcontroller, IPM, power circuitry components, sensing components, and user interface components (e.g., display and buttons).

Circuit Design:

- Design the schematic for the VFD circuitry, including power supply, microcontroller connections, gate driver circuitry for the IPM, and protection circuits.
- Simulate the circuit using software tools to verify its functionality and performance.

Firmware Development:

- Write firmware for the Atmega328p microcontroller to control the VFD operation. Implement algorithms for PWM generation, motor speed control, and protection mechanisms.
- Develop user interface functionalities for configuring and monitoring the VFD parameters

PCB and Enclosure Design:

- Layout the PCB based on the schematic design, ensuring proper component placement, signal routing, and impedance control.
- Consider factors such as heat dissipation, noise immunity, and safety standards during the PCB design process.
- Design and print the moldable enclosure for the VFD using Solidworks. Ensure moldability (ex: adding proper draft angles and wall thicknesses).

Testing and Validation:

- Prototype the VFD circuit on a breadboard or using a development board. Conduct functional testing to ensure all components operate as expected.
- Perform performance testing to validate motor speed control, efficiency, and reliability.
- Address any issues encountered during testing and refine the design accordingly.

Documentation:

- Document the design process, including schematics, PCB layouts, firmware source code, and testing procedures.
- Create user manuals and guides for operating and maintaining the VFD.
- Compile a bill of materials (BOM) listing all components used in the project.

Deployment and Demonstration:

- Install the VFD system in the intended application environment.
- Demonstrate its functionality to stakeholders and obtain feedback for further improvements.

7 Observed Users

Observed users of Variable Frequency Drives (VFDs) span across a variety of industries and applications.

1. Manufacturing Plants:

- Automotive Manufacturing: Companies like Toyota and Ford use VFDs on conveyor systems, assembly lines, and robotic arms to improve precision and efficiency.
- Electronics Manufacturing: Firms such as Samsung and Intel employ VFDs in their production lines to control the speed of motors in delicate processes.

2. HVAC Systems in Large Buildings:

- Commercial Buildings and Skyscrapers: Buildings such as the Burj Khalifa and Empire State Building use VFDs in their HVAC systems to control the speed of fans, pumps, and air handlers, optimizing energy consumption and maintaining indoor air quality.
- Hospitals: Facilities like the Mayo Clinic and Cleveland Clinic implement VFDs in their HVAC systems to ensure a consistent and sterile environment.

3. Water and Wastewater Treatment Facilities:

- Municipal Water Treatment Plants: Cities like Los Angeles and New York City utilize VFDs in their water treatment facilities to control pumps and blowers, reducing energy use and maintaining efficient water treatment processes.
- Irrigation Systems: Agricultural operations in California's Central Valley use VFDs to manage irrigation pumps, ensuring efficient water usage.

4. Transportation Systems:

- Railways and Subways: Systems like the London Underground and New York City Subway use VFDs in their traction control systems to manage the speed and efficiency of trains.
- Electric Vehicles: Companies like Tesla and Nissan incorporate VFDs to control the electric motors in their vehicles, enhancing performance and energy efficiency.

5. Mining Operations:

- Mining Companies: Firms like Rio Tinto and BHP use VFDs to control the speed of conveyors, crushers, and mills, optimizing the extraction and processing of minerals.

6. Oil and Gas Industry:

- Drilling Operations: Companies such as Shell and ExxonMobil use VFDs to control drilling rig motors and pumps, improving operational efficiency and safety.
- Pipeline Management: VFDs are used by companies like TransCanada to regulate the flow rates in pipelines, ensuring safe and efficient transport of oil and gas.

7. Renewable Energy Projects:

- Wind Farms: Companies like Vestas and GE Renewable Energy use VFDs to control the speed of wind turbine generators, matching generator output with wind conditions.
- Solar Power Plants: Solar farms employ VFDs to manage the tracking systems that adjust the position of solar panels to maximize sun exposure.

Other than the above, navies, commercial shipping, agriculture, pulp and paper industries, and theme parks use VFDs for propulsion, thruster control, irrigation, automated equipment, machinery speed control, and ride operations to enhance efficiency, optimize operations, and ensure precise motor control.

8 User Requirements

The user requirements for the variable frequency drive (VFD) should prioritize efficiency, flexibility, and ease of operation to ensure seamless integration into diverse industrial applications. Users expect the VFD to offer precise speed control, allowing for smooth acceleration and deceleration of AC motors across various load conditions. It should support a wide range of motor sizes and types, enabling compatibility with different industrial setups. Additionally, the VFD interface must be intuitive, featuring clear displays and user-friendly controls for easy configuration and monitoring of motor performance. Robust safety features such as overcurrent protection, overvoltage protection, and fault diagnostics are essential to safeguard equipment and personnel. Moreover, the VFD should incorporate energy-saving capabilities, optimizing motor performance while minimizing power consumption to promote sustainability and cost-effectiveness.

Key points to include in the user requirements:

1. Precise speed control for smooth acceleration and deceleration.
2. Compatibility with various motor sizes and types.
3. Intuitive interface with clear displays and user-friendly controls.
4. Robust safety features including overcurrent and overvoltage protection.
5. Fault diagnostics for easy troubleshooting.
6. Energy-saving capabilities to optimize motor performance and minimize power consumption.

Key Specifications of the VFD that we are Designing:

1. Input Voltage: 230VAC Single Phase
2. Output Voltage Range: Adjustable output voltage from 0 to input voltage.
3. Frequency Range: 20Hz -120Hz
4. Control Method: Maintain a Constant V/F Ratio
5. Power Rating: Three Phase Induction Motors 2.2kW
6. Built-in Protections: Features built-in protections includes Overcurrent, Overvoltage and Thermal Overload Protections for safety.

9 Conceptual Designs and Functional Block Diagrams

The initial conceptual design for the Variable Frequency Drive (VFD) project features a single-phase grid power input, a moldable enclosure for versatile installation, and a considerable body height for efficient component placement and heat dissipation. With a three-phase PWM output and an IPM module as the inverter, this design facilitates current sensing of output phase wires, enhancing safety and operational precision for diverse industrial applications.

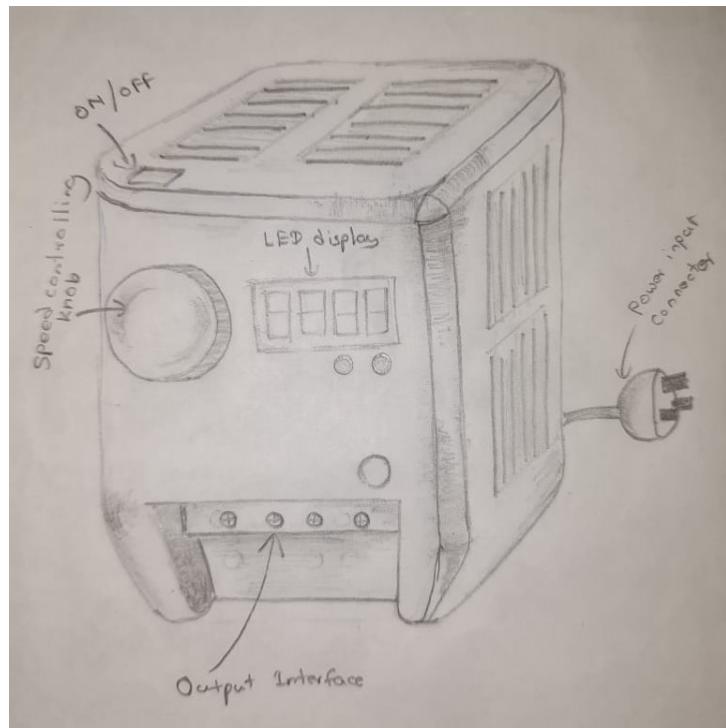


Figure 2: Conceptual Design 1

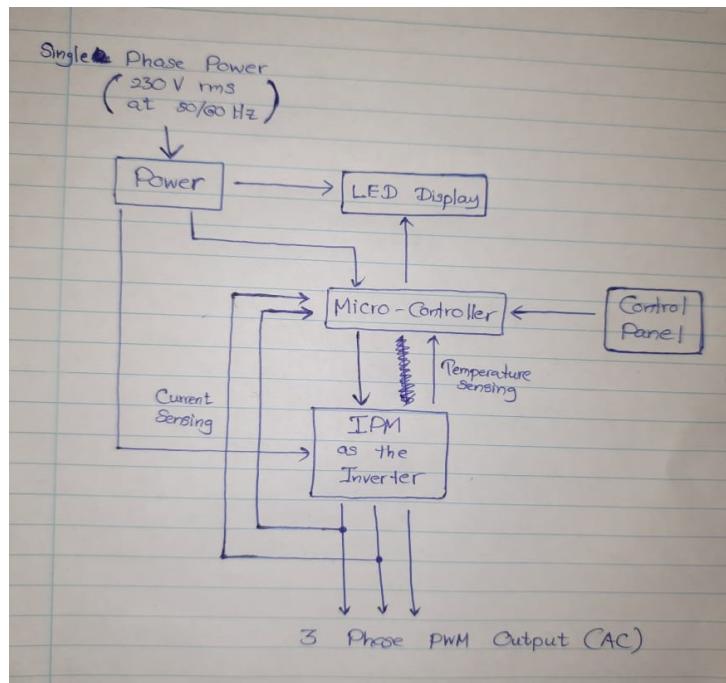


Figure 3: Functional Block Diagram Conceptual Design 1

The second conceptual design for the Variable Frequency Drive (VFD) project incorporates a durable sheet metal enclosure and supports single-phase input power. It features both single and three-phase PWM outputs for compatibility with different motors. With Bluetooth connectivity, it enables wireless control and monitoring, enhancing ease of operation and maintenance.

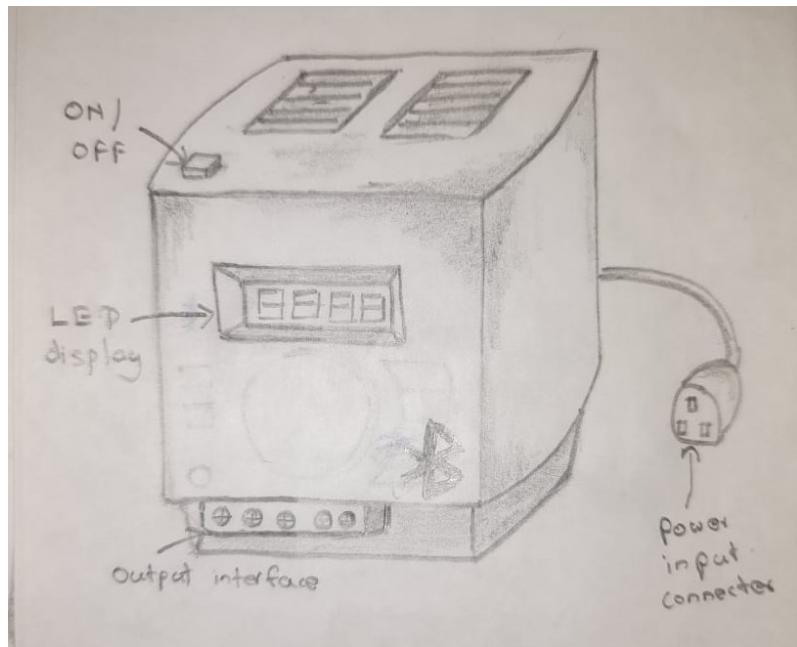


Figure 4: Conceptual Design 2

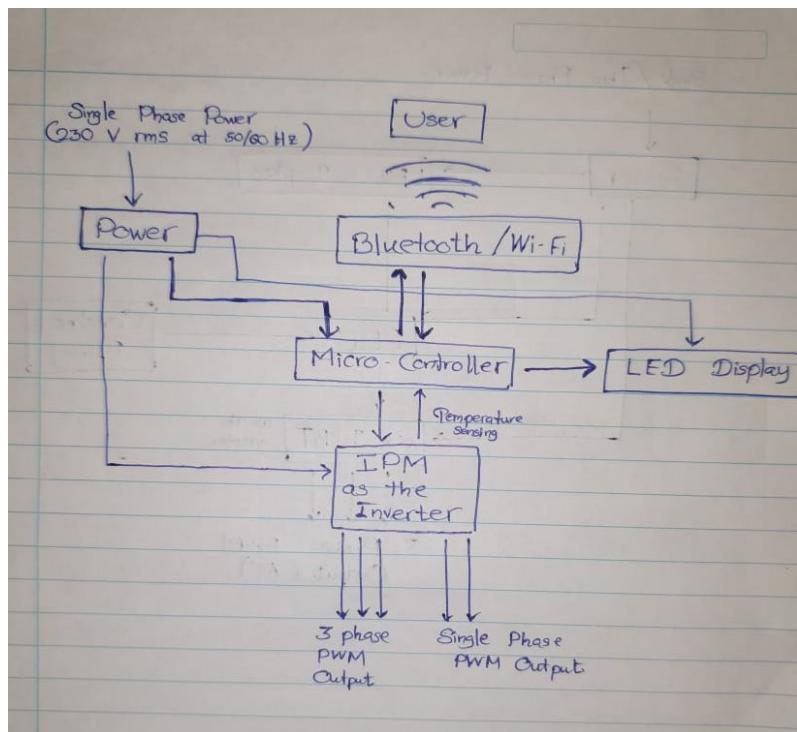


Figure 5: Functional Block Diagram Conceptual Design 2

The third conceptual design for the Variable Frequency Drive (VFD) project offers flexibility with single or three-phase power input. Its compact design features a considerable body width and short height for efficient space utilization. Utilizing a PLC instead of a microcontroller enhances control capabilities, while the three-phase PWM output ensures precise motor control, making it ideal for diverse industrial applications.



Figure 6: Conceptual Design 3

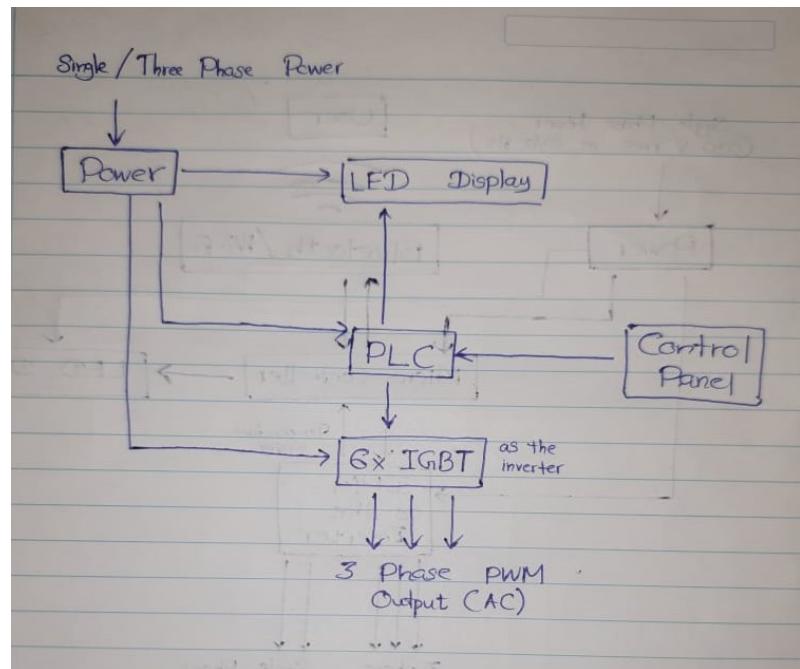


Figure 7: Functional Block Diagram Conceptual Design 3

10 Comparison of Conceptual Designs

10.1 Comparison Criteria

		Conceptual Design 1	Conceptual Design 2	Conceptual Design 3
New Added Features		IPM is used as the Inverter	Bluetooth Capability using a Mobile Application Both 3 Phase and Single Phase Output	Using Discrete Power Components (IGBTs) Both 3 Phase and Single Phase Input PLC is used
Removed Features		No Bluetooth Capabilities No Single phase Output	No Control Panel included in the VFD	IPM is not used No Bluetooth Capabilities No Microcontroller
Enclosure Design Comparison	Functionality	9	8	8
	Aesthetics	9	10	9
	Heat Dissipation	9	7	10
	Assembly and Serviceability	8	8	8
	Ergonomics	10	7	10
	Durability	7	10	7
	Simplicity	8	9	8
Functional Block Diagram Comparison	Functionality	9	8	8
	User Experience	8	7	8
	Manufacturing Feasibility	9	8	7
	Cost	9	7	6
	Performance	8	7	6
	Future Proofing	9	9	9
	Power Efficiency	9	9	8
Total Score (out of 140)		121	114	112

Figure 8: Comparison of Conceptual Designs 8

Enclosure Design Criteria:

1. Functionality: How well does the design support the main functionalities?
2. Aesthetics: How much eye-catching and overall appeal of the user?

3. Heat Dissipation: How much heat is generated and how well it has been managed?
4. Assembly and Serviceability: How easily does the assembly and disassembly is done?
5. Ergonomics: How well does the design allow the user to easily interact with the product?
6. Durability: How well does the design withstand impacts and environmental conditions?
7. Simplicity: Simplicity of the enclosure?

Functional Block Diagram Criteria:

1. Functionality: How well the circuit design meets functional requirements?
2. User Experience: How intuitive and user-friendly is the interaction?
3. Manufacturing Feasibility: Evaluate the feasibility of manufacturing the design
4. Cost: Evaluate the overall cost-effectiveness for the provided functionality
5. Performance: Evaluate the output frequency range, input voltage, capacity?
6. Future Proofing: To what extent does the design allow for easy replacement or upgrade of individual components?
7. Power Efficiency: How effectively does the device manage power consumption?

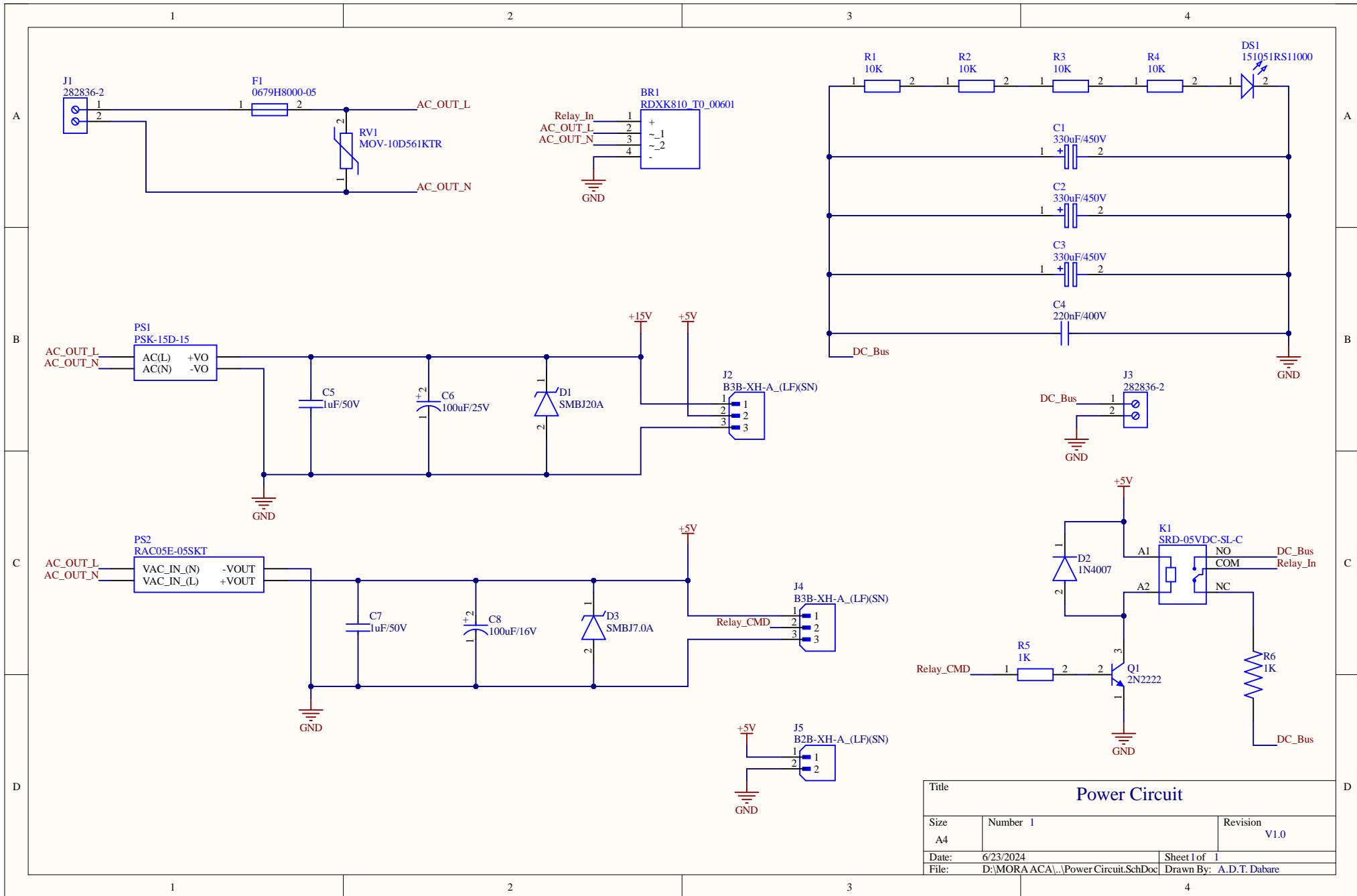
10.2 Selected Design

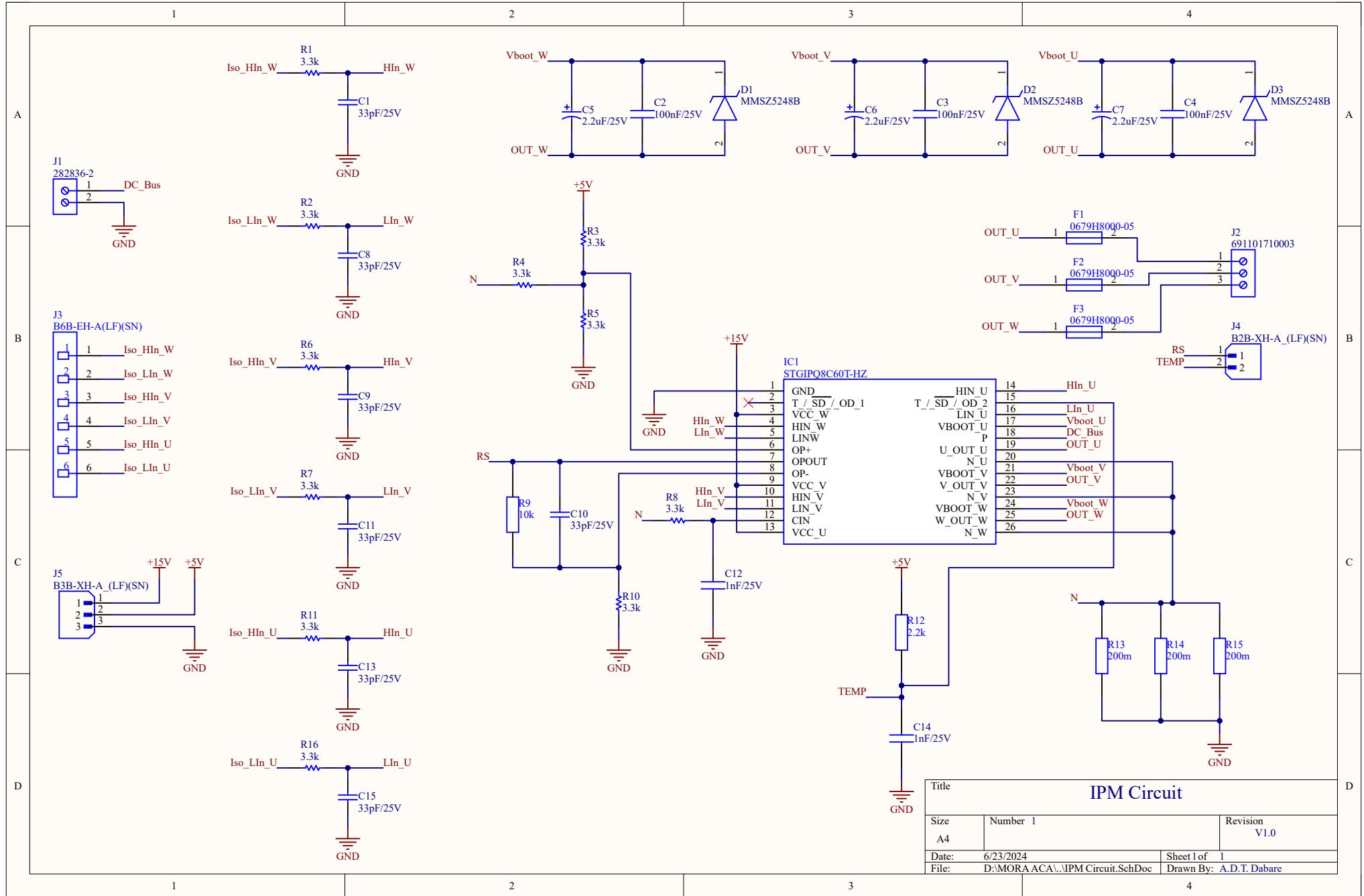
Choosing conceptual design 1 over designs 2 and 3 seems to be primarily driven by practical considerations related to implementation complexity, space constraints, and the specific requirements of the project.

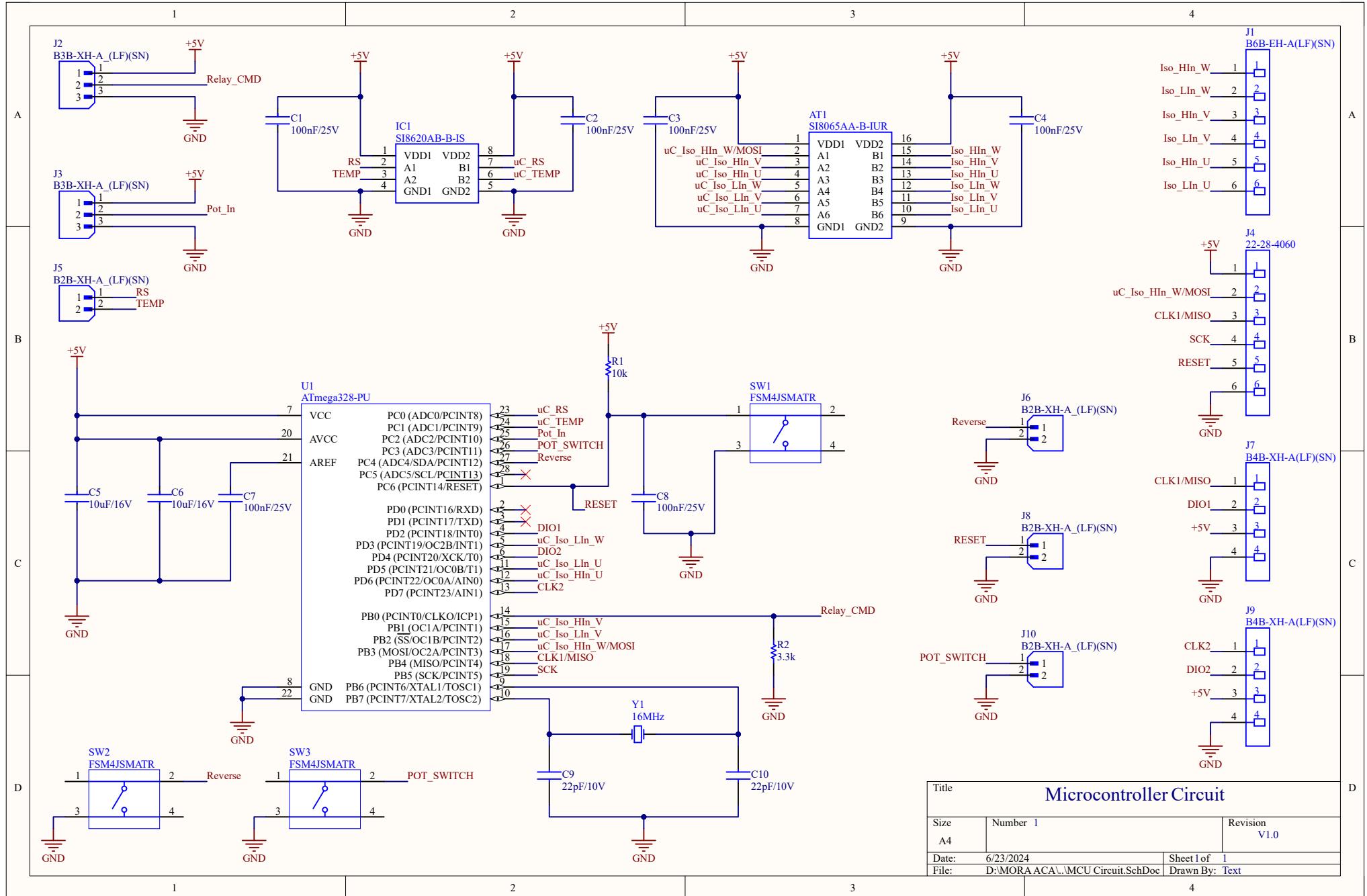
1. **Implementation Complexity:** Utilizing an Integrated Power Module (IPM) as the inverter in the Variable Frequency Drive (VFD) simplifies the design process compared to implementing individual components like Insulated Gate Bipolar Transistors (IGBTs). This simplification reduces the overall complexity of the system, making it more manageable during development and potentially more reliable in operation.
2. **Space Efficiency:** By using an IPM module, the design saves valuable space on the printed circuit board (PCB) that would otherwise be occupied by multiple discrete components. This compactness is advantageous, especially if there are space constraints in the final application or if miniaturization is a priority.
3. **User Interface and IoT Integration :** Making the VFD IoT-enabled might not be necessary for the intended application. This decision could be based on factors such as cost-effectiveness, the target user's preferences, or the nature of the application itself.
4. **Choice of Controller :** Opting for a microcontroller over a Programmable Logic Controller (PLC) for control tasks indicates that the project requirements align better with the capabilities and flexibility offered by a microcontroller. This choice may be influenced by factors such as the complexity of the control algorithms, ease of programming, cost considerations, and the availability of suitable development tools.

Considering these factors collectively, conceptual design 1 appears to be the more suitable option for the project's objectives and constraints. It offers a balance between simplicity, efficiency, and functionality, aligning well with the specific needs outlined for the VFD application. Since we got equal 60 marks for enclosure concepts 1 and 3 and considering the moldability of the enclosure and fastening features (for example mounting boss height, draft angle, and its wall thickness), we chose to design the 3rd enclosure design with the 1st concept functional block.

11 Schematic Design







12 PCB Design

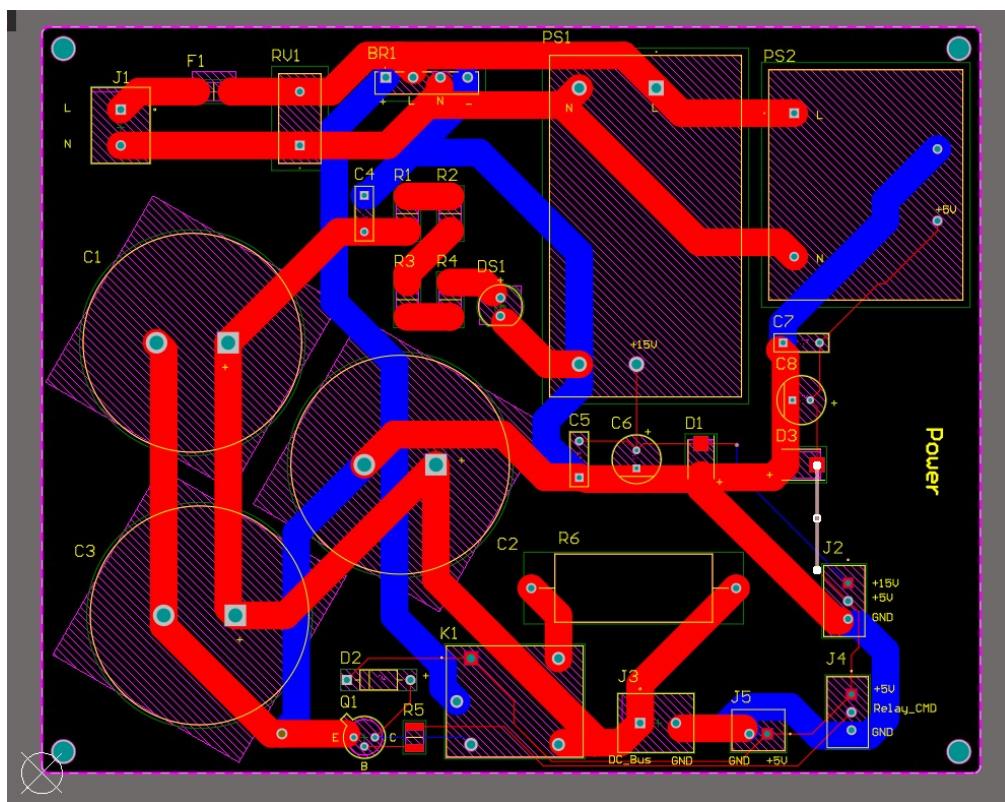


Figure 9: Power Circuit top layer

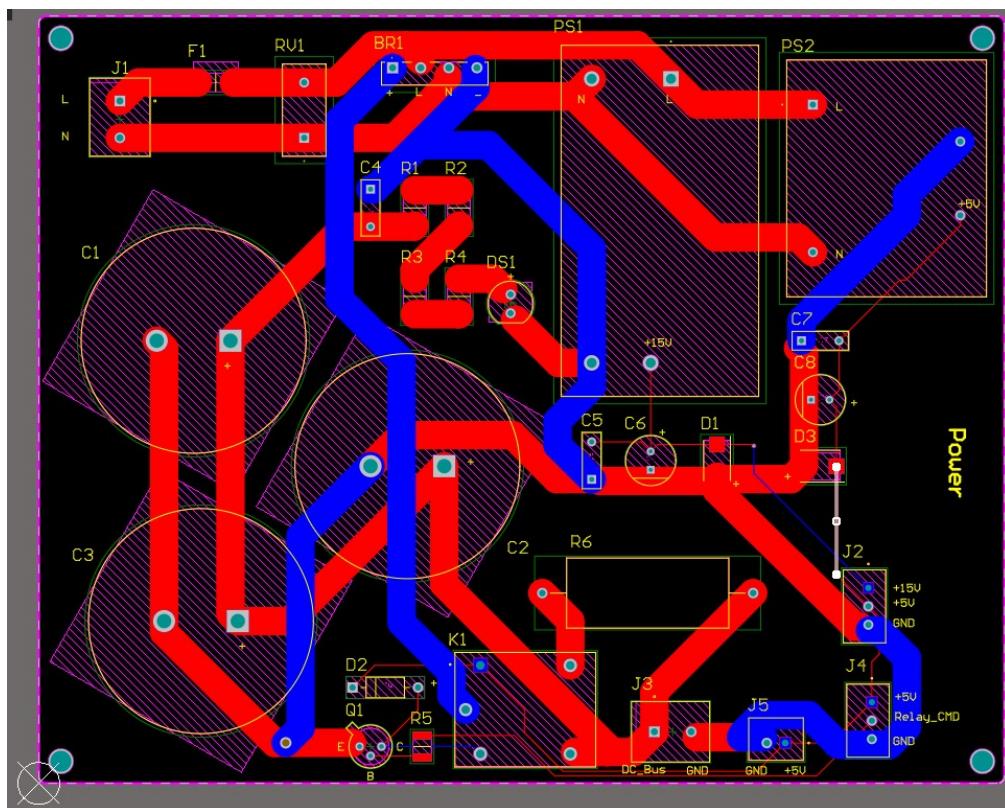


Figure 10: Power Circuit bottom layer

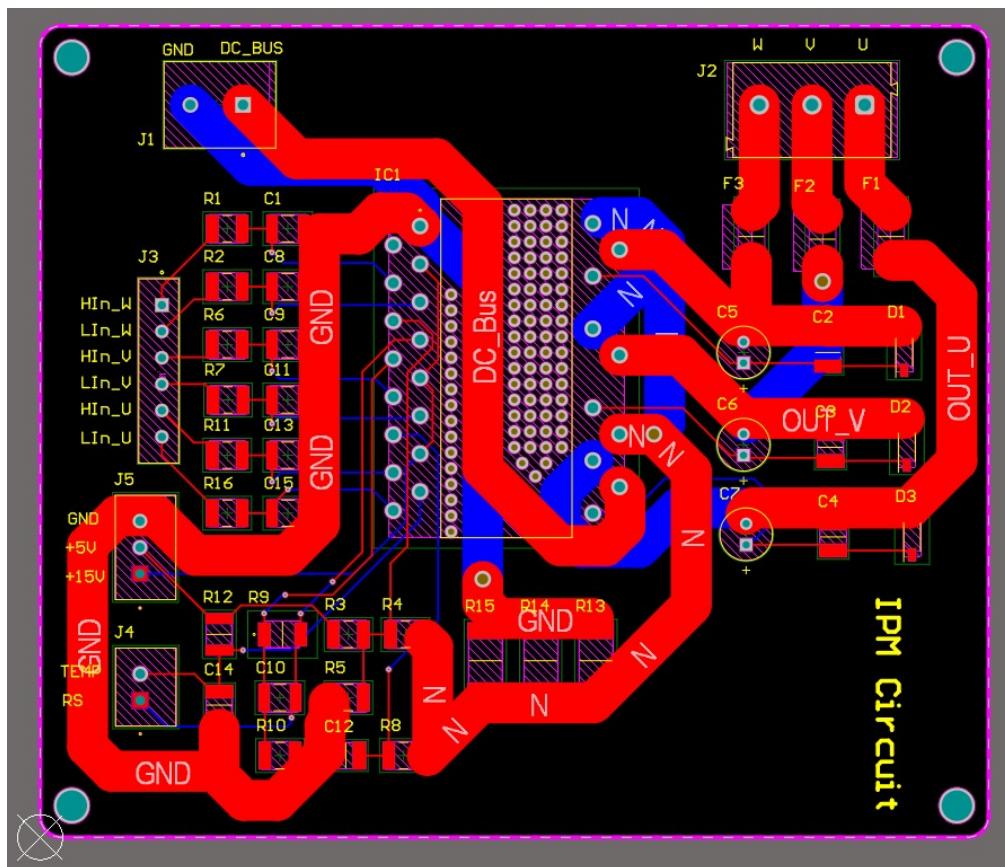


Figure 11: IPM Circuit top layer

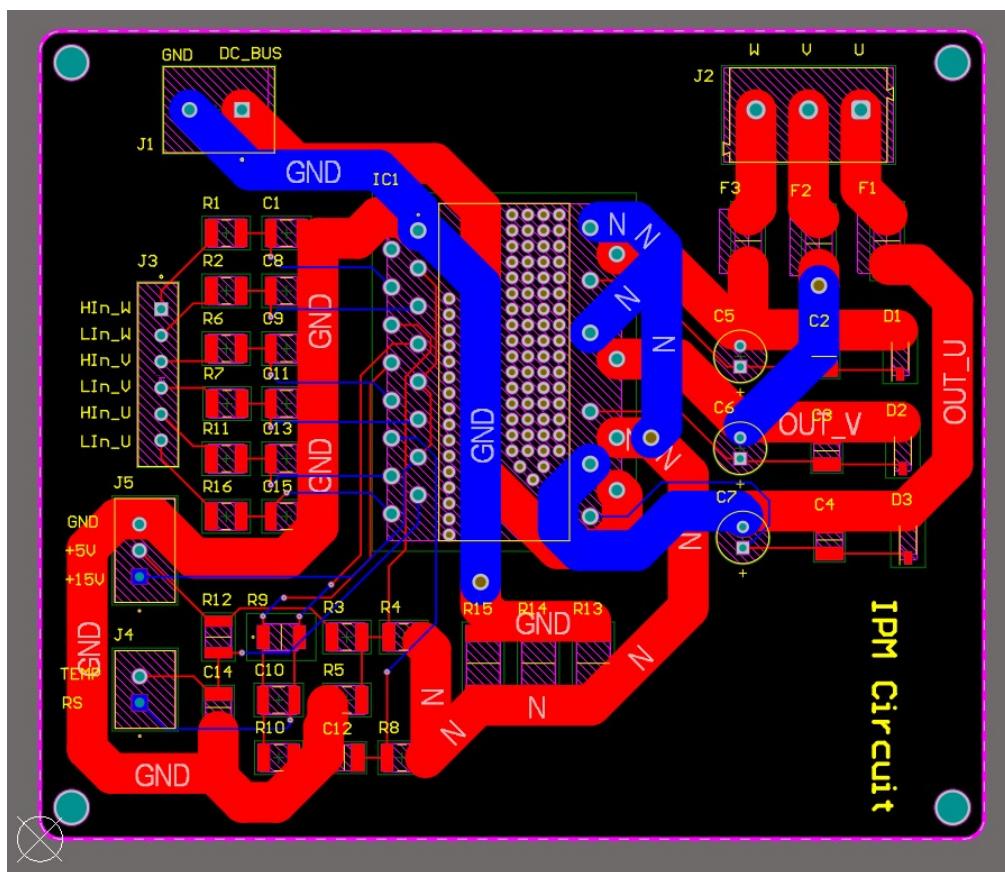


Figure 12: IPM Circuit bottom layer

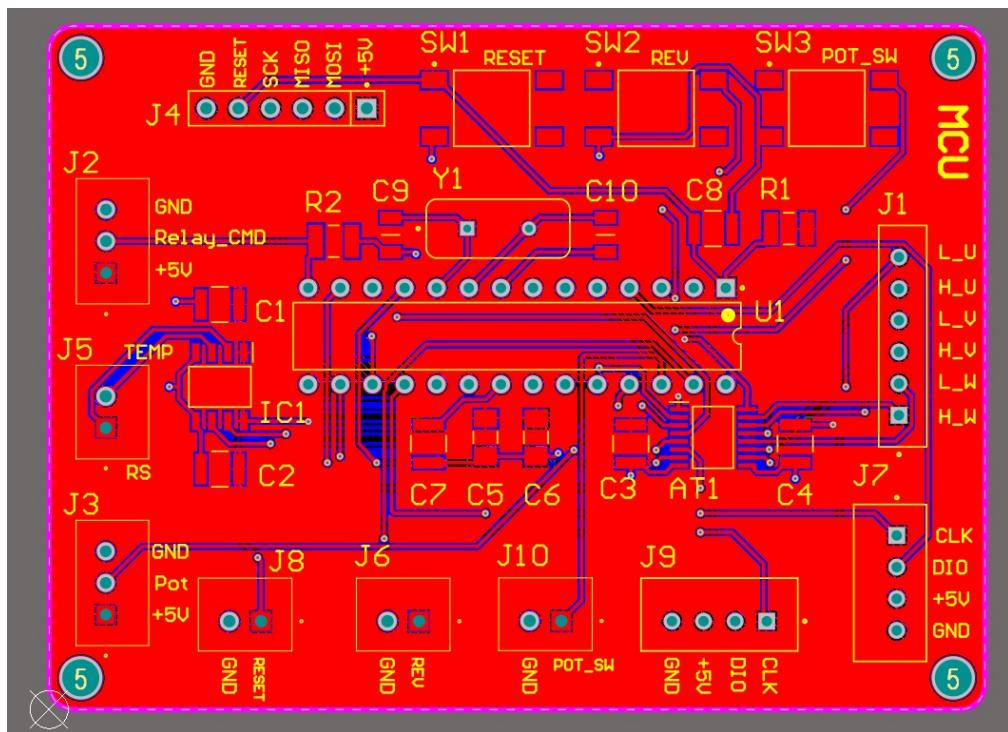


Figure 13: MCU Circuit top layer

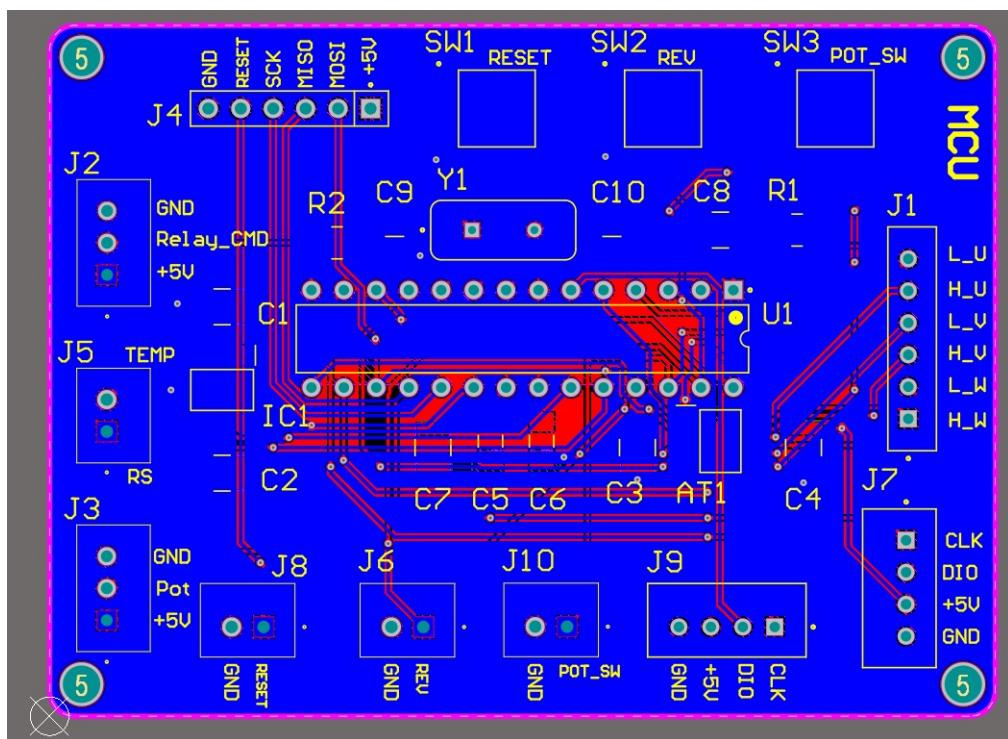
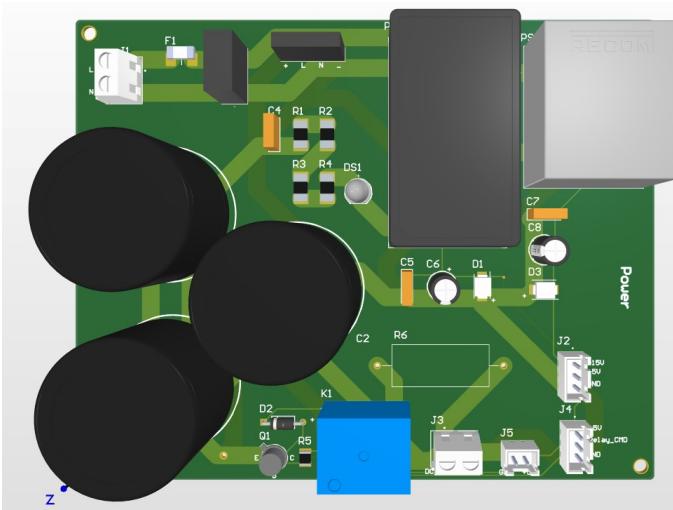
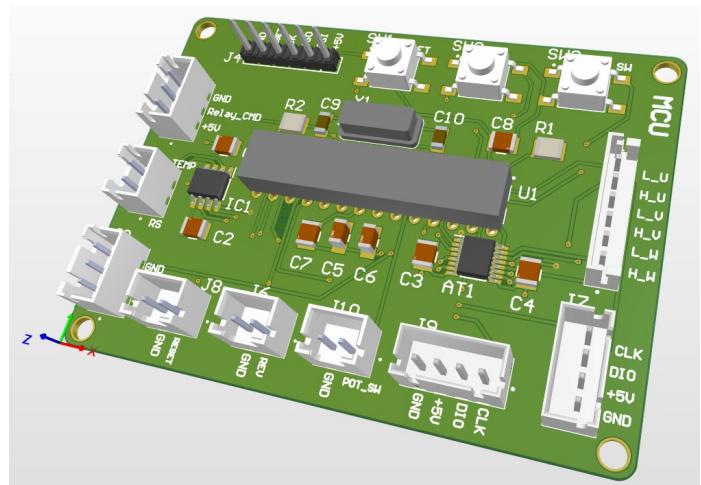


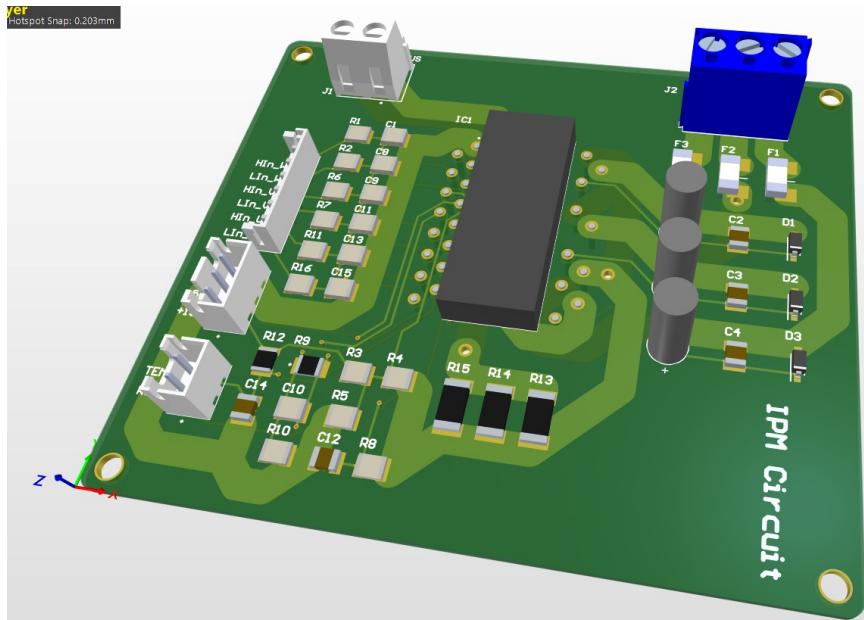
Figure 14: MCU Circuit bottom layer



(a) Power Circuit



(b) MCU Circuit



(c) IPM Circuit

13 Solidworks Design

13.1 Enclosure Assembly

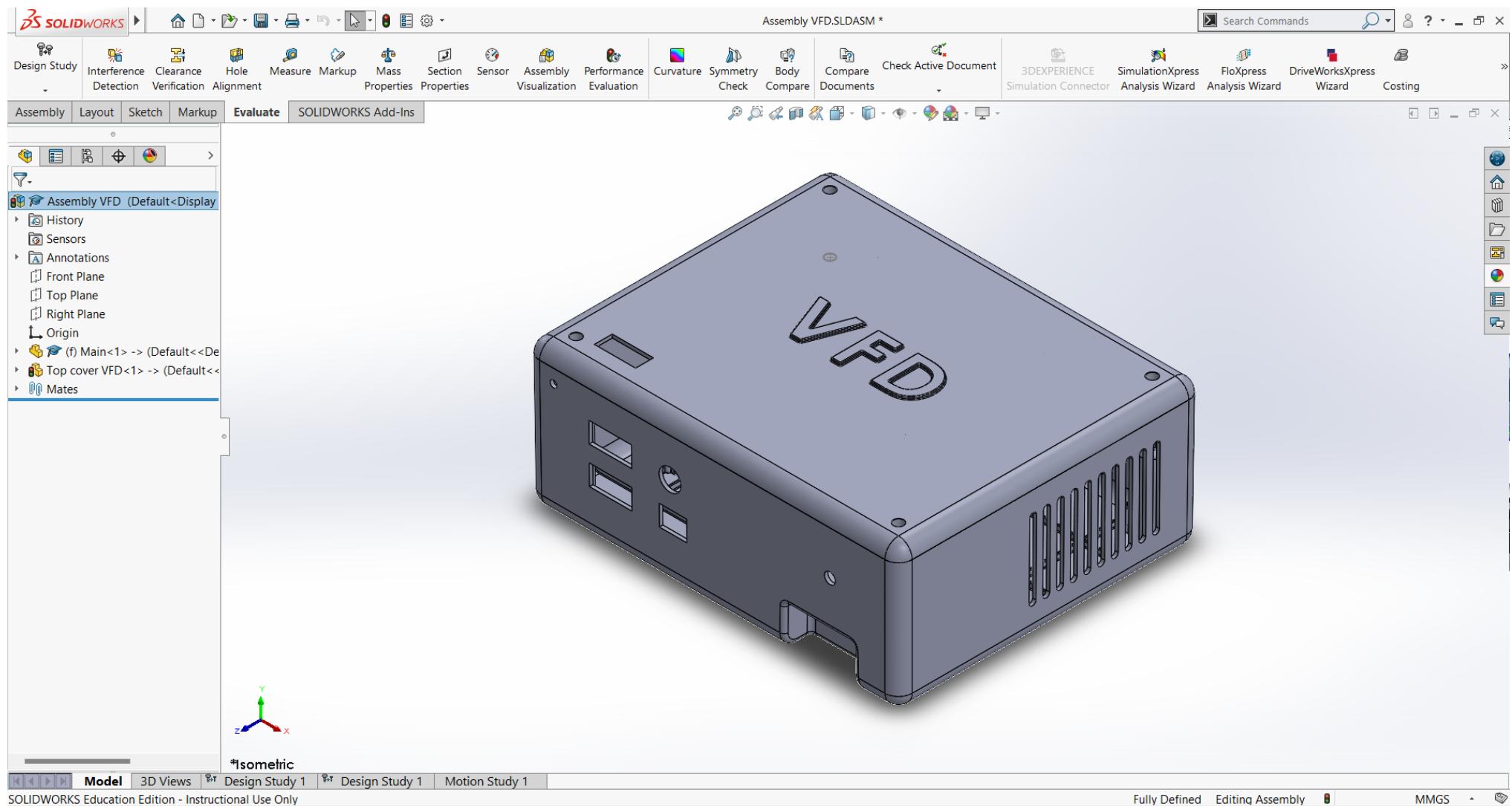


Figure 16: Isometric View

13.2 Bottom Part - Design Tree

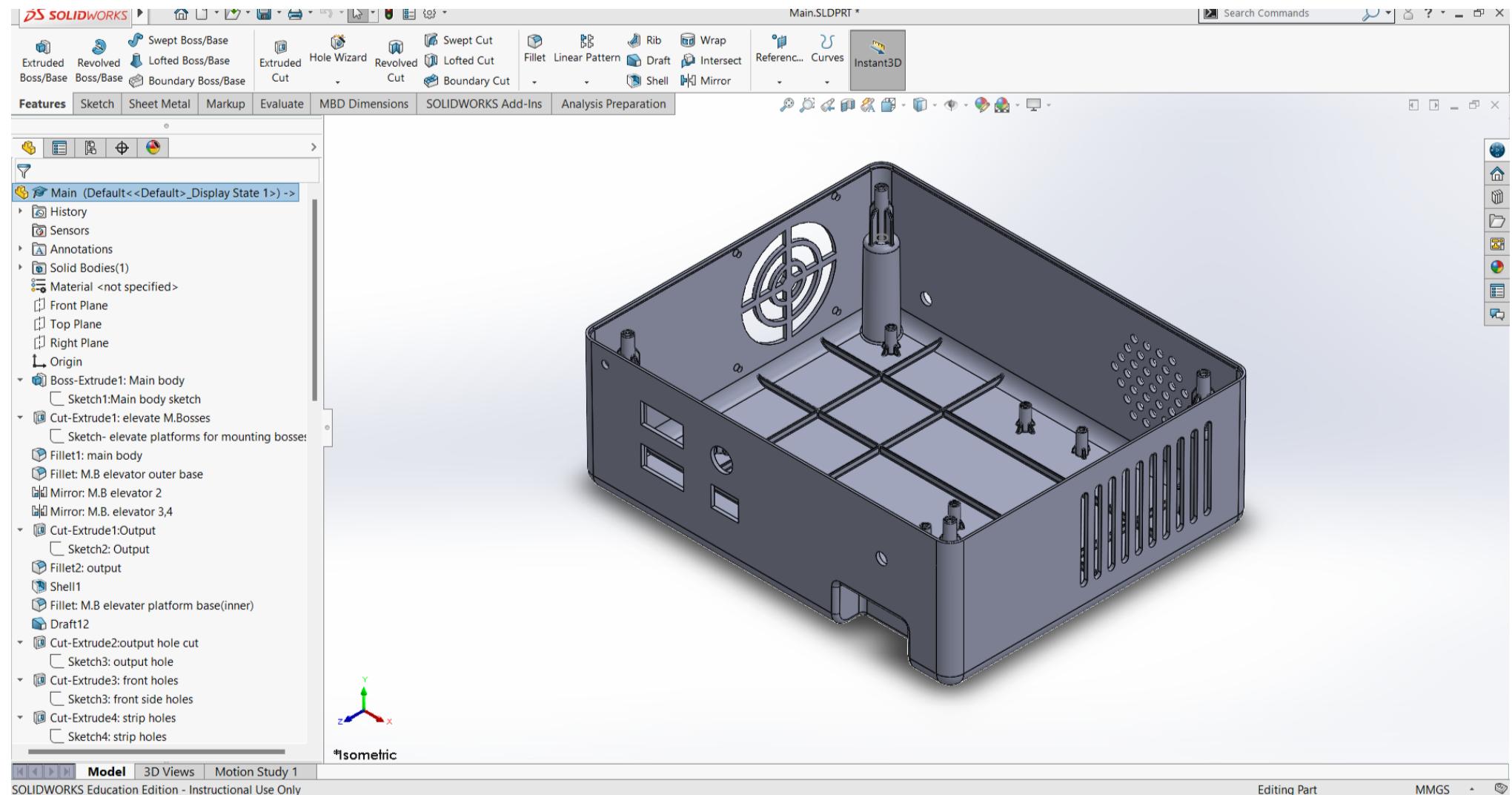


Figure 17: Isometric View - 1

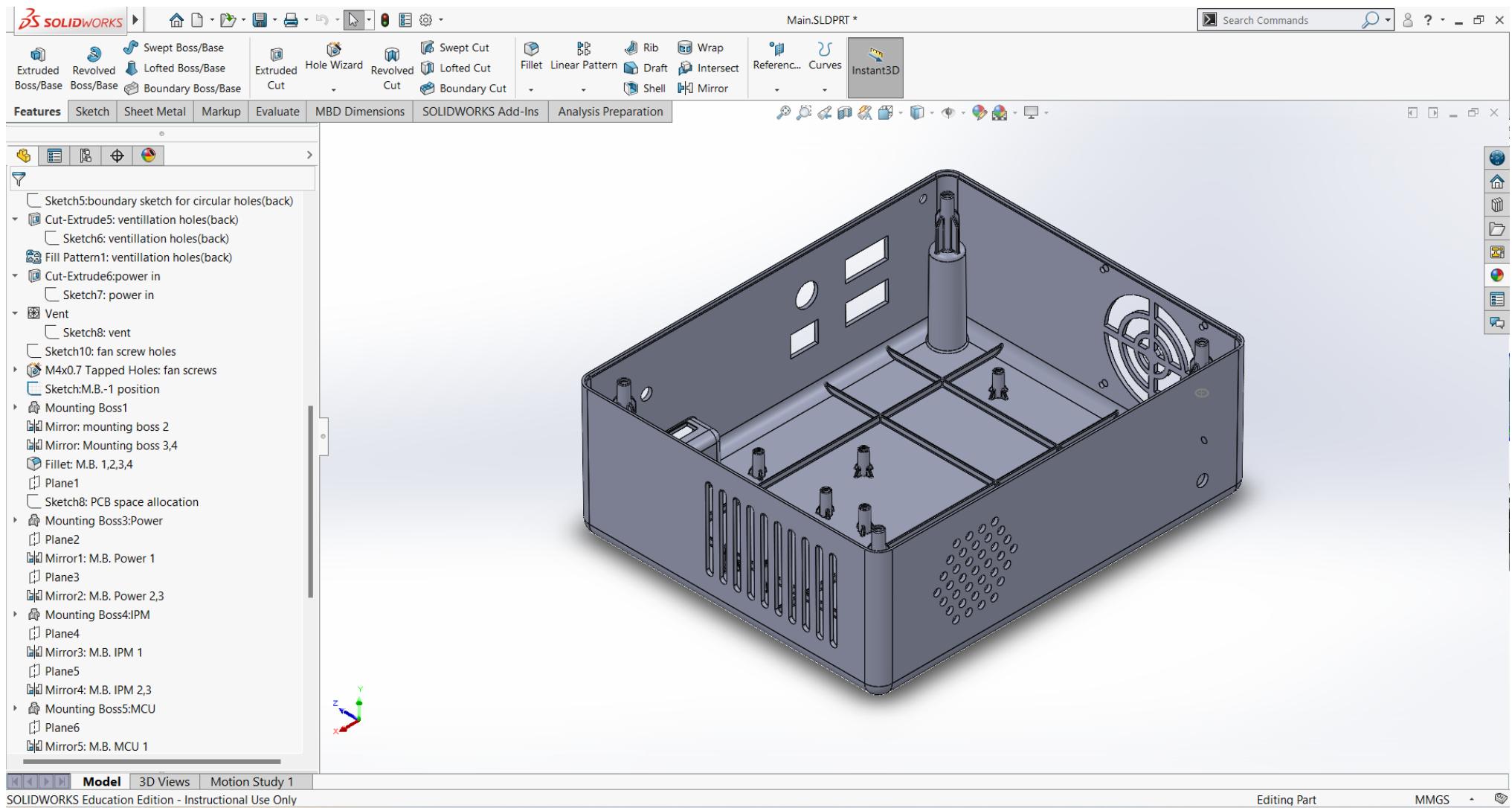


Figure 18: Isometric View - 2

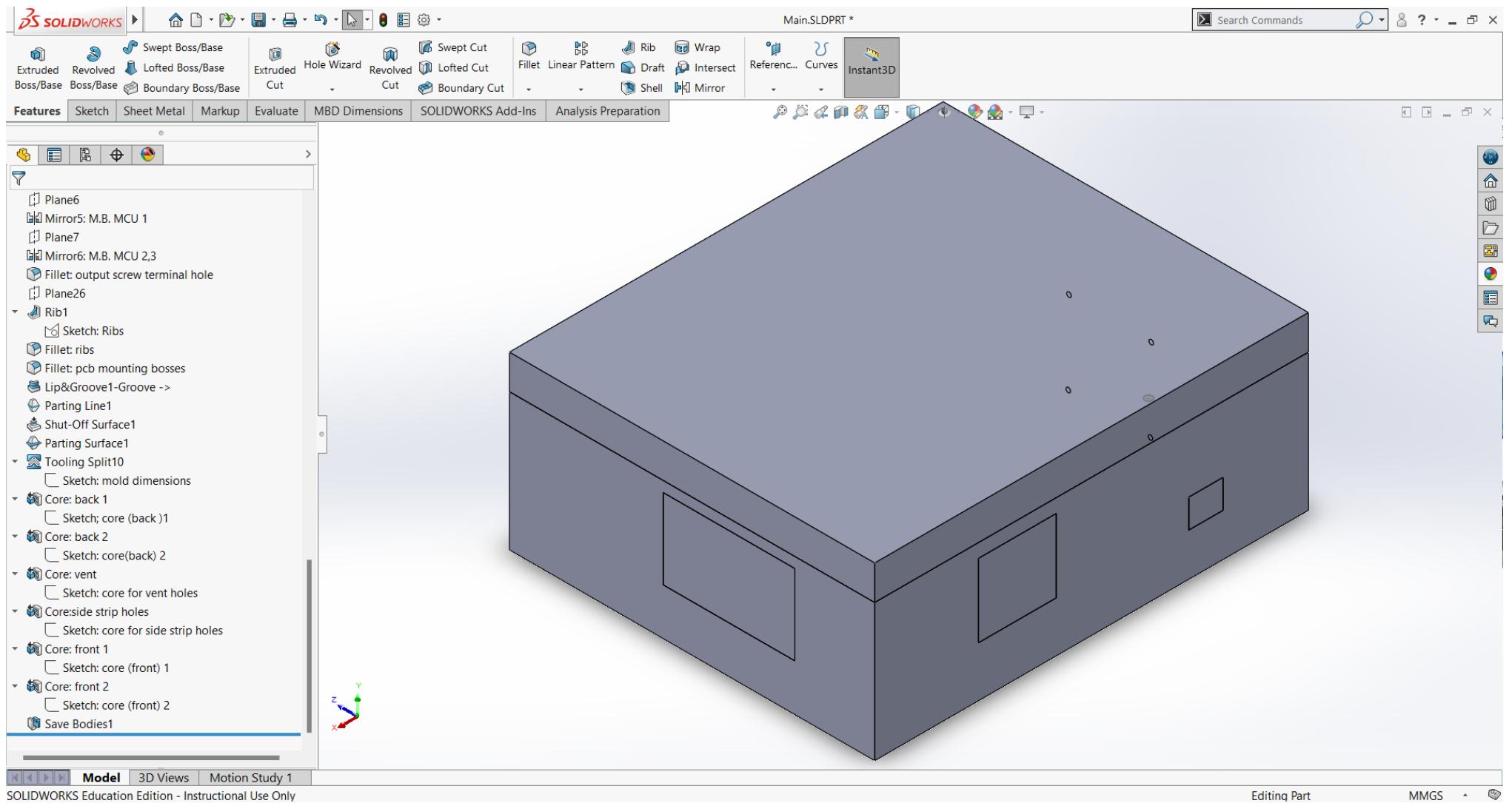


Figure 19: Isometric View - 3 (With The Mold Design)

13.3 Top Part - Design Tree

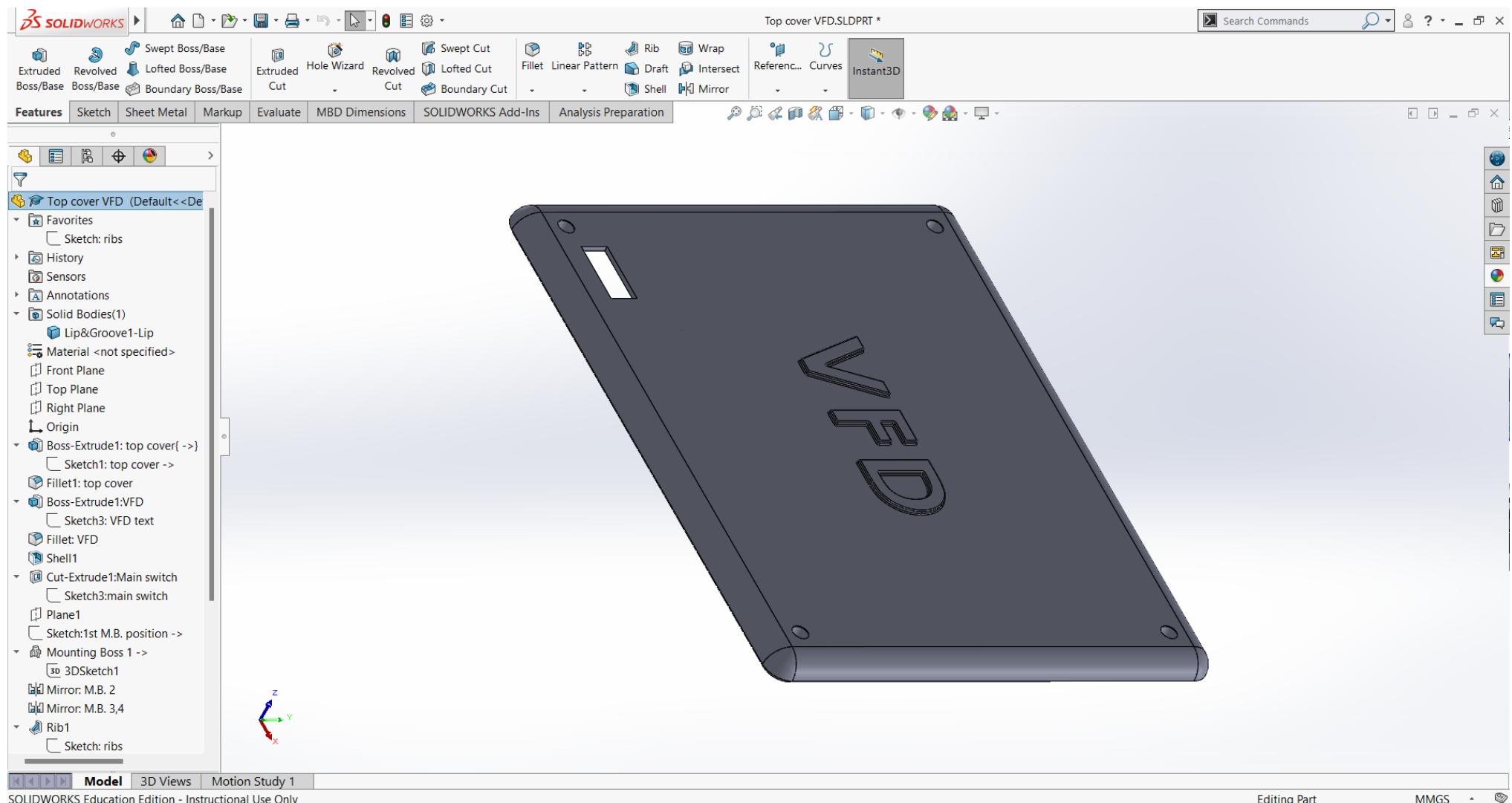


Figure 20: Isometric View - 1

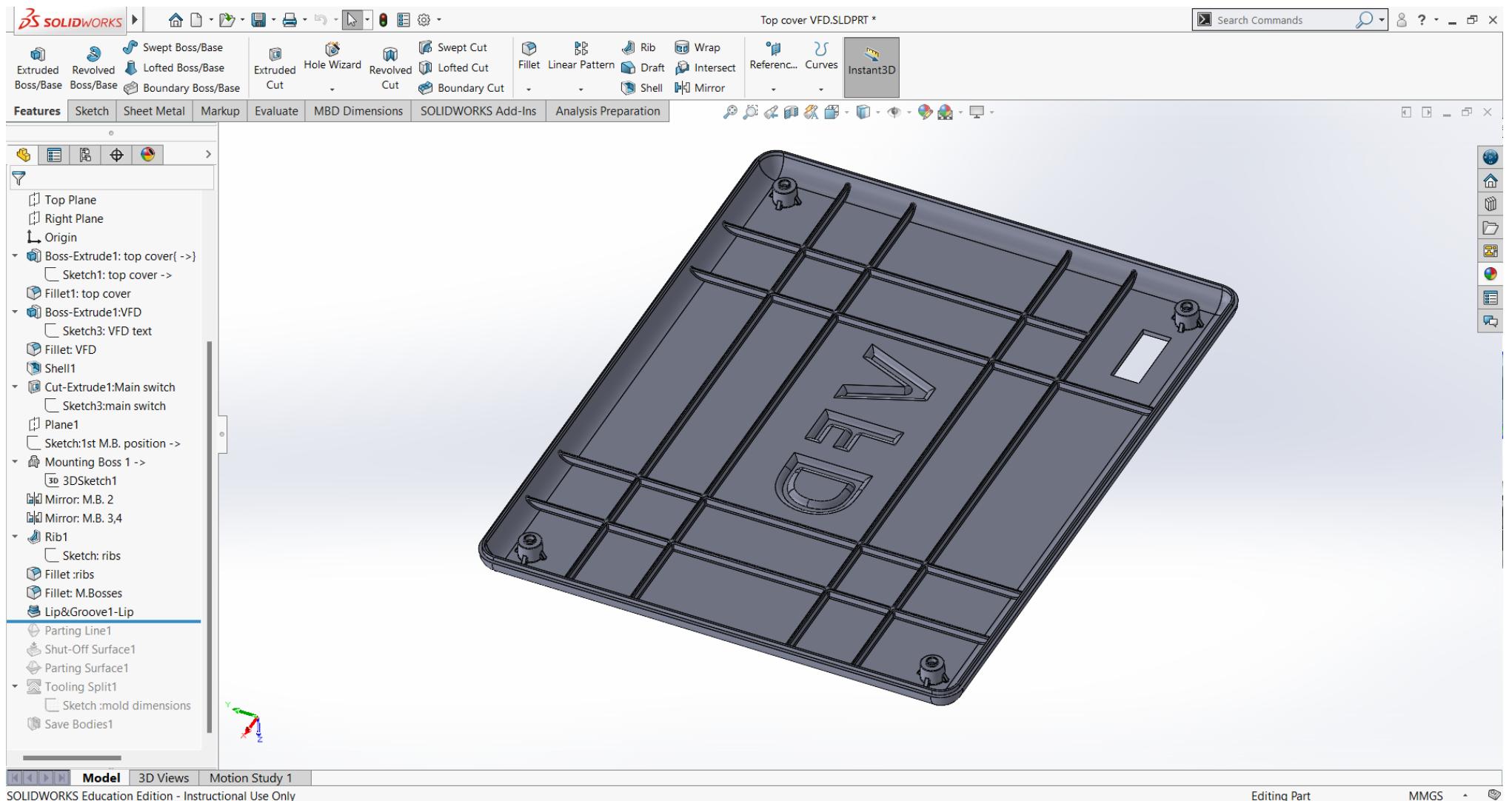


Figure 21: Isometric View - 2

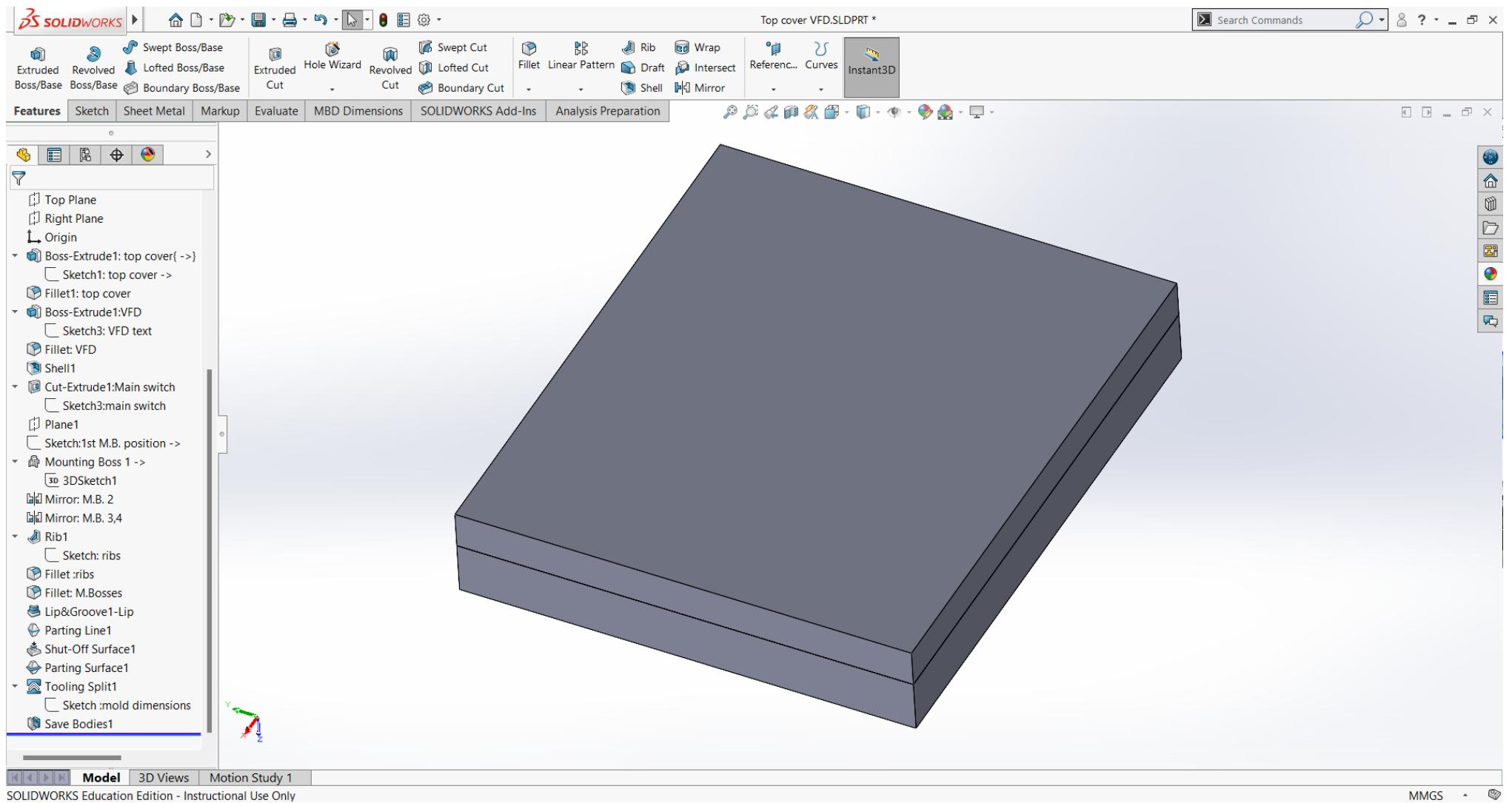


Figure 22: Isometric View - 3 (With The Mold Design)