WBG Devices-Based Matrix Converter for 3-Phase AC to DC Conversion in Industrial Computing Applications

Jack Alagood
Kyle Bedrich
Ian Farrar

CONCEPT OF OPERATIONS

REVISION – 1
15 September 2024

CONCEPT OF OPERATIONS
FOR
WBG Devices-Based Matrix Converter for 3-Phase AC to DC Conversion in Industrial Computing Applications

TEAM 403 URS HONORS ENJETI SECTION 1

APPROVED BY:

_Jack Alagood_____9/15/2024_
Project Leader Date

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Prof. Enjeti Date

_____
T/A Date

Change Record

Rev.	Date	Originator	Approvals	Description
-	9/15/2024	Kyle Bedrich		Draft Release
1	9/15/2024	Jack Alagood Ian Farrar		Revision 1

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1. Executive Summary

This project is the execution and testing of the developed framework behind a 3-phase AC to DC converter for efficient power conversion in certain computing applications. Our motivation is to build, test, and prove the developed framework. Our problem is the design and manufacturing of the board that will be used to test the developed framework, including component selection and simulation. Our research question is, will the 3-phase AC-DC conversion being tested be more efficient than other solutions for power conversion in computing applications?

The importance of our research topic comes from the increased demand for more efficient power conversion, especially at large scales like in industrial computing, where CPUs and GPUs need massive amounts of power to perform computationally expensive tasks. Grid load would decrease with more efficient power conversion, saving consumers and businesses money.

This project differentiates itself in its current research field by being a new topology for this kind of power conversion. It differentiates itself from other power conversion topologies with the same goal by removing the need for multiple stages, increasing efficiency. It also allows for reverse functionality, if the customer ever wanted to supply power back to the grid.

The expected outcomes of this research project are (1) to have a functioning, tested board that successfully steps down 3-phase AC to DC and can supply a load source with sufficient power, and (2) to have members' gain knowledge of the design, simulation, manufacturing, and testing of the board and its components.

2. Introduction

This document outlines a 3x1 matrix converter for AC to DC conversion in supplying power to industrial computing applications. The proposed system aims to improve power delivery efficiency, reducing losses, strain on the power grid, and costs for the user. Reducing these problems in industrial computing will alleviate current limits on data processing and its impact on society.

2.1. Background

Recent trends suggest society's technological demands are pushing the limits of our outdated energy infrastructure. The rise of energy-intensive computing (AI model training, cloud computing, data centers, etc.) creates a need to optimize power delivery to these loads. While many solutions have been presented to the industry over the years, there remains much room for improvement when it comes to overall efficiency and, consequently, cost. Improving efficiency and decreasing costs for industrial computing centers would increase scalability and assist emerging technologies to test the limits of big data.

To address this issue, we will present a three-phase AC to DC matrix converter. This system is composed of a primary and secondary side with power transfer occurring across a high frequency transformer. On the primary side, a 3x1 matrix converter serves as a space- and power-efficient method of converting a lower frequency three-phase input to a high frequency one-phase output [1]. On the secondary side, a rectifier converts the AC signal produced by the matrix converter into a DC output.

A high frequency (HF) transformer allows for high-density power processing [2]. The type of component should be chosen according to rating and power loss, amongst other properties.

Wide-bandgap semiconductors (WBGs) are used for their ability to operate at higher voltages than their regular semiconductor counterparts [1]. The 3x1 matrix converter utilizes WBG MOSFETs to create bidirectional switches that allow power to flow both to and from the load [3]. Sensors send readings about voltage levels and current flow to the control system. This enables soft switching to minimize switching losses and improve efficiency.

A pulse-width-modulation (PWM) buck rectifier limits the overall size of the necessary filtering components [4]. When choosing/designing rectifiers, one must keep in mind the effects of time harmonics to ensure they do not prevent the circuit from behaving as intended [1]. The risk posed by time harmonics can be measured using total harmonic distortion (THD).

As this device is expected to interface with industrial-level computers, its specifications should be designed according to industry standards. Implementing our matrix converter should ideally result in more efficient power delivery to appropriate loads.

2.2 Overview

The hardware will consist of a 3-phase input power filter, digitally controlled 3x1 matrix converter, HF transformer, rectifier, and output filter. The control systems include C2000 microcontroller controlling the FETs in the 3x1 matrix converter and collecting voltage and current data from the test PCB.

2.3 Referenced Documents and Standards

[1] S. Ratanapanachote, Cha Han Ju, and P. N. Enjeti, "A digitally controlled switch mode power supply based on matrix converter," IEEE Transactions on Power Electronics, vol. 21, pp. 124-130, 2006.

[2] J. J. Sandoval, S. Essakiappan and P. Enjeti, "A bidirectional series resonant matrix converter topology for electric vehicle DC fast charging," 2015 IEEE Applied Power Electronics Conference and Exposition (APEC), Charlotte, NC, USA, 2015, pp. 3109-3116.

[3] H. S. Krishnamoorthy, P. Garg, and P. N. Enjeti, "A matrix converter-based topology for high power electric vehicle battery charging and V2G application," in 38th Annual Conference on IEEE Industrial Electronics Society, 2012, pp. 2866-2871.

[4] V. Vlatkovic, D. Borojevic, and F. C. Lee, "A zero-voltage switched, three-phase isolated PWM buck rectifier," IEEE Transactions on Power Electronics, vol. 10, pp. 148-157, 1995.

3. Operating Concept

3.1. Scope

This project serves to further knowledge and research in the field of power conversion and delivery by assembling a PCB with contemporary technologies. The target client is industrial grade computers operating on high voltages and large power demands. Details on which circuit components are selected will be included in the appropriate reports.

3.2. Operational Description and Constraints

Although this system can be used for other purposes, the intended use case for this system is to supply power for industrial computing in large data centers, servers, etc. The system is designed to handle 1 kVA of power and should not be used in applications where more power is needed.

3.3. System Description

The 3x1 matrix converter will be composed of 3 parts: a primary side containing the AC-AC matrix converter, a secondary side containing an AC-DC rectifier scheme, and a control system. A high frequency transformer will facilitate the transfer of power from the primary side to the secondary side of the power module. Wide-bandgap semiconductors will be utilized as switches in the matrix converter and rectifier.

The system will be controlled using a Texas Instruments C2000 microcontroller. Sensors will be implemented in the control scheme to maintain the desired output. The sensors will also be used to implement zero-voltage switching to improve efficiency. A custom PCB will be designed to house the final design. Below is the circuit schematic for our proposed system.

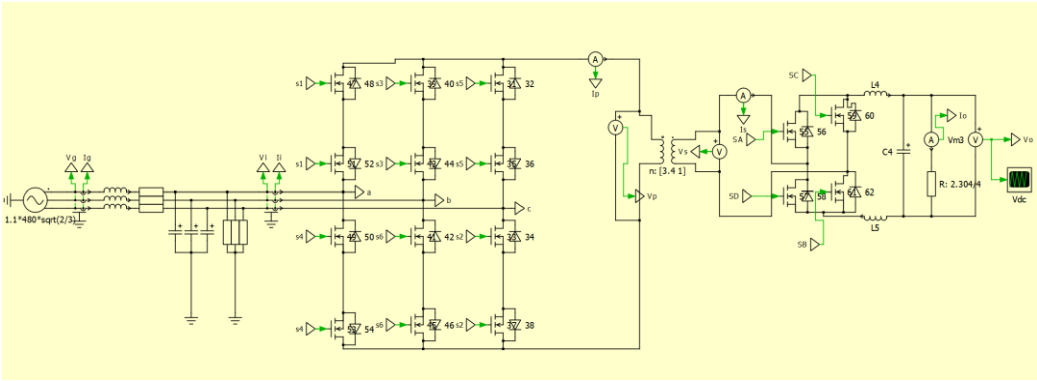

Figure 1: *Proposed 3x1 Matrix Converter Schematic*

3.4. Modes of Operations

The proposed system has two modes of operation. As a bidirectional system, the 3x1 matrix converter will be able to both consume power from the grid as well as supply it. This is useful in instances where the user has alternative power sources (installed solar panels, for example). When the alternative sources of power are able to meet the power demand and more, the 3x1 matrix converter will enter the Load to Grid mode of operation and begin supplying power instead of consuming.

3.5. Users

The primary user of our 3x1 matrix converter system is going to be large tech companies that have a need to supply power to their centralized data and computation centers. Due to the danger of the high voltages that this proposed system will interface with, electricians who have been trained to safely handle high voltage applications will be needed for installation.

This proposed system will most directly benefit the tech companies as they will be able to power their data centers at a reduced cost. This will also benefit society as a whole as reducing energy consumption alleviates strain on the power grid that all of society is dependent on.

3.6. Support

A user manual would be supplied to the user that describes how the 3x1 matrix converter interfaces with the grid (input) and the system being powered (output). A datasheet outlining system performance and behavior would also be provided so that the user can identify if the 3x1 matrix converter would suit their needs. A schematic similar to *Figure 1* would also be provided in this datasheet to aid in debugging if the user encounters issues in implementation.

4. Scenarios

4.1. Grid to Load

In a scenario where the user consuming power needs power from the grid, the proposed 3x1 matrix converter will operate in the Grid to Load mode of operation. Due to the heavy power consumption in the intended use case of this system (industrial computing), this scenario and mode of operation is where the system will be in the vast majority of the time.

4.2. Load to Grid

In a scenario where the user consuming power gets their needs met from alternative sources of power, the 3x1 matrix converter will enter the Load to Grid mode of operation. In this instance, the grid will be supplied by the excess produced by the alternative sources. This would likely only occur in an instance where the proposed 3x1 matrix converter is implemented outside of its intended use, supplying power for industrial computing. Another instance where this mode may be useful is in a case where a data center suffers damage to its computing infrastructure, wiping out the need for substantial power consumption.

5. Analysis

5.1. Summary of Proposed Improvements

The main improvement that this proposed system provides is that it is highly efficient, reducing energy consumption and costs for the user. This is achieved through utilizing zero voltage switching and a matrix converter which improves power factor more reliably than a typical electrolytic capacitor. This system also allows for bidirectional power flow, although this likely has little benefit for its intended use in industrial computing.

5.2. Disadvantages and Limitations

It’s worth noting the limitations of using a matrix converter, those being a capped voltage transfer ratio according to the input/output signals and notable vulnerability to power surges. Matrix converters also involve more semiconductor devices than their traditional counterparts, and for our specific case, finding and obtaining the necessary components will be a challenge unto itself.

5.3. Alternatives

As has been mentioned in previous sections, the common alternative to a 3x1 matrix converter is a phase-controlled converter which sacrifices control and efficiency for simplicity and affordability. While very applicable in industrial computing, these converters fail to optimize power delivery in part due to the need for multiple energy storage components.

5.4. Impact

One concern with the rise of industrial computing is the energy demand and the emissions produced in supplying that energy. This proposed system will reduce the energy loss in converting AC to DC power for data centers, decreasing energy consumption and emission production. Decreasing energy consumption also makes the computationally intensive tasks

handled in data centers cheaper, meaning problems we face today that require a large amount of computation to solve can be solved quicker and cheaper.

WBG Devices-Based Matrix Converter for 3-Phase AC to DC Conversion in Industrial Computing Applications

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FUNCTIONAL SYSTEM REQUIREMENTS

REVISION – 1
26 September 2024

FUNCTIONAL SYSTEM REQUIREMENTS
FOR
WBG Devices-Based Matrix Converter for 3-Phase AC to DC Conversion in Industrial Computing Applications

PREPARED BY:

_____
Author Date

APPROVED BY:

_Jack Alagood_____9/26/2024_
Project Leader Date

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John Lusher II, P.E. Date

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T/A Date

Change Record

Rev.	Date	Originator	Approvals	Description
-	9/26/2024	Jack Alagood		Draft Release

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1. Introduction

1.1. Purpose and Scope

This specification defines the technical requirements for the development items and support subsystems delivered to the client for the project. Figure 2 shows a representative integration of the project in the proposed CONOPS. The verification requirements for the project are contained in a separate Verification and Validation Plan.

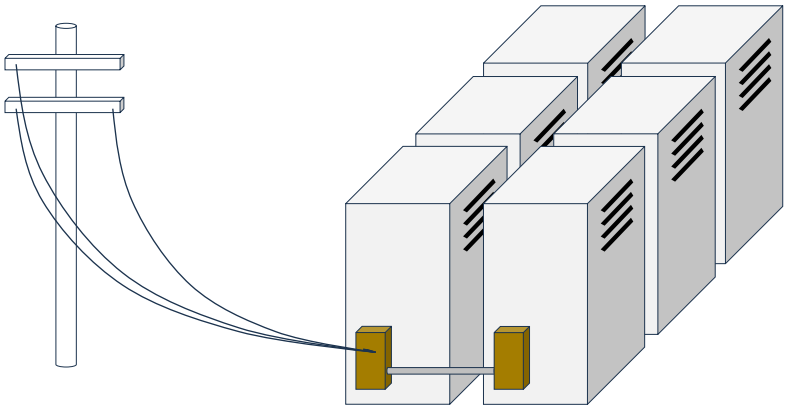

Figure 2. Conceptual application of 3x1 matrix converter

The following definitions differentiate between requirements and other statements.

Shall:	This is the only verb used for the binding requirements.
Should/May:	These verbs are used for stating non-mandatory goals.
Will:	This verb is used for stating facts or declaration of purpose.

1.2. Responsibility and Change Authority

Team leader Jack Alagood shall be responsible for ensuring all requirements are met. Any proposed changes in the design or deliverables shall be approved by Peng-Hao Huang and Jack Alagood. Kyle Bedrich is responsible for the controls subsystem. Jack Alagood is responsible for the primary side of the power electronics module. Ian Farrar is responsible for the transformer and secondary side of the power electronics.

2. Applicable and Reference Documents

2.1. Applicable Documents

The following documents, of the exact issue and revision shown, form a part of this specification to the extent specified herein:

Document Number	Revision/Release Date	Document Title
IEEE-1547-2018	2/15/2018	IEEE Standard for Interconnection and Interoperability of Distributed Energy Sources with Associated Electric Power Systems Interfaces
IEEE 519-2022	05/13/2022	IEEE Standard for Harmonic Control in Electric Power Systems
IEEE 1100-2005	12/09/2005	IEEE Recommended Practice for Powering and Grounding Electronic Equipment
ANSI/TIA-942	05/07/2024	Telecommunications Infrastructure Standard for Data Centers
IEC 61558	09/29/2017	Safety of Transformers, Reactors, Power Supply Units, and Combinations Thereof

2.2. Reference Documents

The following documents are reference documents utilized in the development of this specification. These documents do not form a part of this specification and are not controlled by their reference herein.

Document Number	Revision/Release Date	Document Title
SBAA565	Nov 2022	A Basic Guide to I2C

2.3. Order of Precedence

In the event of a conflict between the text of this specification and an applicable document cited herein, the text of this specification takes precedence without any exceptions.

All specifications, standards, exhibits, drawings or other documents that are invoked as “applicable” in this specification are incorporated as cited. All documents that are referred to within an applicable report are considered to be for guidance and information only, except ICDs that have their relevant documents considered to be incorporated as cited.

3. Requirements

3.1. System Definition

The project includes the design, fabrication, and testing of a 3-1 matrix converter topology. A PCB will be fabricated consisting of the components needed to operate, and a DSP or FPGA controller will be used to switch the 3-1 matrix converter.

Subsystems include:

- The power circuitry, which consists of FETs, LC tanks, a transformer and a rectifier circuit
- The control system, which controls the FETs in the 3-1 matrix converter
- The test board design, layout, and fabrication

These subsystems working in conjunction with each other create an operational system that can be tested with multiple 3-phase input voltage signals in any load condition.

3.2. Characteristics

3.2.1. Functional / Performance Requirements

3.2.1.1. Unity Power Factor

Unity power factor is the number one priority in any AC-DC conversion circuit, since it minimizes power loss due to reactive load, which results in money wasted.

- **Risk mitigation:** Extensive testing through simulations and bench testing will be done during and after control logic design and implementation to verify the simulations and unity power factor.

3.2.1.2. >1kW Load Capability

To meet the goal of this project, which is to supply servers that demand up to 1kW of power, this performance requirement must be met.

- **Risk mitigation:** FOS > 1.1 is required when selecting or designing components like FETs, transformers, or rectifier components.

3.2.1.3. Protection Circuitry

Since large AC voltages are being used in this project, protection circuitry will be used to protect the circuit from failure and the team from shocks.

- **Risk mitigation:** Protection circuitry will be implemented in the power circuitry and control logic/circuitry.

3.2.1.4. Inputs

a. Inputs to the control DSP/FPGA will be protected. One of the inputs is the 3-phase transmission line, whose signal is fed into a PLL which then goes to generate the 3-1 matrix converter switching signals.
b. Inputs to the power circuitry include an LC tank.

Rationale: Safety for the team, design, and customer are requirements.

3.2.1.4.1 Power Consumption

a. The maximum power provided to the load shall not exceed 1kW.

Rationale: This is a requirement specified by our customer due to constraints of their system as defined by the project.

3.2.1.4.2 Input Voltage Level

The input voltage level shall be between +120VAC to +230VAC.

Rationale: This is a system requirement defined by the customer, and is also a limitation of current materials technology.

3.2.1.5. Outputs

3.2.1.5.1 Performance Output

The control circuitry shall analyze the input and output signal/power to output efficiency, power factor, and other metrics important to the customer.

Rationale: The verification of system functionality and performance is a requirement to the customer.

4. Scenarios

The environment where this circuitry will be used in consist of:

- Operating at grid voltage with fluctuating voltage and frequency
- All load cases from 0W up to 1kW
- Hot enclosures with adequate airflow

The customer would use this type of circuit in an industrial computing application to power a server not exclusively but related to data storage, machine learning, CPU/GPU rendering, and cloud hosting/computing.

Appendix A: Acronyms and Abbreviations

AC	Alternating Current
CMOS	Complementary Metal Oxide Transistor
CPU	Central Processing Unit
DC	Direct Current
EN	Enable
FET	Field Effect Transistor
FPGA	Field Programmable Gate Array
GaN	Gallium Nitride
GPU	Graphics Processing Unit
IC	Integrated Circuit
IMS	Insulated Metal Substrate
I/O	Input/Output
MC	Microcontroller
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PCB	Printed Circuit Board
PWM	Pulse Width Modulation
RMS	Root Mean Square
SMT	Surface Mount
SR	Slew Rate
TIM	Thermal Interface Material
TH	Through Hole
THD	Total Harmonic Distortion
TTL	Transistor-Transistor Logic
V	Voltage
WBG	Wide Band Gap
3x1	Three to One
3-Φ	Three Phase

Appendix B: Definition of Terms

Boost	Increase in the context of voltage or current
Buck	Lower in the context of voltage or current
Duty Cycle	The fraction of a period in which a pulse is on
Power Density	The concentration of power per unit volume
Primary side	The main component(s) of the circuit
Pulse Width Modulation	Transform DC signals to AC
Rectify	Transform AC signals to DC
Secondary side	Supporting elements of a circuit
Step Down	Lower in the context of voltage or current
Step Up	Increase in the context of voltage or current
Topology	The structure or arrangement of circuitry
Total Harmonic Distortion	The distortion from an amplifier given as harmonic signals

WBG Devices-Based Matrix Converter for 3-Phase AC to DC Conversion in Industrial Computing Applications

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INTERFACE CONTROL DOCUMENT

REVISION – 1
26 September 2024

INTERFACE CONTROL DOCUMENT
FOR
WBG Devices-Based Matrix Converter for 3-Phase AC to DC Conversion in Industrial Computing Applications

PREPARED BY:

_____
Author Date

APPROVED BY:

_Jack Alagood_____9/26/2024_
Project Leader Date

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John Lusher II, P.E. Date

_____
T/A Date

Change Record

Rev.	Date	Originator	Approvals	Description
-	9/26/2024	Jack Alagood		Draft Release

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1. Overview

The Interface Control Document (ICD) for the 3x1 Matrix Converter provides quantitative data for the primary and secondary subsystems as well as listing what controls are in place for monitoring circuit behavior. Also included are the methods in which these pieces come together to accomplish the tasks set out in previous reports.

2. References and Definitions

2.1. References

IEEE Standard for Interconnection and Interoperability of Distributed Energy Sources with Associated Electric Power Systems Interfaces (IEEE-1547-2018)
15 Feb 2018

IEEE Standard for Harmonic Control in Electric Power Systems (IEEE 519-2022)
13 May 2022

IEEE Recommended Practice for Powering and Grounding Electronic Equipment (IEEE 1100-2005)
9 Dec 2005

Telecommunications Infrastructure Standard for Data Centers (ANSI/TIA-942)
7 May 2024

Safety of Transformers, Reactors, Power Supply Units, and Combinations Thereof (IEC 61558)
29 Sep 2017

2.2. Definitions

FPGA	Field-Programmable Gate Array
DSP	Digital Signal Processor
PCB	Printed Circuit Board
GaN	Gallium Nitride
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PWM	Pulse Width Modulation
WBG	Wide Band Gap
AC	Alternating Current
DC	Direct Current

3. Physical Interface

3.1. Weight

The majority of the weight in this power module will come from the transformer. Using a transformer similar to what will be using, the transformer should weight around 30-35 pounds and the system as a whole should be less than 50 pounds.

3.2. Dimensions

3.2.1. C2000 Development Board

- 2300 mil X 5500 mil

3.2.2. FPGA

- 9.5” X 7.53” X 0.061”

3.2.3. High Frequency Transformer

- 8.13” X 6.38” X 6.00”

4. Thermal Interface

Due to the high power passing through this power module, thermal management techniques need to be applied to cool the heat generating components like inductors, transformers, and MOSFET's. Heat sinks shall be placed on the PCB to help distribute heat. Data centers utilize specialized air condition units, fans, and other cooling techniques to keep the computing racks cool. This power module should be provided with similar resources to maintain a cool operating temperature.

5. Electrical Interface

5.1. Primary Input Power

Power for the matrix converter is supplied by 12V sources which can be stepped down to 5V or 3.3V using buck converters.

5.2. Voltage Sensors

The AMC3330 voltage sensor runs off of 3.3V or 5V and is responsible for tracking the performance of the matrix converter with precise voltage measurements. The device operates within the range of temperatures expected in its application(s).

5.3. User Interface for Performance Analysis

The TI F2837x board will be used to analyze the performance metrics of the 3x1 matrix converter, including but not limited to power factor, input and output factor.

6. Communications / Device Interface Protocols

6.1. Universal Serial Bus (USB)

In order to program the DSP or FPGA used to control the FET gates in the 3-1 matrix converter, USB must be used to connect and program it. USB will also be used in the final design to communicate with a PC to analyze performance metrics.

WBG Devices-Based Matrix Converter for 3-Phase AC to DC Conversion in Industrial Computing Applications

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Ian Farrar

EXECUTION PLAN

REVISION – 3
28 April 2025

Execution Plan Revision - 3

WBG Devices-Based Matrix Converter for 3-Phase AC to DC Conversion in Industrial Computing Applications

ECEN 403	Owner(s)	8/19/2024	8/26/2024	9/2/2024	9/9/2024	9/16/2024	9/23/2024	9/30/2024	10/7/2024
URS Program Application	Each								
Analyze Prior Studies	Each								
Acquire Software Licenses	Each								
Concept of Operations Report	Group								
Research	Each								
Functional System Requirements	Group								
Interface Control Document	Group								
Validation Plan	Jack								
Design and Simulation	Each								
Midterm Presentation	Group								
PCB Design	Jack								
		10/14/2024	10/21/2024	10/28/2024	11/4/2024	11/11/2024	11/18/2024	11/25/2024	12/2/2024
PCB Design	Jack								
Status Update Presentation	Group								
Final Presentation	Group								

Legend
Complete
In Progress
Overdue
Not Started

ECEN 404	Owner(s)	1/12/2025	1/19/2025	1/26/2025	2/2/2025	2/9/2025	2/16/2025	2/23/2025	3/2/2025
Schematic 3-phase Extension	Jack								
PCB 3-phase Extension	Jack								
Transformer Design	Ian								
DSP Debugging	Kyle								
DSP Testing	Kyle								
Simulations	Each								
		3/9/2025	3/16/2025	3/23/2025	3/30/2025	4/6/2025	4/13/2025	4/20/2025	4/27/2025
Transformer Testing	Ian								
Assembly	Group								
Testing	Group								
Final Presentation	Group								
Final Demo	Group								
Final Report	Group								

WBG Devices-Based Matrix Converter for 3-Phase AC to DC Conversion in Industrial Computing Applications

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VALIDATION PLAN

REVISION – 3
28 April 2025

WBG Devices-Based Matrix Converter for 3-Phase AC to DC Conversion in Industrial Computing Applications

Task	Deadline	Status
URS Program Application	9/3/2024	Complete
Analyze Prior Studies	9/5/2024	Complete
Acquire Software Licenses	9/5/2024	Complete
Concept of Operations Report	9/15/2024	Complete
Research	9/19/2024	Complete
Functional System Requirements	9/26/2024	Complete
Interface Control Document	9/26/2024	Complete
Validation Plan	9/26/2024	Complete
Design and Simulation	10/10/2024	Complete
Status Update Presentation	10/23/2024	Complete
Midterm Presentation	10/10/2024	Complete
PCB Design	11/25/2024	Complete
Final Presentation	12/7/2024	Complete

Task	Deadline	Status
Schematic 3-phase Extension	1/31/2025	Complete
PCB 3-phase Extension	2/21/2025	Complete
Transformer Design	2/28/2025	Complete
Transformer Testing	3/28/2025	Complete
DSP Debugging	2/14/2025	Complete
DSP Testing	2/28/2025	Complete
Simulations	3/7/2025	Complete
Board Assembly	4/4/2025	Complete
Board Testing	4/11/2025	Complete
Final Presentation	4/16/2025	Complete
Final Demo	4/26/2025	Complete
Final Report	4/28/2025	Complete

Legend
Complete
In Progress
Overdue
Not Started

WBG Devices-Based Matrix Converter for 3-Phase AC to DC Conversion in Industrial Computing Applications

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SUBSYSTEM REPORTS

REVISION – 2
28 April 2025

SUBSYSTEM REPORTS
FOR
WBG Devices-Based Matrix Converter for 3-Phase AC to DC Conversion in Industrial Computing Applications

PREPARED BY:

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_Jack Alagood_____4/28/2025_
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John Lusher II, P.E. Date

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T/A Date

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-	12/4/2024	Jack Alagood		Draft Release
1	4/28/2025	Jack Alagood		Final Submission

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1. Introduction

The 3x1 matrix converter functions as a step down AC/DC converter and is intended for use in high voltage environments such as data centers. The system is divided into three subsystems: primary side, secondary side, and controls.

2. Primary Side Subsystem Report

2.1. Subsystem Introduction

Shortly after the project's proposal, the elephant in the room for designing the matrix converter was a complete lack of knowledge of PCB design as well as Altium Designer. In retrospect, an attempt to create the final product right out of the gate would have likely ended in failure; we needed at least an elementary understanding of PCB design standard practices and the Altium interface to create something cohesive. After discussing with our faculty advisor Dr. Prasad Enjeti and his graduate assistant Peng-Hao Huang, it was decided that our team would spend the first portion of the project timeline making a single-phase prototype converter, then adapt it to be three-phase once most of its issues were resolved. As a result of this plan, a majority of issues were addressed prior to making the final product.

2.2. Subsystem Details

Like the matrix converter, the single-phase converter was given no limitations on size or weight beyond industry standards, which were quite lax, thus initial drawings for the prototype could take any form, so long as the following PCB best design practices were maintained:

1. Minimum part dimensions set at 1206 (for easier soldering)
2. Low and high voltage systems must be far enough apart to prevent risk of shorting
3. Where copper pours are not appropriate, HV traces must be very thick (~50 mils)
4. Traces should be as short as possible
5. Decoupling capacitors should be placed adjacent to their respective power supply

Following these guidelines, we came to the following layout. High voltage components are contained in a central area surrounded by low voltage traces and pours that reach around to connect the voltage sensors back to their designated pins.

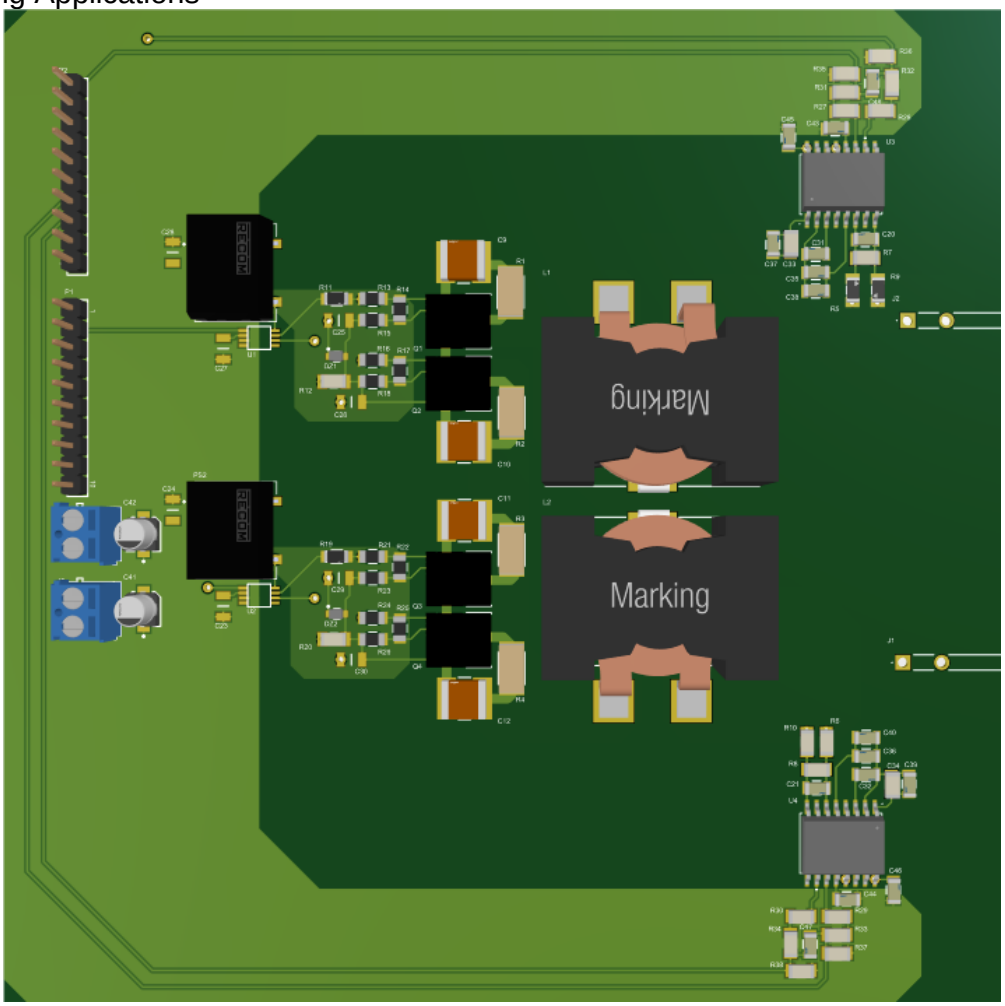


Figure 1. Single-phase converter PCB prototype

Note that in comparison to the end product, this prototype is incomplete. Several changes such as bringing the two switches closer to one another, resizing the traces to the left of the GaN FETs, and adjusting the position and orientation of the LC filters to better align with the RC snubbers are needed. The smaller details were also ignored for the time being.

The 3x1 matrix converter would ultimately take on a different layout than its predecessor. Rather than surrounding HV components with LV, we have LV components north of the board and HV to the south (**Figure 2**). This allows for easier access to HV inputs and outputs and ensures most connections stay relatively straight.

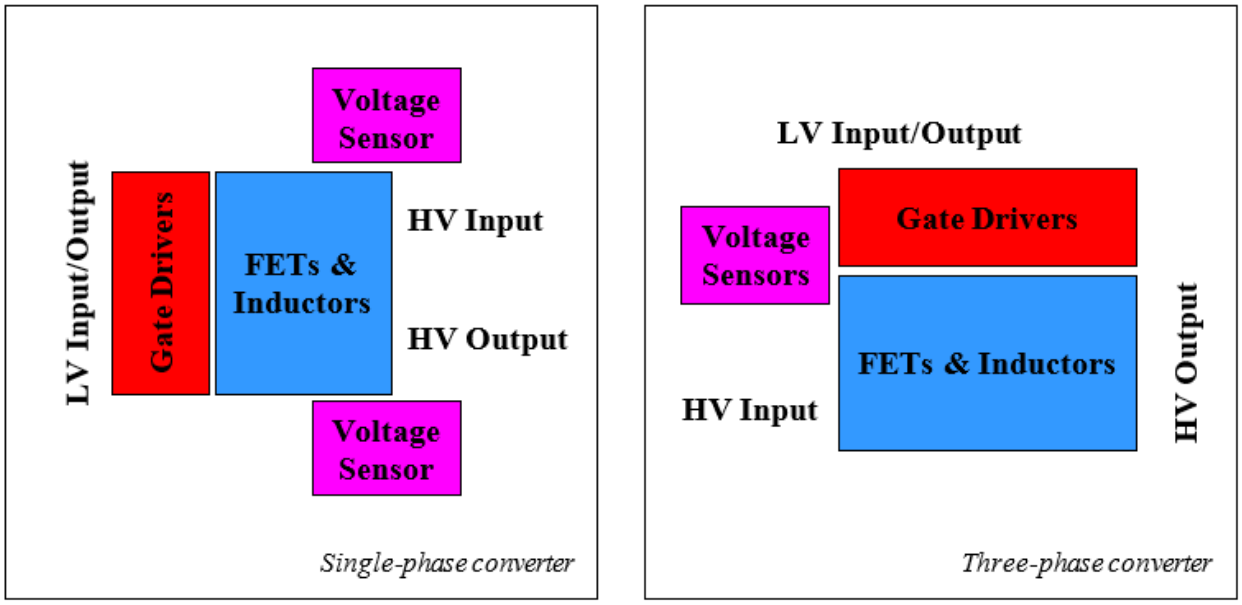


Figure 2. Single- and three-phase converter PCB layouts (not to scale)

Whereas the prototype PCB only uses a top and bottom layer, the three-phase board requires six: one layer per phase, two for input/output signals, and one layer for separation. From top to bottom, the netlists with copper pours per layer are:

1. **A**, **A_src**, and **GND**
2. **B**, **B_src**, and **GND**
3. **C**, **C_src**, and **VEE**
4. **+5 V** (aka **EN**)
5. **+12 V** and **Vmc_P**
6. GND and **Vmc_N**

Netlists **A_src**, **B_src**, and **C_src** are the per phase input powers from a 230 V transmission line (note that additional protections would need to be put in place prior to making this connection). Signals **Vmc_P** and **Vmc_N** are the positive and negative matrix converter outputs, respectively; they are to be the inputs for the HF transformer described in section 3.2. Layer 4 separates the inputs from the outputs, and PCB stands allow for vertical stacking.

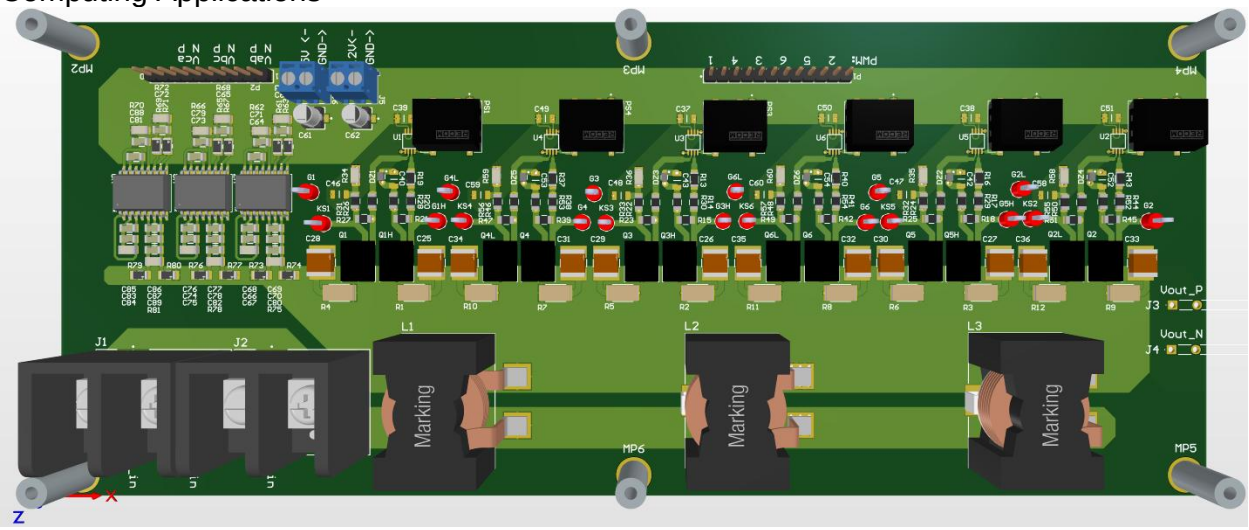


Figure 3. 3-phse matrix converter (top view)

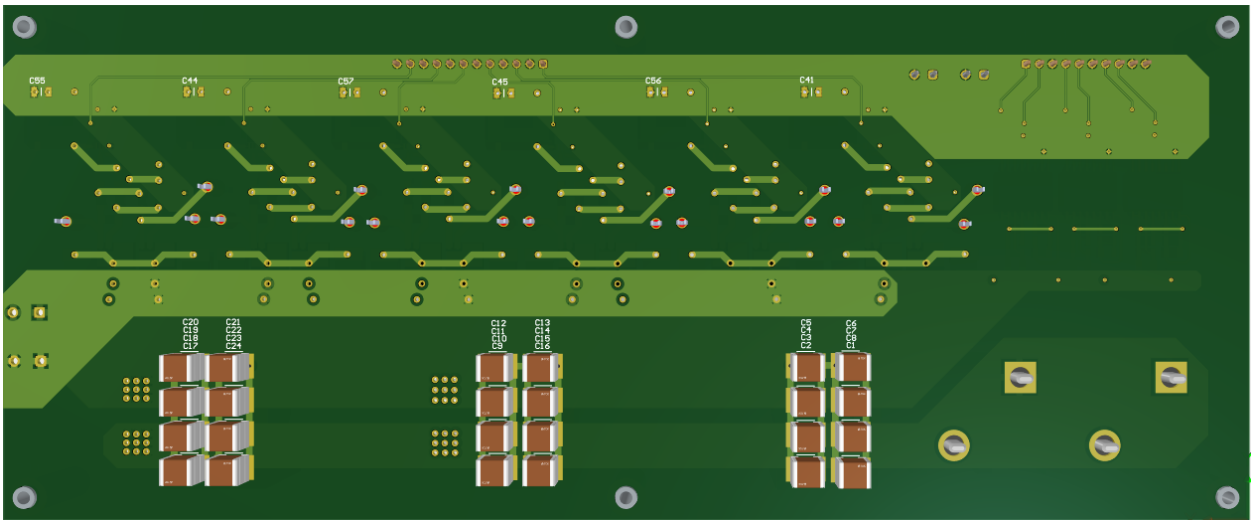


Figure 4. 3-phase matrix converter (bottom view)

To summarize the power flow through the board, we begin at the north edge where there are six pins dedicated to the PWM signals sent from the controls described in section 3.3. Each **PWM** pin is juxtaposed with **GND** pins to avoid shorting and is arranged closest to its corresponding gate driver. The gate drivers are ordered 1-4-3-6-5-2 left to right because this arrangement minimizes the length of connections within netlists **A**, **B**, **C**, **Vmc_P**, and **Vmc_N**. The gate drivers can operate with 3.3 V or 5 V, but we selected 5 V as no other components require 3.3 V. To the right of each gate driver is a RECOM® power supply labeled that accepts 12 V.

Each gate driver's output is fed through a series of resistors and capacitors before reaching the gate and Kelvin source terminals of two GaN FETs. These signals are designated test points. One FET is attached to a filtered input phase voltage **A** (drivers 1 and 4), **B** (3 and 6), or **C** (5 and 2) at its drain. The other's drain is connected to either **Vmc_P** or **Vmc_N** and is designated an "H" for high or "L" for low.

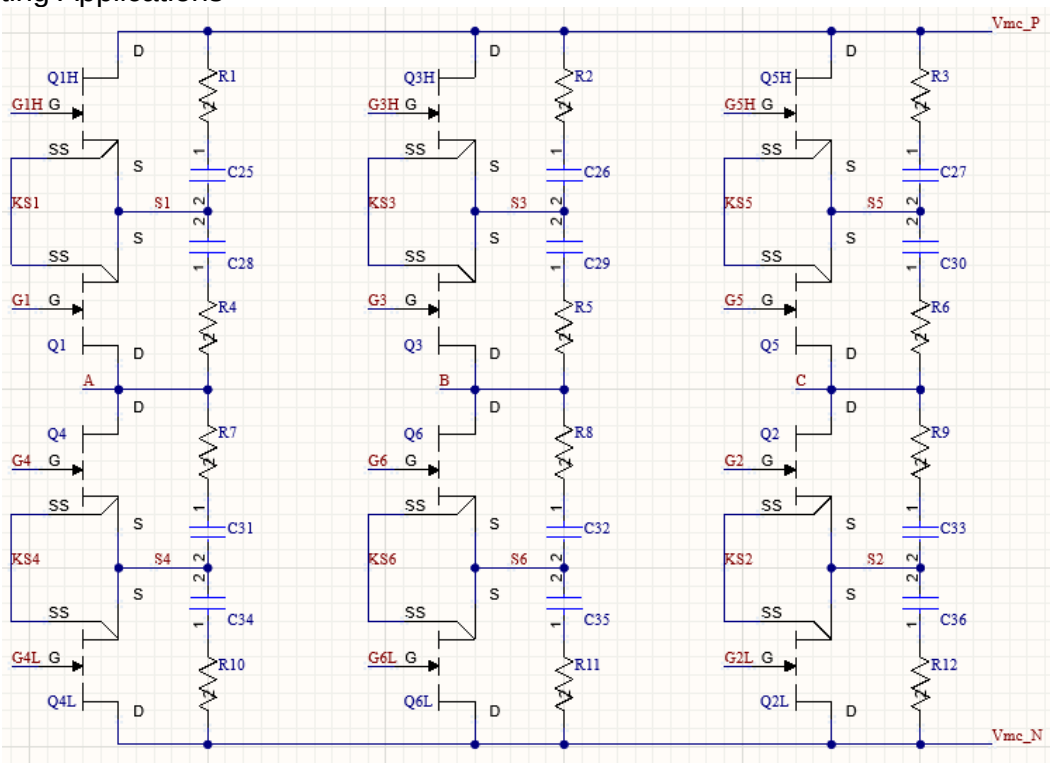


Figure 5. 3-phase matrix converter schematic

It is at this point that by the switching algorithm from the controls scheme, the PWM signals and gate drivers should have successfully gated the FETs to transform our 3-phase AC input to a single-phase high frequency AC output. **Vmc_P** and **Vmc_N** are sent to the output tabs “Vout_P” and “Vout_N” found on the right side of the board. The remaining outputs all come from the voltage sensors; signals **A**, **B**, and **C** enter resistors R73 through R81 on the south side of the sensors, and the voltages between phases are input as **Vab**, **Vbc**, and **Vca**. The voltage sensors then output a much lower but proportional voltage that’s safe to be read by lab equipment. These voltages, **SENab**, **SENbc**, and **SENac** can be measured at pin header “P2”, placed near the board’s northwest corner.

2.3. Subsystem Validation

Validation was conducted in three parts: board continuity, component continuity, and voltage verification. To ensure that the manufactured PCB had no flaws, all 421 board connections were checked using a multimeter. The positive and negative terminals were placed at separate pads or vias that are part of the same net, and if the multimeter beeped, then the connection between the two is marked as “TRUE”. If even one connection did not pass this test, the board would have to be deemed defective, and one of the backup boards would go through the same procedure. Fortunately, all 421 connections were confirmed on the first board, meaning 100% continuity.

With a properly manufactured PCB, the next step is to solder the components. It was recommended that parts be affixed to the board by section and in order of ascending height. Because the GaN FETs are much more expensive relative to the rest of the parts, we were

instructed to solder those last, or have someone more experienced solder them instead. The order for which sections of the PCB would be soldered first is given below:

1. Voltage sensors
2. Gate driver
3. Power supply
4. Stands
5. Low voltage input
6. Input filter
7. High voltage output
8. GaN FETs

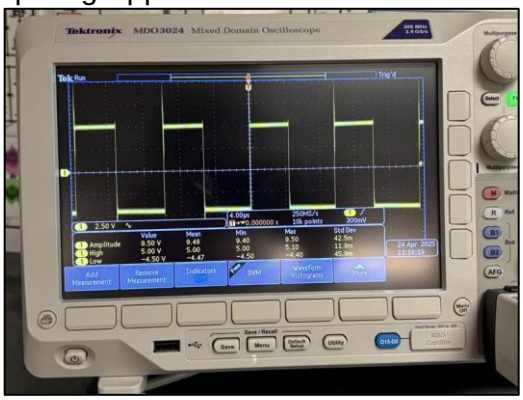
Due to time constraints, only one leg of the matrix converter would be soldered and tested for the time being. It is also better to test one leg before moving on to the rest. With 223 successfully soldered connections for input **A**, component continuity remains at 52.97% until the first leg of the converter is confirmed operational, at which point the remaining components for inputs **B** and **C** will be added.

The third stage of validation is voltage verification. Using a power supply to provide the board with +5 and +12 volts, the voltage at every point in the board is tested and compared to their expected value. Due to time constraints, only the most important part of the board, the gate driver, has been tested. Measured and expected voltages for the **VEE** and **VDD** terminals of gate drivers U1 and U4 are given below. These values are all accurate enough to meet our expectations.

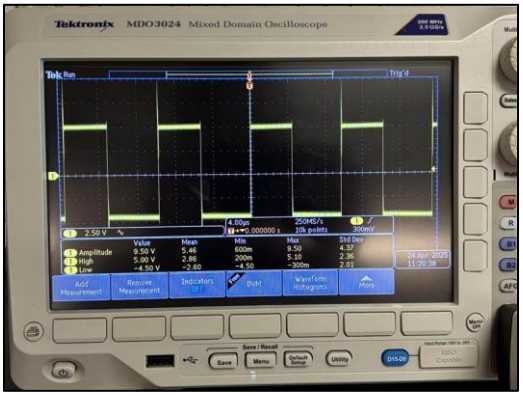
Table 1. Gate driver terminal voltages

From Net	To Net	Volts Measured	Volts Expected	Difference
VDD1	**T1**	6.141	6	0.141
VEE1	**T1**	-3.447	-3	-0.447
VDD1	**VEE1**	9.580	9	0.580
VDD4	**T4**	6.191	6	0.191
VEE4	**T4**	-3.396	-3	-0.396
VDD4	**VEE4**	9.590	9	0.590

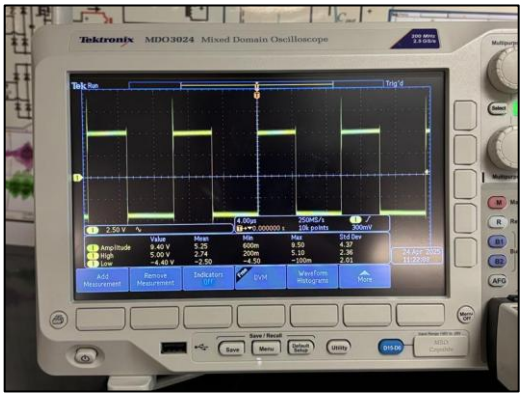
Figure 6 shows the square-wave behavior from the gate terminal outputs with respect to their Kelvin source for the aforementioned drivers.



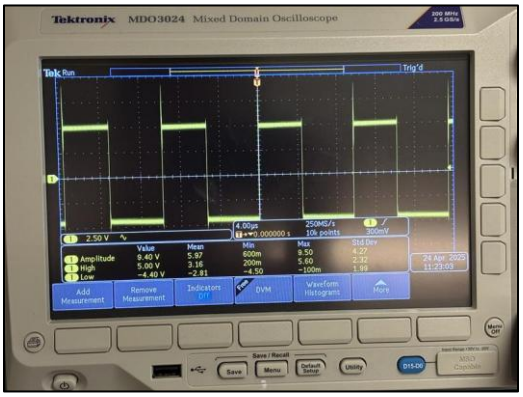
G1



G1H



G4



G4L

Figure 6: Gate driver gate terminal outputs

2.4. Subsystem Conclusion

The drivers work as intended, as does the general power flow of the PCB, but there is more to be done before a complete demonstration can happen. Future versions of this design will include a heat sink for prolonged operation and ideally utilize a cheaper FET as gallium nitride technology becomes more mainstream in the market.

3. Secondary Side Subsystem Report

3.1. Subsystem Introduction

The secondary side is composed of the high frequency, step down transformer, rectifier, and a filter to reduce ripple. With the rectifier and filter design already being completed, the focus of the

3.2. Subsystem Details

The high frequency transformer needs to step down 400 V (RMS) to 50 V (RMS). It needs to be able to handle at least 5.4 A (RMS) from the primary winding and output 18 A (RMS) on the secondary winding. The transformer will be designed to handle 430 V (RMS) and 7 A (RMS) on the primary side and 60 V (RMS) and 21 A (RMS) on the secondary side to ensure

functionality at the required values. It will need to be able to handle switching frequencies of 100 kHz while minimizing losses.

3.3. Subsystem Validation

The first step taken in the transformer design process was to create a transformer model in Ansys Maxwell to become familiar with the software. The main limitation of this model was the lack of parameterization, making it difficult to make tweaks to the design. A toroid core was chosen to minimize losses. This first model created is shown below in *Figure 6.*

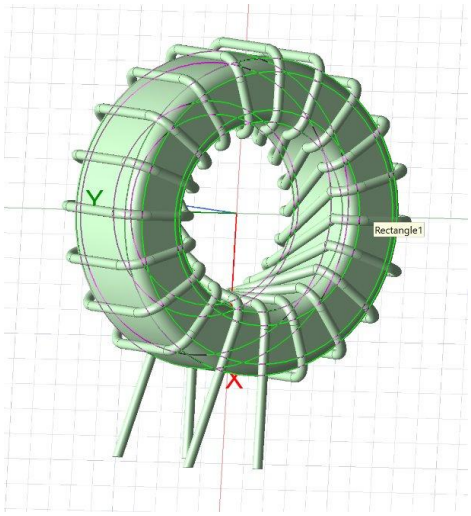


Figure 7: Initial Ansys Maxwell model

The next task was to begin parameterizing models to make tweaking values easier. The task for the semester also became designing an inductor first as an introduction to electromagnetic design. E cores became the focus of model development due to the ease of winding and assembly, although toroid core designs will be later developed for comparison before making a final decision. Below is the first parameterized E core design. Core and winding dimensions and number of turns (limited by core arm length) are all easily adjusted using model variables.

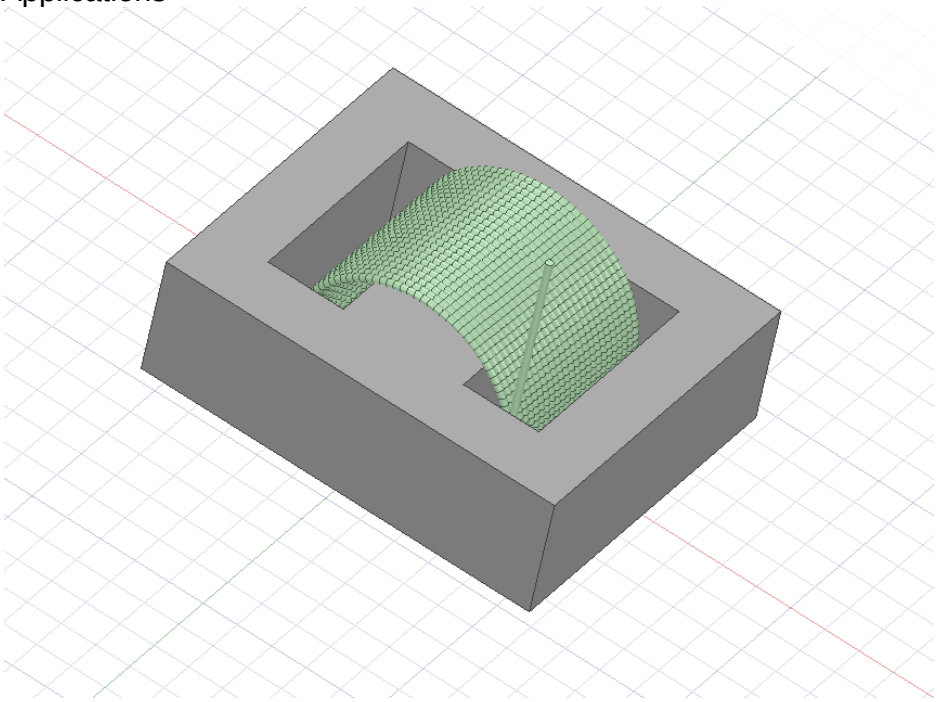
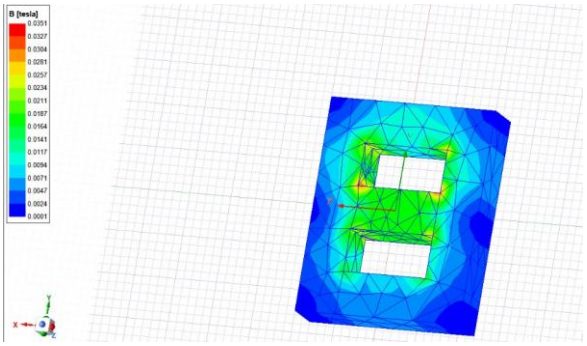


Figure 8: Parameterized E core model

Using this model, simulations were conducted. The performance of the model was poor due to poor dimensioning. The priority at this point was completing a model and running simulations before going back and redesigning and changing parameters to achieve desired behavior.



	Time [us]	HysteresisLoss [kW] Setup1 : Transient
1	0.000000	0.000000
2	0.100000	0.335077
3	0.200000	1.459293
4	0.300000	3.977158
5	0.400000	7.561780
6	0.500000	12.096791
7	0.600000	17.409311
8	0.700000	23.328920
9	0.800000	29.574853
10	0.900000	35.968416
11	1.000000	42.198275
12	1.100000	48.012673

Figure 9: Preliminary simulation results

After successfully running simulations, the next task was to go back and improve the model. An inductance of 1.5 mH was set as the goal for the inductor design. A Mu Kool Core was selected due to its high saturation limits. The 114LE E Core with a relative permeability was chosen due to its high inductance per turn squared. Because the device will be operating at high frequencies, reducing the number of turns is important to reduce parasitic effects. With a value of 445 nH / Turn Squared, at least 58 turns would be needed to achieve the desired inductance. This would require multiple layers of winding due to the limited space along the core's arm.

The next model attempt is seen below in *Figure 10*. A more complex winding geometry was introduced to more closely emulate the real winding geometry and more efficiently utilize the window area between core arms. Alongside the complexity of this winding geometry came difficult to resolve errors that inhibit simulation.

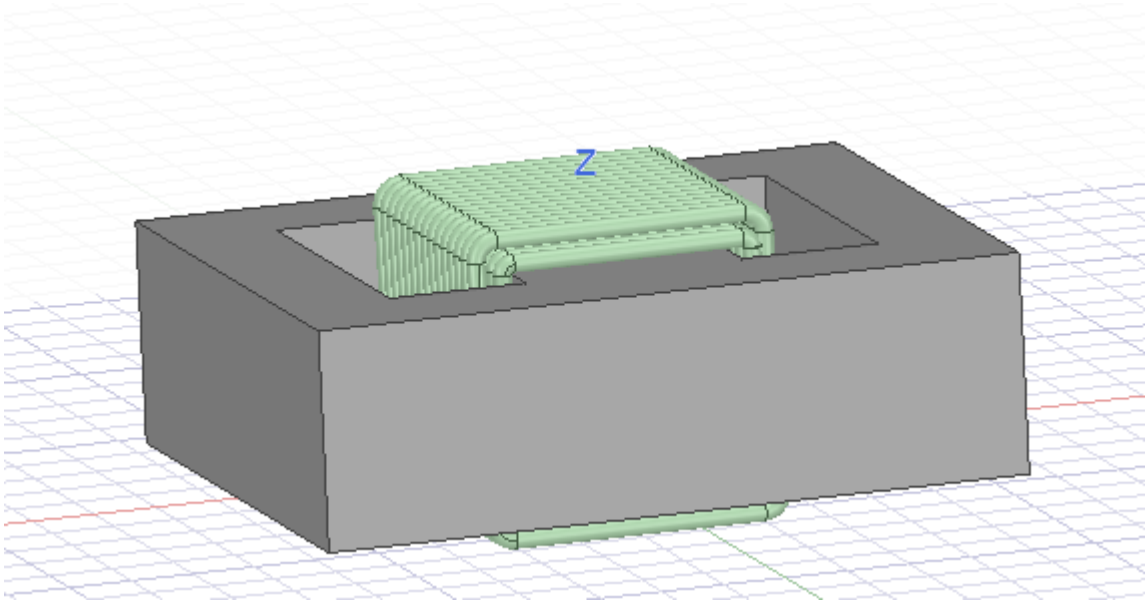


Figure 10: E Core with multi-layer winding and more complex winding geometry

Currently, a new model utilizing the winding geometry seen in *Figure 7* is underway to more simply implement multi layered winding and complete simulations. While not as close in resemblance to what a real inductor winding would look like, the simulation results should prove sufficient.

3.4. Subsystem Conclusion

Significant progress in understanding Ansys Maxwell and inductor design has been made. Final steps in completing inductor design, modeling, and simulation will take place over the last few days of the semester before moving onto transformer design.

4. Controls Subsystem Report

4.1. Subsystem Introduction

The controls subsystem is the control logic and circuitry that controls the gate drivers. It is connected to the 3-1 matrix converter, which converts a 3-phase signal into an AC signal.

4.2. Subsystem Details

The control subsystem is comprised of logic and hardware. The logic converts a 3-phase signal to an AC signal using a logic circuit consisting of a PLL, sine wave generators, PWM generators, and digital logic.

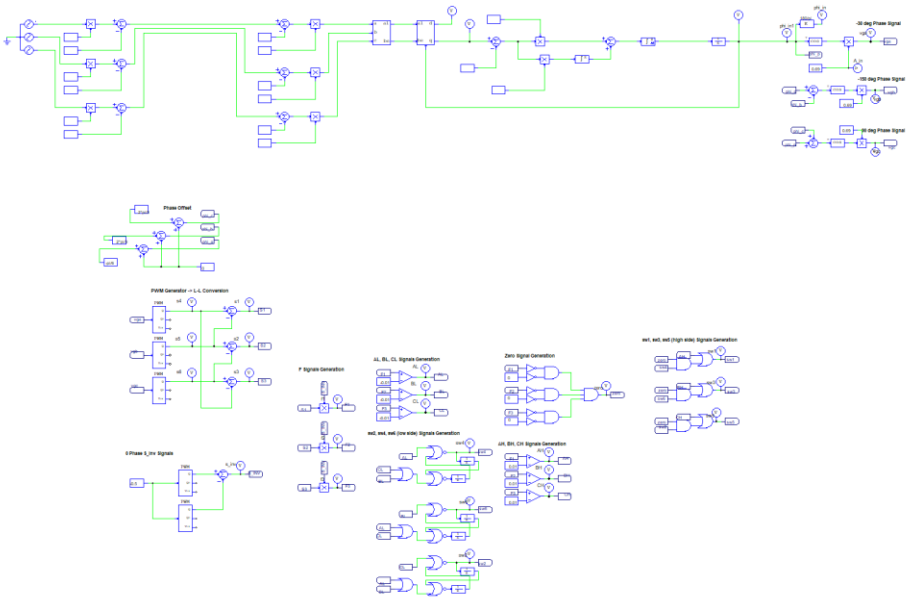


Figure 11. Control system logic in PowerSim

To create the signal in real life, a TI F28379D controlCard in conjunction with a expansion board with ADC, DAC, and GPIO is used. The input to the control logic is inputted to the ADC, and the switching signal for the gate drivers is outputted from the GPIO pins.

Figure 12. TI F28379D Experimenter's Kit used for control logic processing

4.3. Subsystem Validation

Control subsystem validation will occur in 3 stages: logic validation, hardware validation, and logic + hardware validation.

Logic validation consists of implementing the control logic along with the power circuitry in PowerSim and simulating how the logic controls the simulated circuit.

Hardware validation consists of testing code generation, compiling, uploading, and testing on the TI F28379D controlCard. This ensures that the board is able to handle the logic and successfully input and output signals.

Logic + hardware validation consists of implementing the control logic, code generation, and hardware together and testing the entire system. In this validation, HIL (hardware-in-the-loop) testing is conducted using the entire controls subsystem to validate the functionality of the subsystem before it is fully implemented with the other subsystems.

Figure 13. PLECS RT Box for hardware-in-the-loop testing

4.4. Subsystem Conclusion

The control logic design and the first 2 stages of subsystem validation have been completed. The logic + hardware validation is ongoing. So far, this subsystem is showing good performance and can be easily implemented with the other subsystems.