

3 Phase Matrix Converter

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FINAL REPORT

REVISION – 3

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3 Phase Matrix Converter

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CONCEPT OF OPERATIONS

REVISION – 3

CONCEPT OF OPERATIONS FOR 3 Phase Matrix Converter

TEAM 20

APPROVED BY:

Project Leader _____ **Date** _____

Prof. Kalafatis Date

T/A Date

Change Record

Rev	Date	Originator	Approvals	Description
1	2/10/2024	Chase Barnes		Draft Release
2	2/24/2024	Chase Barnes		ECEN 403 Midterm Report
3	11/28/2024	Daniel Loeza		ECEN 404 Final Report

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1. Executive Summary

This project aims to design and construct a three-phase matrix converter, which will power a quarter horsepower AC induction motor varying from 0 to 60 Hz. Compared to traditional three-phase variable frequency drives, referred to as VFDs, which accomplishes AC-DC-AC conversion, this proposed matrix converter executes direct AC-AC conversion. This provides higher efficiency, as there are less devices that degenerate efficiency during the conversion process. This converter will have three subsystems, which are the matrix of bidirectional switches with appropriate filters for the three-phase, the pulse generator circuit to control the switches, and the firmware, which will control the frequency of the output. The input will be 208V AC 60Hz three-phase power, with an output of 208V AC varying at 0 to 60 Hz.

2. Introduction

The motor industry is experiencing robust growth, currently valued at \$134 billion and anticipated to reach \$186 billion by 2027. Amidst its expansion, there is a burgeoning demand for motor controllers. With advancements in transistor design, there is a notable surge in the market for motor controllers featuring enhanced efficiency, sought after for their potential to curtail power costs. This project aims to develop a device that surpasses the efficiency levels of conventional three-phase motor controllers, while offering other benefits such as compact design and simplicity, aligning with the evolving needs of the industry.

2.1. Background

Three-phase motors typically utilize Variable Frequency Drives, commonly referred to as VFDs. These act as a system that takes in a 3 Phase AC input, rectifies the AC to DC, filters the DC, then converts it to a simulated AC voltage and frequency. As seen below with the circuit representation of the VFD:

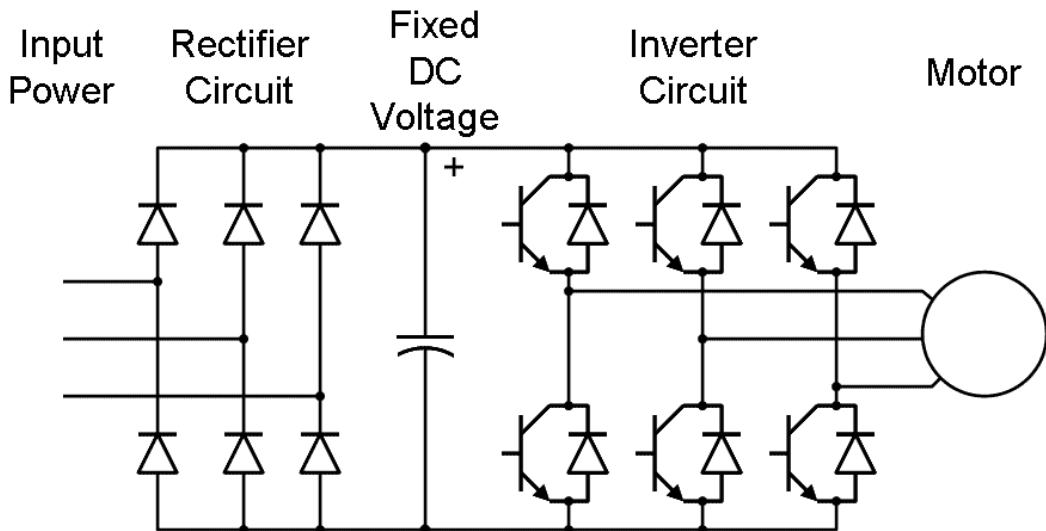
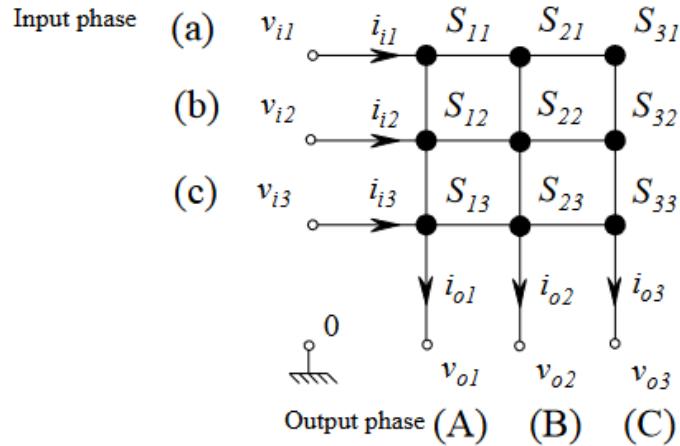


Figure 1: Circuit Representation of Variable Frequency Drive
Source: Adapted from [3]

The conversion process from DC to AC will introduce inefficiencies within the system, resulting in greater power consumption across the system compared to matrix converters.

For matrix converters, rather than doing AC-DC-AC, they directly execute AC-AC motor control. This will allow for higher efficiency across the system, with less power consumption across the system. As illustrated below, the matrix representation of the matrix converter highlights that only a single device exists between the input and output phases.



*Figure 2: Matrix Scheme of Three-Phase Matrix Converter
Adapted from [4]*

This is able to maintain much higher efficiency at both lower and higher speed. This is also able to reduce footprint, with less devices in place on the system [1], [2], [4]. Along with VFDs and matrix converters, there are other technologies that are used to drive motors. Such technologies include combustion and steam engines, which are more traditional and mechanical modes of driving motors, compared to the electronic controllers. These engines typically use either fuel or steam to drive motors, and have their own advantages and disadvantages when compared to the VFD.

2.2. Overview

This system consists of twelve total boards, nine of which will act as one bidirectional switch, with a set of three switches being associated with each input phase and output phase, with an input filter board and an output filter board. To power these switches, the twelfth board will be a pulse generator. The board will be powered by a programmed microcontroller that will rapidly alternate the switches to create a seamless way of changing the frequency of the three-phase AC.

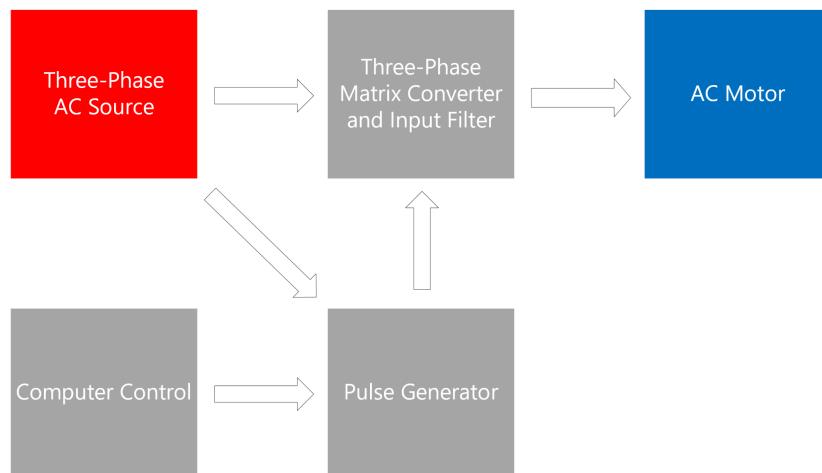


Figure 2: Block Diagram of the Three-Phase Matrix Converter System

2.3. *Referenced Documents and Standards*

- [1] M. E. De Oliveira Filho, A. J. Sguarezi Filho, and E. Ruppert, A Three-Phase to Three-Phase Matrix Converter Prototype, <https://www.scielo.br/j/ca/a/wFx5xXr7bM96SmpRD6M3BMC/?format=pdf&lang=en> (accessed Jan. 2024).
- [2] M. Matteini, "Control Techniques for Matrix Converter Adjustable Speed Drives," thesis, University of Bologna, Bologna, 2001
- [3] File:PWM VFD Diagram.png, https://commons.wikimedia.org/wiki/File:PWM_VFD_Diagram.png (accessed Feb. 2024).
- [4] L. Zarri, "Control of Matrix Converters," dissertation, University of Bologna, Bologna, 2007

3. Operating Concept

3.1. Scope

The objective of this project is to design a three-phase matrix converter. The end goal of the matrix converter is to power a $\frac{1}{4}$ horsepower AC induction motor to vary between 0 to 60 Hz.

3.2. Operational Description and Constraints

The three-phase matrix converter is intended for use anywhere a VFD would be located and operated in. This would have the following constraints:

- Installed indoors, within normal room temperature, between 20-40 °C.
- Budget of \$500 for all parts purchased.
- Located in an area that is free from oil, mist and dust, material shavings, any combustible or radioactive material, excessive vibration, and direct sunlight.
- System requires a computer on hand in order to change the frequency of the system.

3.3. System Description

The three-phase matrix converter converts three-phase 60Hz 208V AC input into three-phase variable 0-60Hz 208V AC output, which will be used to control the speed of an AC motor. This is executed with direct AC-AC conversion, which differs from traditional variable frequency drives that execute AC-DC-AC conversion. This project consists of three major subsystems:

The Matrix Converter Circuit

This is the complex power electronics system designed to perform direct AC-AC conversion without an intermediate DC link. It will utilize a 3x3 matrix of bidirectional semiconductor switches, in this case Insulated Gate Bipolar Transistors, or IGBTs, to achieve this conversion. The source three-phase AC power will be directly connected to the input stage of the converter, which also includes an input filter. From the input filter, each of the three phases will be connected to the matrix configuration, allowing each switch to connect any output phase to any input phase. During one part of the switching cycle, the matrix converter acts as a rectifier, and in another part, it acts as an inverter, allowing bidirectional power flow for regenerative braking and energy recovery. Each bidirectional switch in the matrix requires a gate driver to control its switching operation. These ensure that the transistors switch on and off at the correct times according to the control signals.

The Pulse Generator Circuit

This is responsible for generating the appropriate signals to drive the gate drivers and control the switching of the bidirectional switches. The pulse generator ensures that the matrix converter operates according to the AC-AC conversion requirements. The control system of the pulse generator is a microcontroller that generates pulse-width modulation, or PWM, signals that are then shaped into the final control signals that are sent to the gate drivers of the IGBTs. It utilizes sensors that read the AC input voltages to precisely and efficiently create the final control signals.

The Microcontroller Firmware

The microcontroller code and firmware for the matrix converter serve a fundamental role in orchestrating the variable frequency drive in an open-loop configuration. The code acts as the brains of the operation, interpreting user-defined parameters and executing a control algorithm to adjust the switching patterns of the bidirectional switches. It enables the converter to tailor its output frequency and voltage to match the specified requirements driven by user commands. If the desired output frequency needs adjustment, the firmware calculates the necessary changes and communicates this information to the pulse generator. These changes can include varying PWM signals, duty cycles, and frequency and voltage settings. This ensures stability and efficiency within the predetermined operating parameters.

3.4. Modes of Operations

System will turn on and off, and will vary from 0 to 60 Hz. While off, the firmware, pulse generator, and matrix converter will provide no output to any system. During operation the pulse generator, utilizing the firmware, will generate pulses to the specific bidirectional switches that will provide the requested output frequency. During operation, you can change the frequency with an attached computer to the system providing the change.

3.5. Users

There is a wide range of potential users for the project. The target audience for this project encompasses the same audience that uses AC-AC variable frequency drives (VFDs). VFDs are used in many industries, mostly the mechanical and electrical industries. Thus, engineers and tradesmen are the primary users of this project.

3.6. Support

We will provide a user manual, which will detail how the systems work in conjunction with each other, along with how to interface with the device. We will also provide schematics and diagrams of the system, to help with any troubleshooting.

4. Scenario(s)

4.1. Pumpjacks

VFD's fulfill consistent roles across diverse applications. They are commonly used in the oil and gas industry to control the speed of pumpjacks. Pumpjacks (also known as nodding donkey pumps) are mechanical devices used to extract crude oil from oil wells. The main benefit is variable speed operation, which is used for adapting to changing well conditions, which also improves energy efficiency by operating at optimal speeds. They also offer smaller benefits such as a soft start function, which is used for gradually ramping up the speed of the pumpjack motor in order to reduce mechanical stress on the equipment during startup, minimize wear and tear, and avoid sudden torque surges. It can also offer regenerative braking, useful for recovering energy during the downward stroke of the pumpjack, and remote monitoring and control.

4.2. Electric Traction Systems

One of the most commonly used purposes of VFDs are for controlling and regulating AC rotational motor speed and torque. This is one of the most crucial roles in electric traction systems, which are widely used in various transportation applications such as electric trains, trams, and electric vehicles. VFDs offer precise adjustments for efficiency and adaptability to operating conditions. It also enables regenerative braking, optimized energy use, and reduced wear.

4.3. HVAC Systems

In heating, ventilation, and air conditioning systems, VFDs precisely regulate the speed of motors, such as those driving fans, pumps and compressors. For air-handling units, the VFD can match the airflow to the actual heating or cooling demand, saving on energy costs and ensuring efficient operation. The same premise goes for pump control, which is used to circulate water or other fluids for heating or cooling, allowing for variable flow rates. More so, variable refrigerant flow (VRF) air conditioning requires VFDs for controlling compressor motors to match the cooling and heating load.

5. Analysis

5.1. Summary of Proposed Improvements

The three-phase matrix converter will be able to accomplish AC-AC frequency conversion, as compared to traditional VFDs that do AC-DC-AC frequency conversion. There are a few advantages to this.

Matrix converters inherently support bidirectional power flow by their design. The bidirectional nature of the semiconductor switches in a matrix converter allows for power flow in both directions, making it suitable for applications where bidirectional power flow is essential, such as regenerative braking or when energy recovery is required, as the matrix converter can efficiently transfer power back to the source during braking or deceleration.

The emission of the intermediate DC link reduces the number of conversion stages, removes the electrolytic energy storage requirements, and improves overall efficiency. Specifically, the rectification and inversion stages from traditional VFDs each involve some level of energy loss. By directly converting AC power to AC in a single stage, those losses are negated, saving on energy costs. This also simplifies the design of the power electronics, by eliminating the need for components such as rectifiers, DC-link capacitors, and inverters, creating a more straightforward system design. Since some of those power components can be rather large, such as the capacitors and inductors, the matrix converter is also a much more compact VFD design. This is advantageous in applications where space is limited or where a smaller footprint is desirable. The rectification and inversion stages of traditional VFDs can also introduce unwanted harmonics in the system leading to lower power quality compared to direct AC-AC converters.

5.2. Disadvantages and Limitations

Our system is much more limited in scope for both horsepower for the motors, singular voltage, and limited frequency ranges. It also is not a closed loop control system, nor are there any specific modes for IPM/PM Motors. There is also no braking system setup for the motors. The system will also not be hardened for the environment, and will be unable to operate in some environments that traditional or commercial VFDs can operate in. This is also restricted to strictly three-phase input and output. It will also require a computer on standby in order to change the frequencies.

5.3. Alternatives

Alternative solutions include utilizing traditional VFD designs. These have a much longer history, along with further development done across them. Given their longer history, and much more industrial work and usage, they have a much greater range of utilization, featuring greater frequencies, ability to change voltages, and support higher capability regarding different types of motors. However, given the AC-DC-AC conversion, they encounter some efficiency issues and electrolytic DC link storage issues that result in a shorter lifespan of the product. There are also commercial matrix converters on the market, such as the U1000 Matrix Drive. These devices are much grander in scope than our design, however they do also feature a much higher price tag. You could also alternatively power your motor directly on mains.

5.4. Impact

The device, given higher efficiency than traditional VFDs, will be able to provide more ethical power consumption, given that there is less power consumed over the course of usage. The device requires usage of silicon, plastics, copper, and other assorted elements, as well as mining, transportation, and production of which collectively contribute to greenhouse gas emissions.

3 Phase Matrix Converter

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FUNCTIONAL SYSTEM REQUIREMENTS

REVISION – 3

FUNCTIONAL SYSTEM REQUIREMENTS FOR 3 Phase Matrix Converter

PREPARED BY:

Author Date

APPROVED BY:

Project Leader _____ **Date** _____

John Lusher PE Date

T/A Date

Change Record

Rev	Date	Originator	Approvals	Description
1	2/24/2024	Daniel Loeza		Midterm Report
2	11/11/2024	Chase Barnes		Power Modifications
3	11/28/2024	Daniel Loeza		ECEN 404 Final Report

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1. Introduction

1.1. Purpose and Scope

The 3-Phase matrix converter is a device that will produce 3-phase voltage at a varying frequency of 0 to 60 hertz at 208V with AC-AC conversion with the ability to provide the amperage necessary to power a ¼ horsepower motor. This system will have sensors along the phases to allow for information about the input and output phase to be utilized to determine the correct way to generate the desired frequency to be outputted, along with protections in place to stop the device in the event of shorts being detected. This frequency will be determined by user input on a computer that is connected to the device to allow for clear communication. This specification defines the technical requirements for the development items and support subsystems delivered to the client for the project. Figure 1 shows a representative integration of the project in the proposed CONOPS. The verification requirements for the project are contained in a separate Execution and Validation Plan.

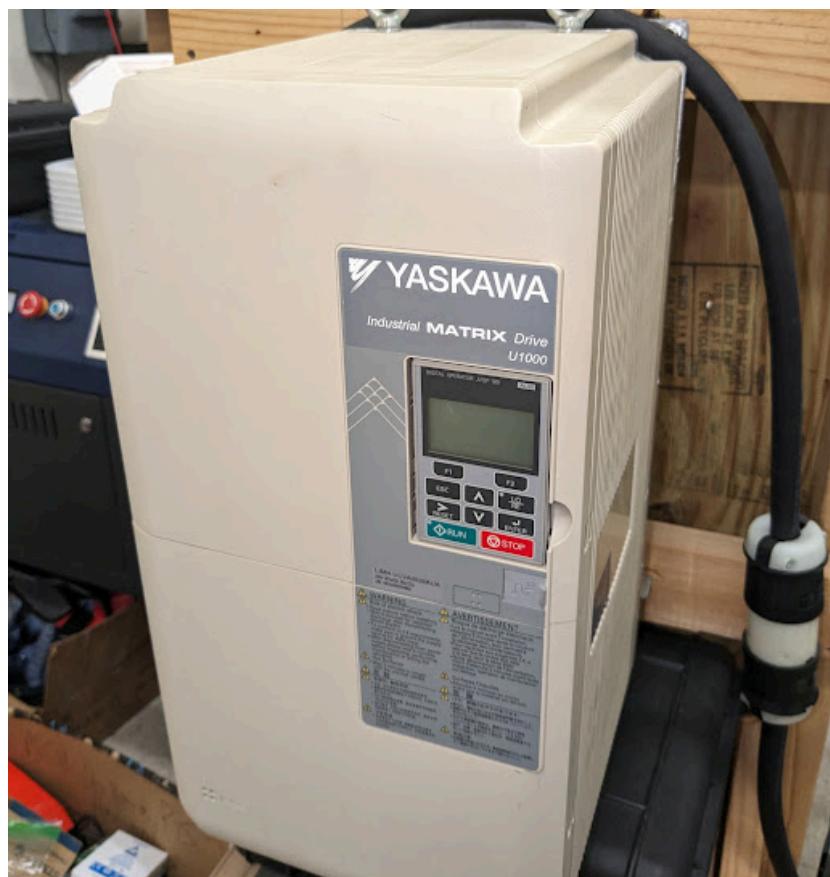


Figure 1. 3 Phase Matrix Converter Conceptual Image

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

With each team member in charge of their primary subsystem, they will be respectively in charge of their own individual requirements to be met. Collective requirements will be the responsibility of all of the team members. Team discussion will occur before changes to the system will be made, with the client able to make changes within reason after informing the team.

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.

Release Date	Document Title
8/30/2011	A Three-Phase To Three-Phase Matrix Converter Prototype
2001	Control Techniques for Matrix Converter Adjustable Speed Drives

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.

Manufacturer	Document Title
STMicroelectronics	Trench Gate IGBT Datasheet
STMicroelectronics	Arm Cortex Datasheet
STMicroelectronics	STM32 Microcontroller Datasheet
Avago Technologies	IGBT Gate Drive Optocoupler Datasheet
Intel	MAX 10 FPGA Datasheet
Intel	MAX 10 Dev Board Datasheet

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

This section defines the minimum requirements that the development item(s) must meet. The requirements and constraints that apply to performance, design, interoperability, reliability, etc., of the system, are covered.

3.1. System Definition

The three-phase matrix converter system consists of three subsystems, which are broken up in the block diagram below (in gray). This system consists of twelve circuit boards. The matrix converter circuit board will be the power electronics system designed to perform the direct AC-AC conversion without an intermediate DC link. It contains a 3x3 grid of bidirectional switches, each switch being its own board, with a set of three switches being associated with each input phase and output phase, with both of the input and output being filtered on their own separate boards. To power these switches, the twelfth board, a pulse generator powered by a programmed microcontroller will rapidly alternate the switches to create a seamless way of changing the frequency of the three-phase AC.

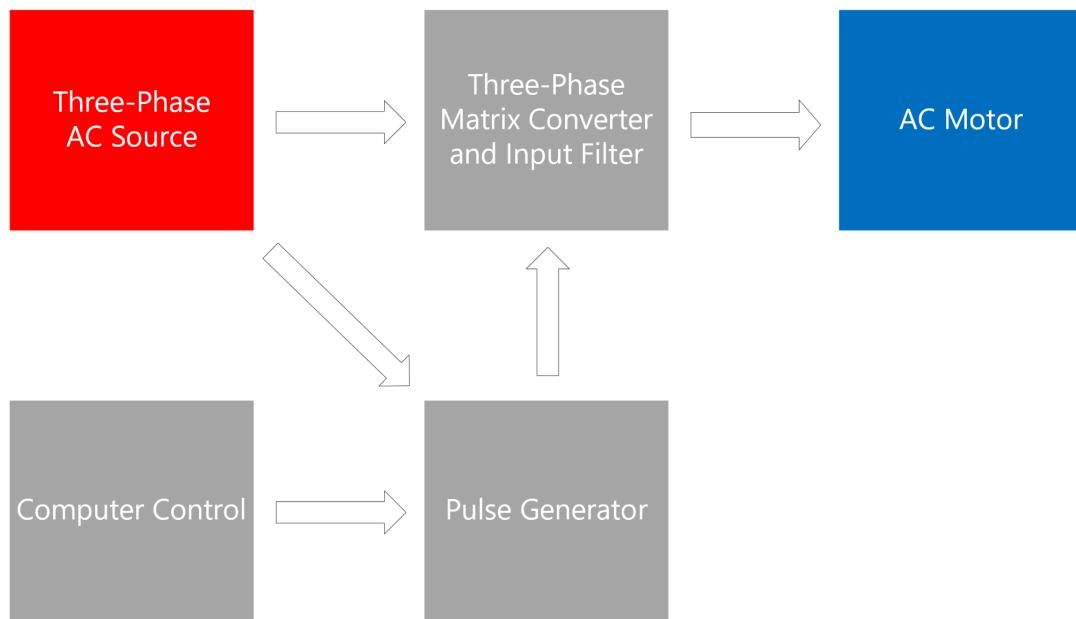


Figure 2. Block Diagram of System

The block diagram depicts the three subsystems in gray for the three-phase matrix converter. The red block represents the inputs for our system, which are the three-phase 208V AC source. The blue block represents the output for our system, which is the $\frac{1}{4}$ horsepower induction motor load. The three-phase AC source will have each phase feed into a set of nine switches, and it also powers the power supply for the pulse generator circuit board. Computer control references the firmware programming for the MCU and the FPGA, which control the output of the pulse generator.

3.2. Characteristics

3.2.1. Functional / Performance Requirements

3.2.1.1. Ability to output 3 phase 208V AC to power a quarter horsepower motor

The Matrix converter shall meet the requirement of being able to generate a 0 to 60 Hz 3-phase 208V AC output with 10 amps of current. This will enable it to power a $\frac{1}{4}$ horsepower motor.

Rationale: This is the core performance requirement specified by the client.

3.2.1.2. Ability to communicate with external computer

The Matrix converter shall meet the requirement of communicating with an external computer in order to determine the frequency that is set for the output.

Rationale: This is the core performance requirement specified by the client.

3.2.2. Physical Characteristics

No applicable standards on this topic.

Rationale: This is a requirement not specified by our customer due to lack of constraints for the system.

3.2.3. Electrical Characteristics

3.2.3.1. Input Power

All power will be supplied by the 208v 3-phase AC voltage. The AC voltage will be used directly for powering the $\frac{1}{4}$ horsepower motor, and will be used to power the power supply, which will supply 5V that will be used as inputs for the lower-voltage components of the system. An additional 3.3v regulator and 15V DC-DC Converter will be utilized for the components.

Rationale: The input power requirement is specified by the client, with the additional regulation being done to power the discrete components

3.2.3.1.1 Power Consumption

The maximum peak power of the system shall not exceed 3.6 kWatts.

Rationale: This is the maximum power of the system due to the combined power of the three phases.

3.2.3.1.2 Input Voltage Level

The input voltage will be 208V 3 Phase AC.

Rationale: This requirement has been provided by the client.

3.2.3.1.3 Bidirectional Switching Operation

The Bidirectional switches will provide current in both directions up to 10 amps.

Rationale: This is necessary for the matrix converter to be able to function

3.2.3.1.3.1 Bidirectional Switch Timing

The Bidirectional switches will be able to switch off within 200ns.

Rationale: This speed is necessary for the matrix converter to be able to function properly

3.2.3.1.3.2 Bidirectional Switch Isolation

The Bidirectional switches will be optocoupled for electrical isolation.

Rationale: Electrical isolation provides necessary protection in case of voltage spikes or surges.

3.2.3.2. Signal Interfaces

This refers to the control and communication signals passed between the components.

3.2.3.3. Zero crossing Sensor

The zero crossing sensor will provide the sign of the voltage, with 1 indicating positive voltage, and 0 indicating negative voltage.

Rationale: This is required for the Space Vector Modulation Algorithm to be able to function.

3.2.3.3.1 Zero Crossing Sensor Timing

The zero crossing sensor will be able to provide the current voltage sign within 200ns.

Rationale: This is required for the Space Vector Modulation Algorithm to be able to function.

3.2.3.4. Current Signal Detector

The current signal detector will be able to provide the current sign, with 1 indicating positive current, and 0 indicating negative current.

Rationale: This is required for the Commutation system to be able to function correctly.

3.2.3.4.1 Current Signal Timing

The current signal detector will be able to provide the current sign within 200ns

Rationale: This is required for the Commutation system to be able to function correctly.

3.2.3.5. FPGA to Gate Driver Signals

The FPGA will provide 19 output signals, with 1 to each of the gate drivers, and 1 short signal to the microcontroller. It will also provide a safe way of changing from one load to the next load

Rationale: This safety is required for the matrix conversion to function.

3.2.3.5.1 FPGA to Gate Driver Timing

The FPGA will change the output signals at or just above the maximum turn off delay of the IGBT Transistors.

Rationale: This is done to allow for the IGBT transistors to properly change within the timeframe.

3.2.3.6. MCU to FPGA Signal

The Microcontroller, utilizing space vector modulation, will provide 8 output signals to the FPGA, 6 being related to the load requested for each phase, with 2 signals per phase, 1 being the reset, and 1 being the parity bit.

Rationale: This safety is required for the matrix conversion to function.

3.2.3.6.1 MCU to FPGA Timing

The Microcontroller will provide the modulation data to the FPGA within the time frame required to have the device modulation between 0 and 60Hz.

Rationale: This timing is required to allow for function of the external system

3.2.3.7. MCU to Gatedriver signal

The Microcontroller and FPGA will be able to provide the gate drivers with appropriate signals to allow for the matrix converter to function at the desired frequency.

Rationale: This is necessary for the matrix converter to function.

3.2.4. Failure Propagation

The 3 Phase Matrix Converter shall not allow propagation of faults beyond their point of fault. Protection measures such as overvoltage protection and short-circuit detection will stop any faults from propagating further.

3.2.4.1. Failure Detection, Isolation, and Recovery (FDIR)

3.2.4.1.1 Short Circuit Detection

The 3-phase matrix converter should have a group of sensors that will provide short circuit detection that will allow a signal to be sent to the processing units in order to stop the function of the matrix converter.

Rationale: This will allow for components that could be potentially harmed during a fault to not be.

3.2.4.1.1.1 Short Circuit Stopping Speed

The short detectors should be able to detect a short and propagate a signal to the main controls within 6 microseconds.

Rationale: This is necessary to prevent short errors from propagating across the matrix resulting in greater damage to the device.

3.2.4.1.2 Isolation and Recovery

The 3-phase matrix converter should provide for short isolation and recovery by enabling subsystems to be reset or disabled based upon the result of the short circuit detectors.

Rationale: This is a requirement based on the reference document “A Three-Phase To Three-Phase Matrix Converter Prototype”.

3.2.4.2. Overvoltage Protection

A total of six varistors, three on the input phases and three on the output phases, will be added for overvoltage protection.

Rationale: This is necessary during the stopping operation of the matrix converter, which results in overvoltage of the input and outputs.

3.2.4.3. Control Unit Transmission Error Correction

The 3 Phase Matrix Converter microcontroller to external computer may have parity bits to ensure that the correct information has been propagated, and in the event of failure, will wait for the next valid transmission before proceeding with further data processing or retransmitting the information.

Rationale: This will allow for better verification that requested frequency is as desired.

4. Support Requirements

The three-phase matrix converter system paired with a computer shall have all the necessary components to run under the specifications listed in this document. The three-phase matrix converter system will come with an instruction manual that will include information on setup, operation, and troubleshooting. Users will need a computer equipped with a functioning terminal interface.

Appendix A: Acronyms and Abbreviations

A	Amp
Hz	Hertz
ICD	Interface Control Document
kHz	Kilohertz (1,000 Hz)
mA	Milliamp (.001 Amp)
MCU	Microcontroller Unit
mm	Millimeter (.001 Meter)
FPGA	Field Programmable Gate Array
FSR	Functional System Requirements
MHz	Megahertz (1,000,000 Hz)
mW	Milliwatt (.001 Watt)

Appendix B: Definition of Terms

FPGA Field-programmable Gate Array - a configurable digital logic IC that can be configured by the user.

Gate Drivers To increase the current output of the digital logic, isolated power switches are utilized to provide them.

IGBT Insulated-gate Bipolar Transistor - 3-terminal power semiconductor device. It acts as a switch.

Turn off Delay IGBT Transistors have a maximum time after they've been signaled off, before they actually turn off.

Appendix C: Interface Control Documents

3 Phase Matrix Converter

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INTERFACE CONTROL DOCUMENT

REVISION – 2

INTERFACE CONTROL DOCUMENT

FOR

3 Phase Matrix Converter

PREPARED BY:

Author _____ **Date** _____

APPROVED BY:

Project Leader _____ **Date** _____

John Lusher II PE Date

T/A Date

Change Record

Rev	Date	Originator	Approvals	Description
1	2/24/2024	Shanelle Algama		ECEN 403 Midterm Report
2	11/28/2024	Daniel Loeza		ECEN 404 Final Report

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1. Overview

This ICD covers the 3-phase matrix converter, its subsystems, and how it will accomplish the requirements provided in the FSR. This includes electrical input and output, signal and sensor output, physical interface of the device, thermal protection, and the communication standards across the device.

2. References and Definitions

2.1. References

Refer to Section 2.2 of the *FSR* document.

2.2. Definitions

A	Amp
Hz	Hertz
ICD	Interface Control Document
kHz	Kilohertz (1,000 Hz)
mA	Milliamp (.001 Amp)
MCU	Microcontroller Unit
mm	Millimeter (.001 Meter)
FPGA	Field Programmable Gate Array
FSR	Functional System Requirements
MHz	Megahertz (1,000,000 Hz)
mW	Milliwatt (.001 Watt)

3. Physical Interface

3.1. Weight

The system will not weigh more than 20 pounds.

3.2. Dimensions

The system will fit within a 500x250x250mm volume.

3.2.1. Dimension of Pulse Generator Subsystem

The Pulse Generator Board will be within a 250x250mm square area

3.2.2. Dimension of Matrix Converter Subsystem

The Matrix Converter Subsystem Board will be within a 500x250mm area.

3.3. Mounting Locations

The pulse generator will have 4 mounting holes in each corner.

4. Thermal Interface

The system requires a thermal interface. The IGBTs in particular, generate excess heat during operation. Thermal pads will be installed on the switches to dissipate heat efficiently, along with additional components such as the DC-DC Converter that generate excess heat.

5. Electrical Interface

5.1. Primary Input Power

We will be using two sources of power for our system. A three-phase variable voltage AC source that will be used for the AC-AC conversion, along with a single phase from a three-phase 208V AC power source will power the COTS power supply that will be used for the microcontroller, FPGA, and the bidirectional switches. The power supply will output 5V.

5.2. Polarity Reversal

Reverse polarity will not be implemented for this system.

5.3. Signal Interfaces

The signal interface consists of all components responsible for communication and signal processing within the system. For this device, the microcontroller and FPGA will manage and exchange signals for tasks such as control, synchronization, and data processing. In particular, the microcontroller firmware will be responsible for implementing the Space Vector Modulation algorithm. This will be handling information about the correct load output for each phase that will then be fed into the FPGA. The FPGA firmware will also send and receive several signals. It will communicate a safe commutation system such that changing bidirectional switches will avoid a short circuit or overvoltage. The commutation scheme takes the load current sign and the state machine into account, and will commutate in the smallest possible time to minimize distortion on the output voltage. It will receive several input signals: three bits from the short-circuit detector, 3 analog sources from the current sensor for information about the load current signs, and eight bits from the microcontroller. Six bits will correspond to information about the input voltage source connected to the load, one bit to the start command, and one bit to the MCU regarding short circuit conditions. The FPGA will output eighteen signal commands, one to each gate driver in the bidirectional switches.

5.4. User Control Interface

The system will have a UART interface that will allow an external computer to connect to the device and then send information to the system to change the frequency of the output, and provide different debug information

6. Communications / Device Interface Protocols

6.1. Host Device

We will utilize an external computer terminal interface as the method of changing frequency. This will be done utilizing a serial UART interface that will relay information to the MC in one direction.

6.2. Device Peripheral Interface

We will be utilizing a serial UART interface, with a 2 way asynchronous packet being sent for information between the computer and the device, with a human readable information and interface

3 Phase Matrix Converter

Chase Barnes

Daniel Loeza

Shanelle Algama

VALIDATION PLAN

Validation Plan

3 Phase Matrix Converter

	Complete
	Incomplete

Paragraph #	Test Name	Success Criteria	Methodology	Status	Responsible Engineer(s)
3.2.1.3	Computer Communication Check	Connected computer is able to communicate appropriate frequency to Microcontroller	Connect Computer to MC and send info confirm output with debug output		Chase Barnes
3.2.3.1	Linear Voltage Regulator Check	The Voltage Regulator will produce a 3.3 V output given a 5 V input	Use of a multimeter to check the output Voltage of the Voltage Regulator		Daniel Loeza
3.2.3.1	Load Testing	System remains stable and operates within specifications under different load conditions to the matrix converter	Apply different load conditions and observe response of switches, filters, varistors		Shanelle Algama
3.2.3.1.3	Switching Operation Test	Bidirectional switches switch on and off correctly from gate drive signals	Utilizing variac and a signal generator and oscilloscope, confirm that switches are functional		Shanelle Algama
3.2.3.1.3	Current Handling Capacity	Bidirectional switches are tested under various load conditions and can handle specified current	Utilizing variac, signal generator, oscilloscope and gradually raising the voltage, confirm that switches remain operational		Shanelle Algama
3.2.3.1.3.1	Switching Operational Speed	Gate drivers will be able to switch the state of the bidirectional switch within 200ns	Utilizing the prior, confirm switching speed		Shanelle Algama
3.2.3.1.3.2	Isolation Test	Sufficient electrical isolation between input and output stages of the bidirectional switches	During switch operation, utilize oscilloscope to confirm input voltage and current is operating within acceptable bounds		Shanelle Algama
3.2.3.3	Zero Crossing Firmware Response	Zero Crossing Sensor is able to be interpreted by Microcontroller	Utilize Oscilloscope to see output of Zero Crossing		Chase Barnes
3.2.3.3	Zero Crossing Detector Check	The output of the detector will be correctly produced given an A/C voltage.	Use of an oscilloscope to check the output of the detector.		Daniel Loeza
3.2.3.4	Current Signal Firmware	FPGA is able to convert Analog input to Current Sign	Utilize Oscilloscope to determine commutation		Chase Barnes

Validation Plan

3 Phase Matrix Converter

	Response		change		
3.2.3.4	Current Signal Detector Check	The output of the detector will be correctly produced given a voltage.	Use of an oscilloscope to check the sign of the detector.	Daniel Loeza	
3.2.3.5	FSM Commutation Algorithm Check	Commutation state machines produces correct output given predetermined inputs.	Verilog Testbench that will provide sufficient tests	Chase Barnes	
3.2.3.5.1	FPGA Commutation Physical Timing	FPGA produces correct output at timing that would be sufficient for IGBT turn on/off	Utilize Oscilloscope to get timing Based off of Verilog Testbench	Chase Barnes	
3.2.3.6	Space Vector PWM Algorithm Check	Produces correct load choice for given voltage reference and frequency input	C test bench that will provide sufficient tests to conform	Chase Barnes	
3.2.3.6.1	Space Vector PWM Physical Timing	Microcontroller produces correct output with sufficient timing	Utilize Oscilloscope for digital logic analysis Based off of C Testbench	Chase Barnes	
3.2.3.7	Firmware Integration Timing Check	Microcontroller and FPGA will be linked up and produce correct output given appropriate input	Utilize Oscilloscope for output Based off Verilog and C Testbench	Chase Barnes	
3.2.4.1.1	Short Circuit Firmware Response	Upon Short signal, FPGA will turn off gate driver output signal to MCU	Utilize Oscilloscope to see output Pin Turn off Upon signal to short	Chase Barnes	
3.2.4.1.1	Short Circuit Detector Check	The detector will relay a signal if a short is detected	Use of an oscilloscope to check the amplitude of the detector.	Daniel Loeza	
3.2.4.1.1.1	Short Circuit Detector Timing	The detector will relay a signal given a short within 6 microseconds	Use of an oscilloscope to on the shorted circuit to determine it is within acceptable range	Daniel Loeza	
3.2.4.2	Overshoot Protection Test	Varistors clamp the voltage to a safe voltage	Apply a controlled overshoot condition to the system, monitor voltage across varistors	Shanelle Algama	
3.2.4.2	Transient Response Test	Varistors provide rapid protection against transient overvoltages	Introduce transient voltage spikes and observe varistor's response time	Shanelle Algama	

3 Phase Matrix Converter

Chase Barnes

Daniel Loeza

Shanelle Algama

EXECUTION PLANS

Execution Plan 3 Phase Matrix Converter

Not Started
Completed
In Progress
Behind Schedule

This was the execution plan for ECEN 403

	02/1 6/24	02/2 3/24	03/0 1/24	03/0 8/24	03/1 5/24	03/2 2/24	03/2 9/24	04/0 5/24	04/1 2/24	04/1 9/24	04/2 6/24	Responsible Engineer(s)
Midterm Presentation Completed												All Team
Midterm Presentation (2/19)												All Team
Complete Parts Purchase (2/23)												All Team
Commutation System Programmed (2/23)												Chase Barnes
Commutation Programming Validation (2/23)												Chase Barnes
Design Blitz Participation												Chase Barnes, Shanelle Algama
Status/Project Update Presentation Completed												All Team
Matrix Converter Circuit Schematic Designed												Shanelle Algama
Pulse Generator Circuit Schematic Designed												Daniel Loeza
Status/Project Update Presentation (3/4)												All Team
Matrix Converter Circuit Schematic Validation												All Team
Pulse Generator Circuit Schematic Validation												Daniel Loeza
Matrix Converter Circuit Board Designed												Shanelle Algama
Pulse Generator Circuit Board Designed												Daniel Loeza
Isolated Bidirectional Switch Testing												Shanelle Algama
Commutation Physical Integration												Chase Barnes
Space Vector PWM Algorithm Programming												Chase Barnes

Execution Plan

3 Phase Matrix Converter

Microcontroller Integration											Chase Barnes
Commutation Physical Validation											Chase Barnes
Final Presentation Completed (4/1)											All Team
Final Presentation (4/1)											All Team
Sensor Validation											Chase Barnes
Total Firmware Integration											Chase Barnes
Total Firmware Validation											Chase Barnes
Bi-directional Switch Validation											Shanelle Algama
Pulse Generator Validation											Daniel Loeza
Final Demo (4/22)											All Team
Final Report Completed											All Team
Final Report (4/27)											All Team

Execution Plan 3 Phase Matrix Converter

This is the execution plan for ECEN 404

	08/ 26/ 24	09/ 02/ 24	09/ 09/ 24	09/ 16/ 24	09/ 23/ 24	09/ 30/ 24	10/ 07/ 24	10/ 14/ 24	10/ 21/ 24	10/ 28/ 24	11/ 04/ 24	11/ 11/ 24	11/ 11/ 24	Responsible Engineer(s)
Firmware FPGA ADC Functionality Completed														Chase Barnes
Redesigned Pulse Generator Schematic Completed/Validated														Daniel Loeza
Redesigned Pulse Generator PCB Validated														Daniel Loeza
Pulse Generator PCB Ordered														Daniel Loeza
Pulse Generator Components Ordered														Daniel Loeza
Firmware Async Communication Completed														Chase Barnes
Redesigned Bidirectional Switch Components Selected														Shanelle Algama
Redesigned Bidirectional Switch PCB Completed														Shanelle Algama
Redesigned Bidirectional Switch PCB Ordered														Shanelle Algama
Input Filter Board Schematic Completed														Shanelle Algama
Input Filter Board PCB Completed														Shanelle Algama
Output Board Schematic Completed														Shanelle Algama
Output Board PCB Completed														Shanelle Algama
Pulse Generator PCB Received														Daniel Loeza
Pulse Generator Components Received														Daniel Loeza
Firmware SVM Functionality Completed														Chase Barnes
Pulse Generator Assembled														Daniel Loeza
Input Filter Board Assembly														Shanelle Algama

Execution Plan

3 Phase Matrix Converter

Output Board Assembly																	Shanelle Algama
Firmware MC Refactor for STM32G491																	Chase Barnes
Isolated Bidirectional Switch PCB Soldered																	Shanelle Algama
Input Filter Board Validation																	Shanelle Algama
Output Board Validation																	Shanelle Algama
Firmware FPGA Refactor																	Chase Barnes
9x Bidirectional Switch PCB Soldered																	Shanelle Algama
Microcontroller UART Communication Validation																	Chase Barnes
Microcontroller Timing Validation																	Chase Barnes, Daniel Loeza
Microcontroller Zero Crossing Integration Validation																	Chase Barnes, Daniel Loeza
Isolated Bidirectional Switch PCB Validation																	Shanelle Algama
Firmware Integration with Pulse Generator																	Chase Barnes, Daniel Loeza
FPGA Current Sensor Integration Validation																	Chase Barnes, Daniel Loeza
Micocontroller FPGA Communication Validation																	Chase Barnes
FPGA with Gate Driver Timing Validation																	Chase Barnes, Shanelle Algama
System Integration																	All Team
System Shorting Validation																	All Team
System Validation																	All Team

3 Phase Matrix Converter

Chase Barnes
Daniel Loeza
Shanelle Algama

SUBSYSTEM REPORTS

REVISION – 2

SUBSYSTEMS REPORT FOR 3 Phase Matrix Converter

PREPARED BY:

Author Date

APPROVED BY:

Project Leader _____ **Date** _____

John Lusher II PE Date

T/A Date

Change Record

Rev	Date	Originator	Approvals	Description
1	4/27/2024	Shanelle Algama		Original Release
2	11/28/2024	Daniel Loeza		ECEN 404 Final Report

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1. Introduction

The 3 Phase Matrix Converter converts 208V 60Hz 3 Phase power into a variable frequency from 0-60Hz and will be able to power a $\frac{1}{4}$ horsepower motor. The system is broken down into 3 subsystems, the matrix of bidirectional switches, the hardware integration of processing devices and sensors into switches, and the software integration of the digital devices and sensors. Due to errors in the subsystems, had time been available, work would have been completed such that integration will be able to proceed, however there are clear integration connections for the final product as described.

2. Bidirectional Switch Subsystem

2.1. Subsystem Introduction

The bidirectional switch system is the core of the three-phase matrix converter subsystem. The matrix converter circuit is the power electronics system designed to perform the direct AC-AC conversion without an intermediate DC link. It consists of a 3x3 grid of bidirectional switches, with a set of three bidirectional switches being associated with each input phase and output phase. From 403, one bidirectional switch was implemented and tested for functionality. Subsequently, nine copies of the single bidirectional switch will be made for the 3x3 matrix. Over the summer from 403 to 404, the DC-DC converter previously used was no longer being sold due to sanctions, so a new DC-DC converter had to be selected (changing the DC-DC converter from 15V to 15V, to 5V to 15V) and thus, a new bidirectional switch and AC-DC power supply were designed and selected, respectively. The redesign of the bidirectional switch introduced new challenges outlined in this subsystem report, which were ultimately fixed.

2.2. Subsystem Functionality

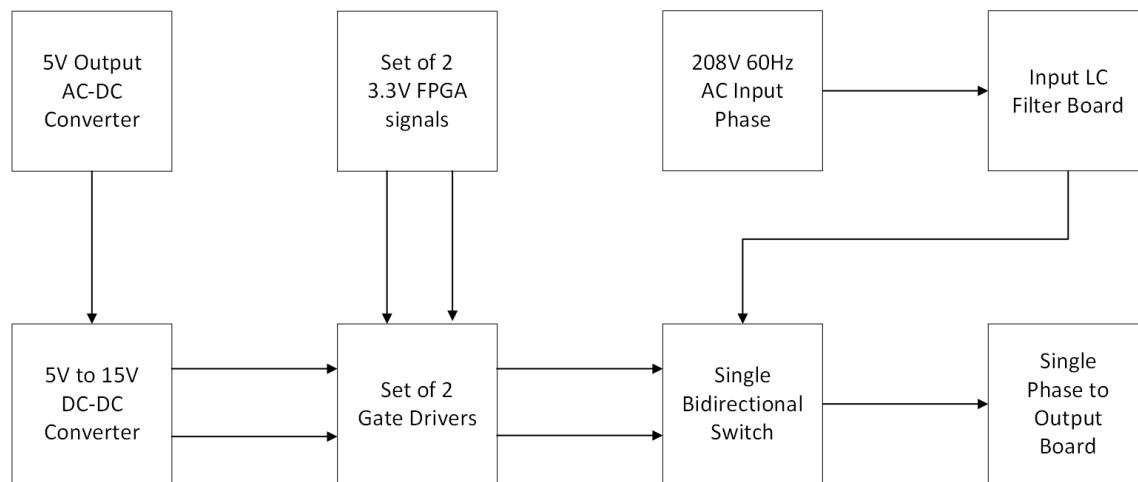


Figure 1: High level block diagram of a single phase for the Matrix Converter Subsystem

The Matrix Converter system for a single phase consists of several components, as illustrated in the block diagram. From top to bottom, the gate drivers are supplied 15V from the 5V-15V DC-DC Converter, which is supplied 5V from the AC-DC power supply from 120Vrms mains AC. There consists a set of two gate drivers, one for each IGBT transistor. The gate drivers take in inputs from the FPGA from the pulse generator, and outputs are fed directly into the IGBTs. The bidirectional switch was first designed in 403 in common-emitter configuration, but was later functionally changed to common-collector configuration for the final board in 403 and was adopted for most of 404 as well. It was much later discovered in 404 that common-emitter configuration ultimately functioned better due to the nine isolated power supplies, and was updated again. The three-phase 208V 60Hz input is fed through an LC network low-pass filter, which also includes overcurrent and overvoltage protection. The output phase is then taken from the second IGBT's collector. A schematic diagram of the complete updated configuration is shown below.

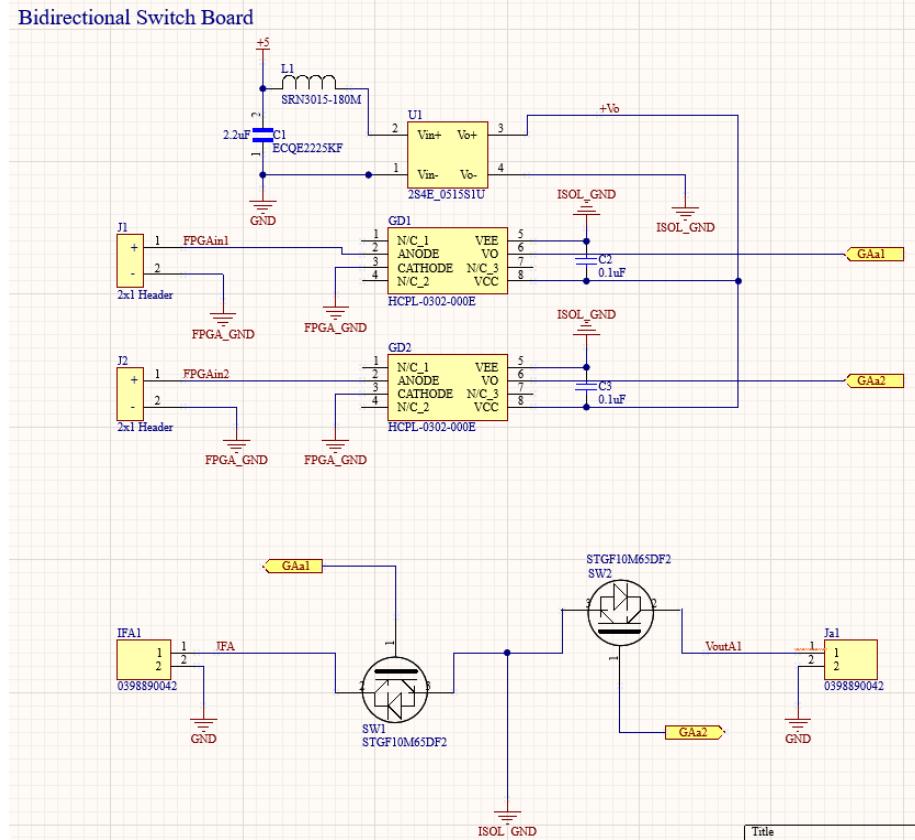


Figure 2: Updated Bidirectional Switch System Schematic with Common-Emitter Configuration

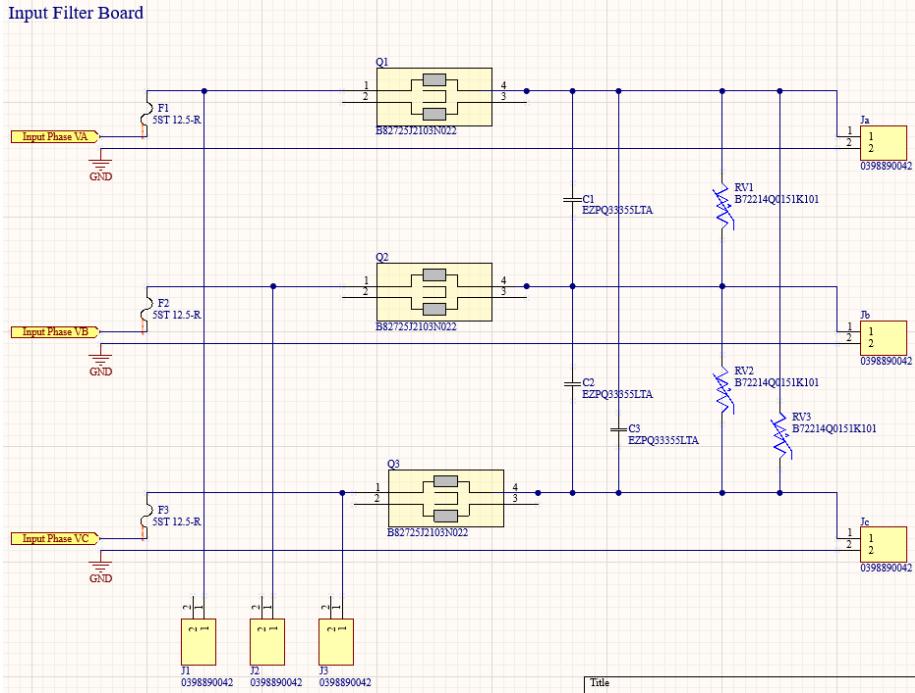


Figure 3: Input Board System Schematic

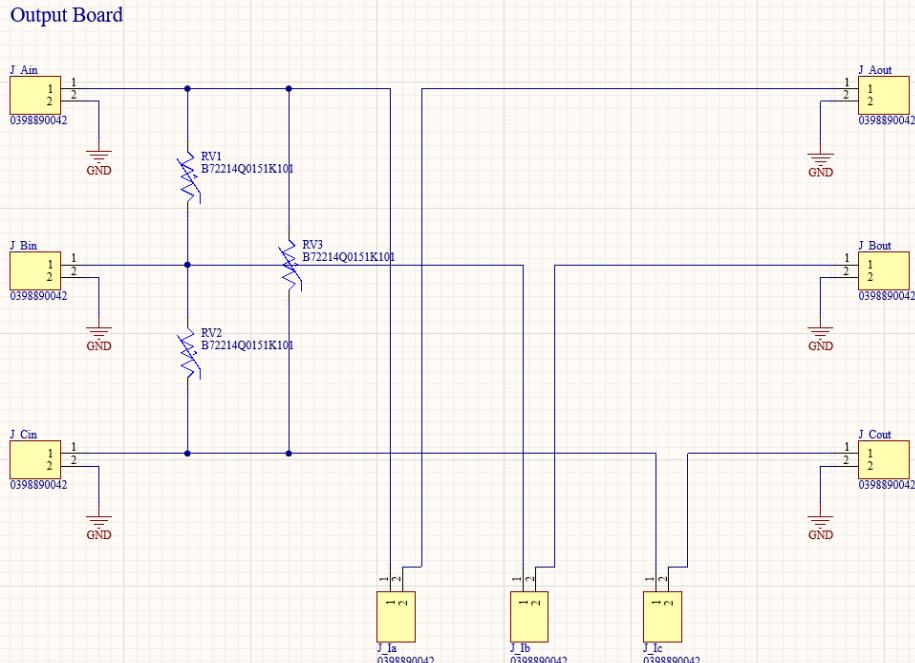


Figure 4: Output Board System Schematic

2.3. Subsystem Details

2.3.1. IGBT Transistor

One bidirectional switch comprises of two IGBT (insulated-gate bipolar) transistors, which are bipolar transistors with an insulated gate terminal. In a single component, it

combines a control input with a MOS structure and a bipolar power transistor which acts as an output switch. IGBTs are used for high-voltage, high-current applications. For this implementation, the STGF10M65DF2 was chosen for its high voltage and current capabilities.

2.3.2. Gate Driver

A gate driver is a power amplifier that accepts a low-power input and produces a high current gate drive for a power device. The power device in this case is the IGBT, which is one of the most popular and efficient semiconductor devices for medium to high power applications. It's responsible for providing the necessary voltage and current to turn the semiconductor on and off quickly and efficiently. The chosen gate driver is the HCPL-0302-000E, selected for its optical coupling and adequate power output to drive the gate of the IGBT, which is the electrically isolated control terminal that acts like a valve between the collector and emitter.

2.3.3. DC-DC Converter

The DC-DC converter is used for electrical isolation between the power supply and the gate driver. Gate drivers also require precise voltage levels for optimal performance, so DC-DC converters serve to efficiently isolate and regulate the voltage to ensure the gate driver receives a stable and accurate voltage despite fluctuations. In ECEN 403, the B1515S-2WR3 was used which converted 15V to 15V. Unfortunately, due to sanctions placed over the summer, a new DC-DC converter had to be selected for use in 404. The new DC-DC converter selected is the 2S4E_0515S1U. It is supplied with 4.5-5.5V input and will output 15V.

2.4. Subsystem Simulation

Although simulation testing was used for the bidirectional switch in 403 for design purposes, it was not used in 404 due to issues that were explained in the 403 report. The most likely conclusion is that the LTSpice models for the gate drivers and IGBTs are inaccurate for simulation testing.

Input Filter Simulation

The matrix converter behaves like a current-source converter, which means that it requires a low-pass filter to modulate the input current so that high-frequency noise and ripple from the converter and the source are attenuated and does not distort the waveform going into the bidirectional switch matrix. The input filter was designed to be a single-stage LC network with a cut-off frequency of 2kHz, which is above the primary signal operating at 60Hz from the input. A capacitance of less than 5uF is desirable for maximum IDF (Input Displacement Factor) which closely corresponds to unity power factor. Working backwards from the cutoff-frequency and capacitance, an inductor of 1.8mH is chosen from the

formula: $\omega_n = \frac{1}{\sqrt{LC}}$. The Q factor is calculated from the formula: $Q = \frac{1}{ESR} \sqrt{\frac{L}{C}}$, which is

approximately 45 using an ESR of 0.5Ω. Although this is a high Q-factor, the bandwidth is limited to less than 1kHz and is out of the range of the primary signal frequency.

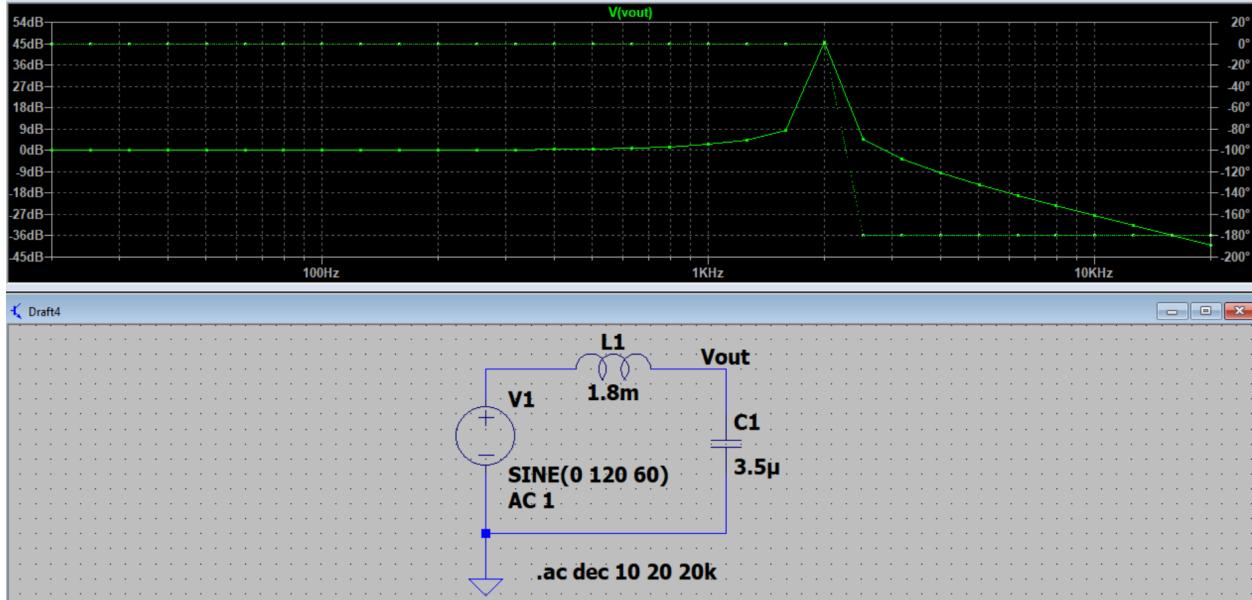


Figure 5: Simulation of Frequency Response of the LC Input Filter

2.5. Subsystem Validation

2.5.1 Bidirectional Switch

The bidirectional switches were validated through physical testing with the VARIAC (a voltage-adjustable source of 60Hz AC power). In isolation, an adjustable power supply was used to supply the 5V input into the DC-DC converter (simulating the AC-DC converter output) as well as the 3.3V inputs to the gate drivers (simulating the signals from the FPGA). The PCB was created off the schematic detailed in the Subsystem Functionality section. The bidirectional switch system was ultimately functional once the issues (detailed below and in Section 3.1 Issues) were fixed. Below are a couple of validation testing results measured on the oscilloscope. Since the bidirectional switches were only fully functional by the very end of the semester, varying voltage inputs for comprehensive validation testing was not able to be completed, however the bidirectional switches proved fully functional up to 108Vrms.

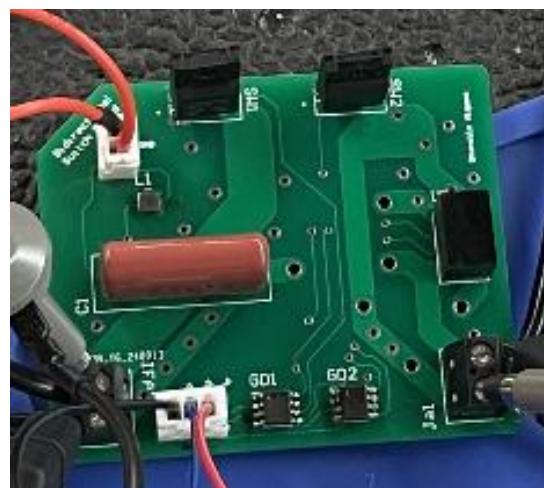


Figure 6: Intended PCB of the Bidirectional Switch before the issues were realized

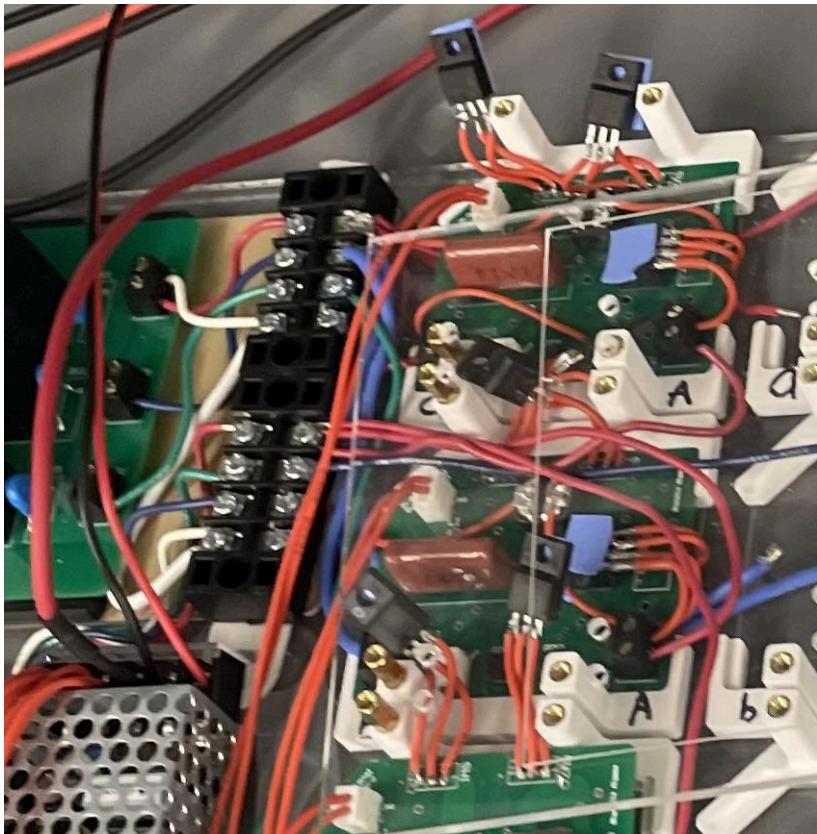


Figure 7: PCB of the Bidirectional Switches after the issues were corrected: IGBTs pinouts swapped from common collector to common emitter, improved current-handling inductor (top-mounted), swapped pins on DC-DC Converter

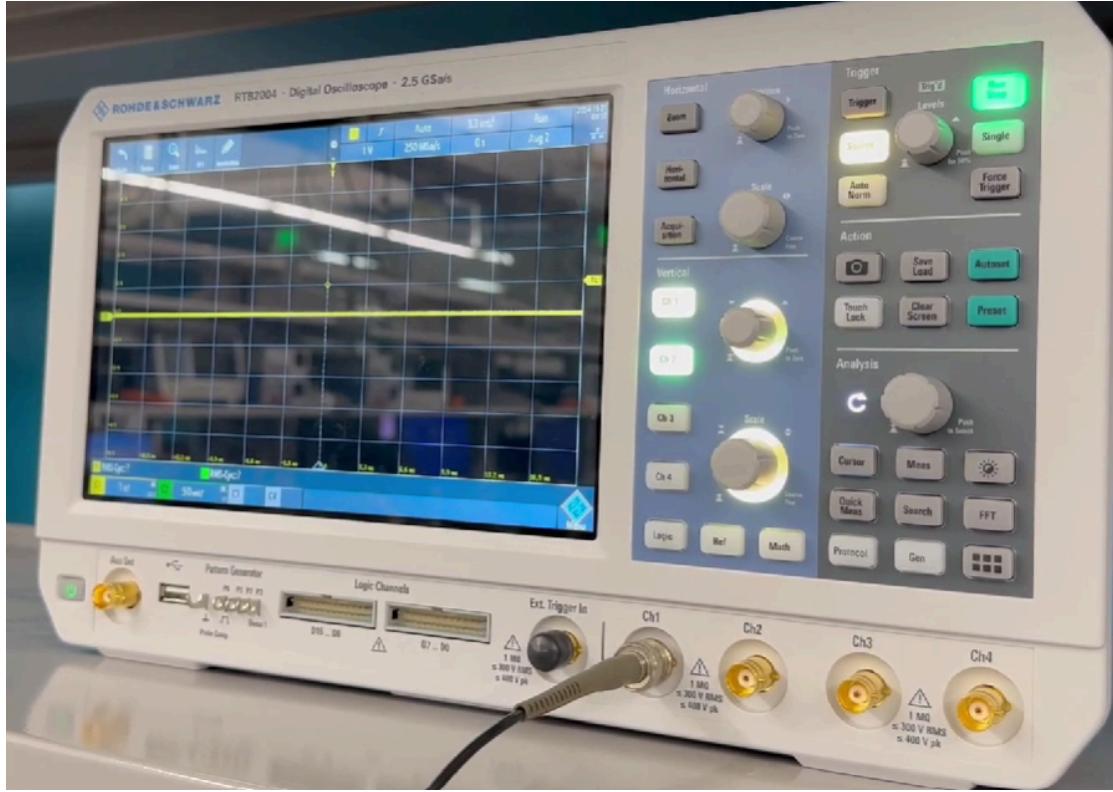


Figure 8: 108Vrms three phase input to three bidirectional switches (single output phase) while gate drivers are off (voltage blocking), with resistive load

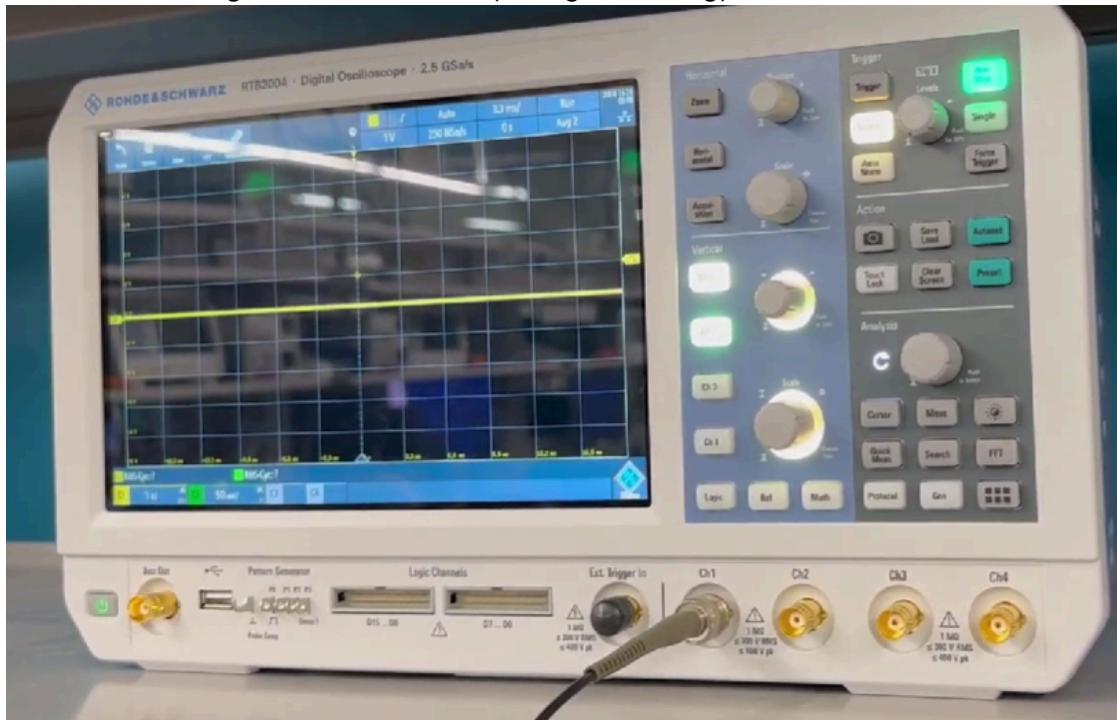


Figure 9: 100Vrms single phase input to two bidirectional switches (gate drivers off, voltage blocking) with resistive load

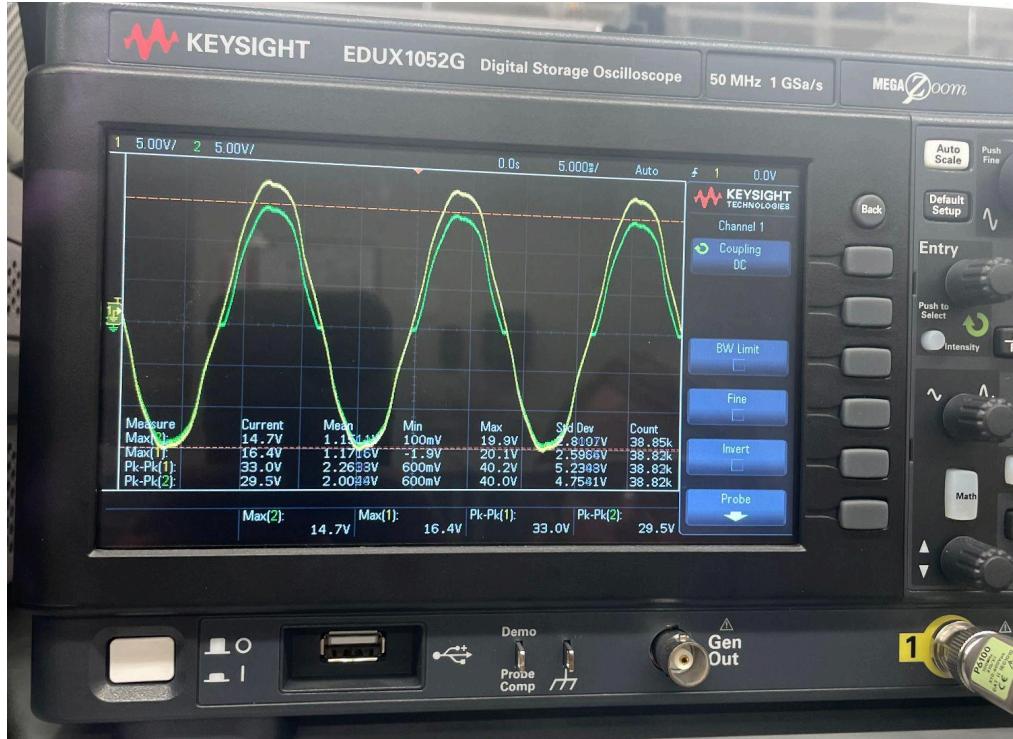


Figure 10: Example of isolated bidirectional switch functionality with gate drivers on (green) for a 33Vpp input (yellow)

2.5.2 Input Filter Board

The input filter is connected to the bidirectional switch directly from the VARIAC input during validation testing. No issues were detected in terms of heat, voltage drops, or poor filtering. The input filter board is validated up to 108Vrms.

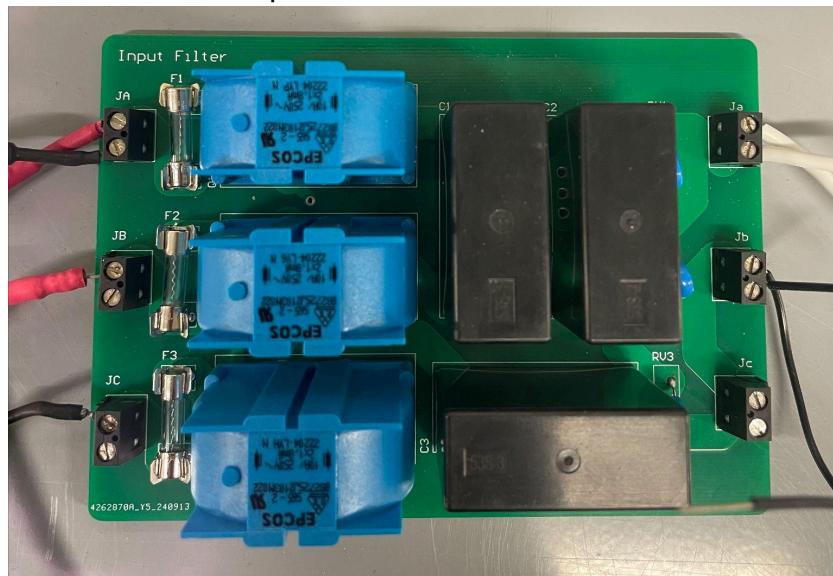


Figure 11: PCB of the Input Filter Board

2.5.3 Output Board

The output filter is connected from the output phases of the bidirectional switches and routes the currents for current signal detection in the pulse generator board. It is also equipped with varistors for overvoltage protection. No issues were detected from the output board. The output board is also validated to 108Vrms.

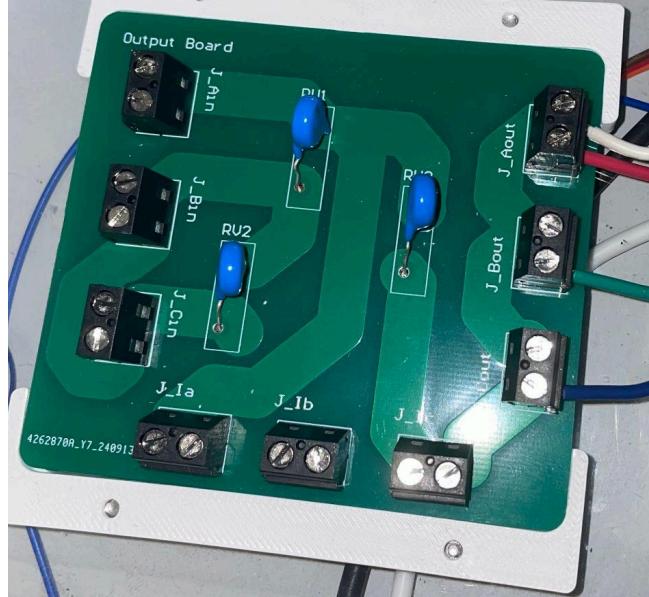


Figure 12: PCB of the Output Board

2.6. Subsystem Conclusion

Despite numerous challenges along the way, the bidirectional switch was finally validated and performed as required right at the end of the semester. One prevalent issue that arose was the IGBTs turning on while the gate drivers are off. However, this was fixed when switching from common-collector configuration to common-emitter. This is because common-collector is configured for six isolated power supplies to the gate drivers while common-emitter is configured for nine (as I've designed). Another issue was the current draw into the DC-DC converter, however it was discovered later that pinouts on the DC-DC converter were switched on the PCB. Once those problems were discovered and corrected, functionality was improved from 403's functionality, however it did not leave us enough time for fixing all nine switches and proving full matrix functionality.

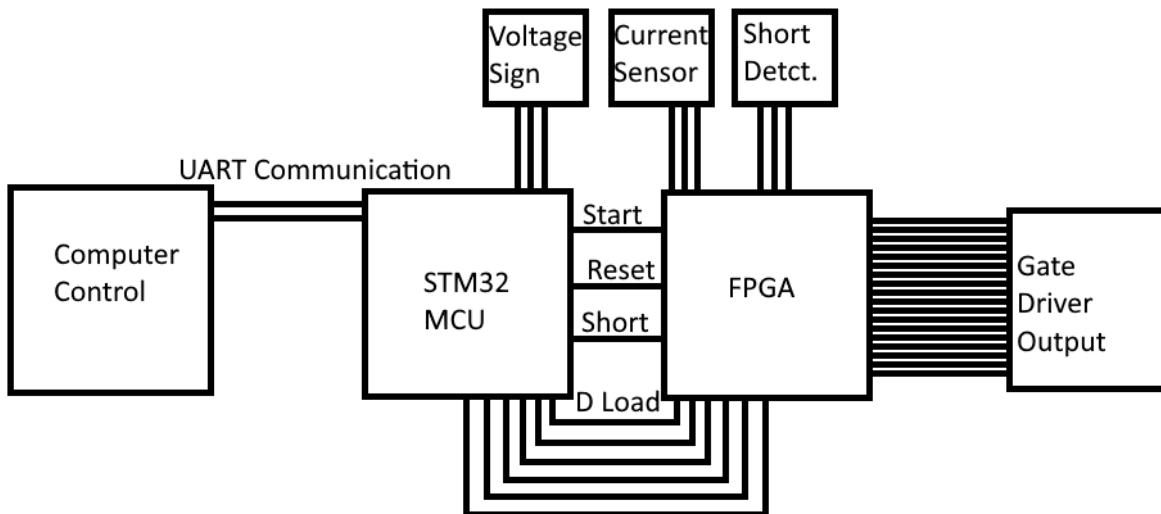
3. Firmware Subsystem

3.1. Subsystem Introduction

The firmware subsystem provides the programming and hardware description of the system, which allows for a user interface in order to provide the desired frequency, and timing and sensor control in order to provide the correct signal sequencing to the gate drivers to allow for proper frequency switching.

3.2. Subsystem Details

Figure 1: Block Diagram of pin outs the subsystem controls



The STM32 communicates using simple UART communication to and from the computer, with 3 digital inputs to the voltage sign representing the 3 phases. When the STM32 output needs to start, it will output a high output to the start pin, and then output the desired load to the 3 input phases via the D Load wires. This is done with 2 wires per pin, with 01 representing A, 10 representing B, and 11 Representing C. Special commutation is required for the bidirectional switches in order to turn on and off, which has 6 outputs per input phase, and also requires knowledge of the current sign, which receives an analog input from the current sensor, and the built in ADC IP interprets the current sign from there. In the event of a short on the input, the FPGA also has 3 short detections to turn off the gate drivers in the event. This is then passed back to the microcontroller, which relays this information to the computer, and then turns off.

3.3. FPGA Firmware

3.3.1. Commutation

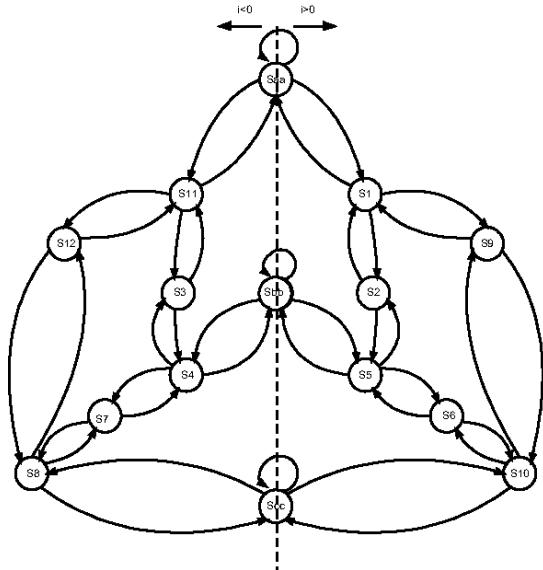
3.3.1.1. Operation

The bidirectional switches, since they are not a discrete component and are constructed of two unidirectional IGBTs, require a safe way of turning off, and then turning on to allow for current to correctly flow, and to prevent shorting during the switching

process. During this process, the IGBTs have a time delay, along with the gate drivers powering the gate inputs on the IGBTs also having a timing delay. In order to correctly transition, the state machine below, along with the table, show the outputs for each. Transition between states requires the output to be set long enough to either allow for the IGBT to turn on, or for the IGBT to turn off.

Figure 2: Commutation State Machine

Table 1: Commutation Output Table



IGBT States						State Name
Sa1	Sa2	Sb1	Sb2	Sc1	Sc2	
1	1	0	0	0	0	Saa
0	0	1	1	0	0	Sbb
0	0	0	0	1	1	Scc
1	0	0	0	0	0	S1
1	0	1	0	0	0	S2
0	1	0	1	0	0	S3
0	0	0	1	0	0	S4
0	0	1	0	0	0	S5
0	0	1	0	1	0	S6
0	0	0	1	0	1	S7
0	0	0	0	0	0	S8
1	0	0	0	1	0	S9
0	0	0	0	1	0	S10
0	1	0	0	0	0	S11
0	1	0	0	0	0	S12

Given the unpredictable timing requirements of the IGBTs, along with the critical path requiring timing requirements from the gate drivers, variable clock timing was enabled to allow for final timing output to be set during integration.

3.3.1.2. Validation

Commutation was validated both in programming, and with a timing analysis. The state machine was validated via testing travel to all directions of desired load, and the overall FPGA code was validated to show proper transition of all 3 output phase changes.

Figure 3: State Machine Validation

Figure 4: Overall Commutation Validation

```
./Comm  
VCD info: dumpfile Comm.vcd opened for output.  
          Initial start passed  
          Check Before Start passed  
          Reset to SABBCC passed  
          SABBCC to SBBCCA passed  
          SBBCCA to SCCABB passed  
          SCCABB to SBBCCA Curr passed  
          Reset passed  
          Reset to SAABRBB passed  
          Shorted passed  
          Shorted After Pulse Off passed  
All tests passed
```

GTKWave Simulation shows timing of the output pins for individual output, and also for all 3 outputs.

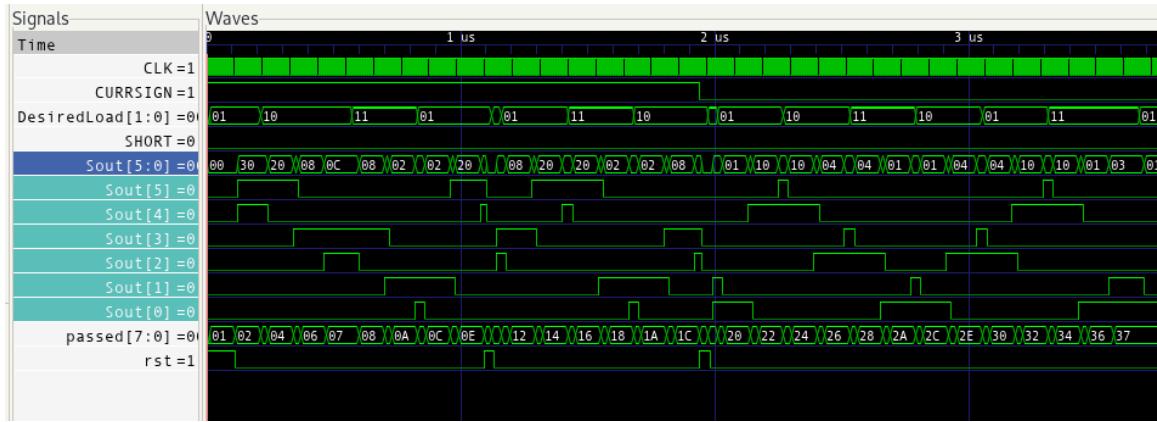


Figure 5: GTKWave of State Machine Validation

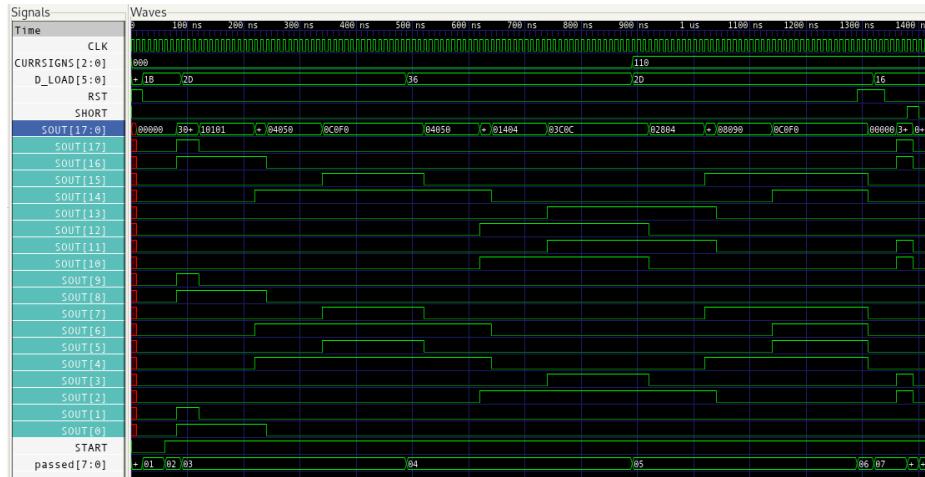


Figure 6: GTKWave of Overall Commutation Validation

Timing analysis was done utilizing an oscilloscope, with the oscilloscope output showing the output for the output phase A for the input phase A, with the desired output phase alternating between A and B for the duration of the test, and a constant current sign. As shown here, there is a correct transition change for commutation. With the clock count of the output being correctly adjusted for final commutation output.

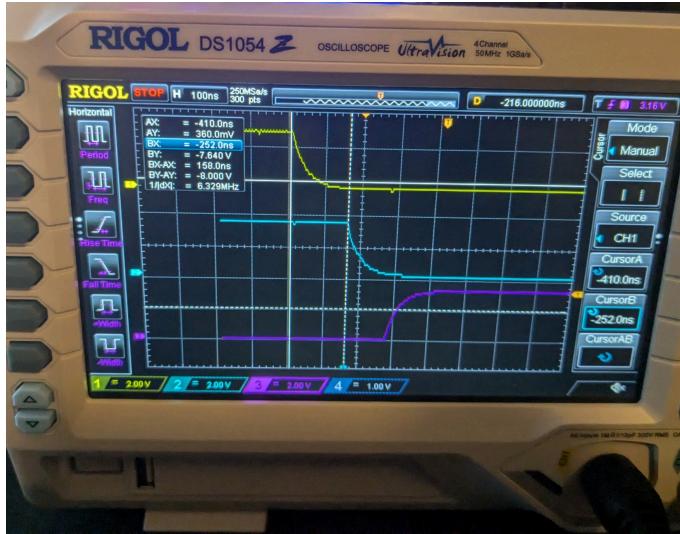


Figure 7: Oscilloscope of Commutation Timing Validation

3.3.2. Sensors

3.3.2.1. Operation

The FPGA is connected to the current sensor, which provides both a digital fault pin, and an analog current sensor that ranges from 0 to 3.3V, with current changing operating at around 1.6 Volts. For interfacing with the onboard ADC, there is IP connected to the system, which allows for the ADC to be connected to a threshold monitor for when 1.6 volts has changed, the system is able to operate. For the short pins, a register has been provided such that during any instance of a short pin turning on, the gate drivers turn off, and short output pin is sent to the microcontroller.

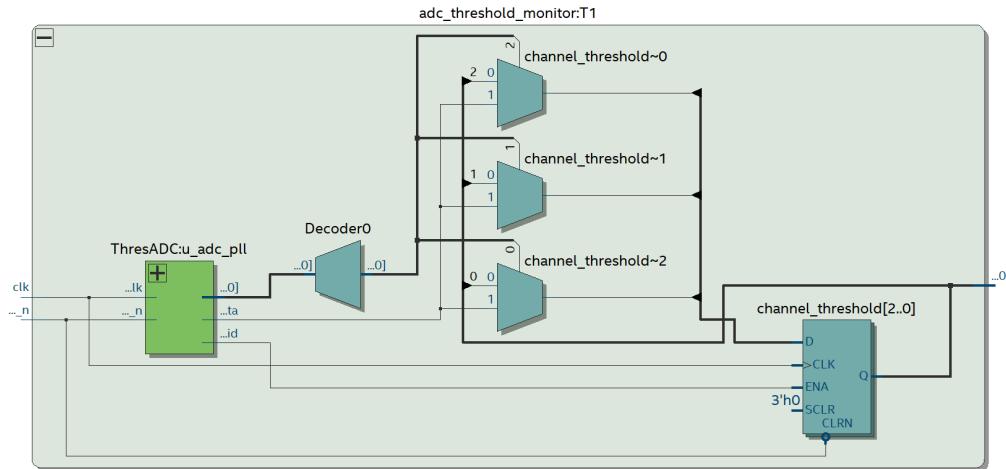


Figure 8: RTL View of Quartus ADC Threshold monitor

3.3.2.2. Validation

The FPGA Short circuit was validated by grounding a 3.3V output, per the current sensor fault functionality, which would then both create a short signal to the microcontroller, and turn off the gate driver output. An additional debug message is sent from the

microcontroller to the computer to indicate that a short has happened, so that the operator can be made aware. Validation was able to be made, with Figure 15 indicated that after the Yellow inverse fault was grounded, the short indication to the microcontroller was able to happen in 28 nanoseconds, well within the 6 microsecond requirement for the IGBTs, allowing for the short circuit detector to be able to have much greater margin of operation.

Figure 9: Oscilloscope view of inverse fault as yellow, Short output as blue



Current Sensing was found to be functional, but was unable to get an appropriate picture to demonstrate the functionality.

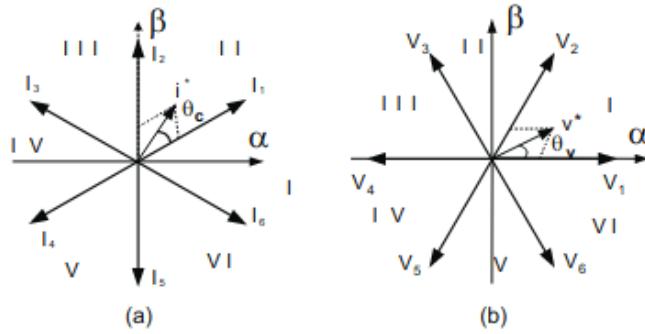
3.4. Microcontroller Firmware

3.4.1. Space Vector Modulation

3.4.1.1. Operation

In order to actually operate the frequency conversion process, a PWM algorithm is required to be sent to the switches. The algorithm chosen for this setup is called space vector modulation, or SVM. This subsystem operates by creating a virtual rectification, and inversion stage connected by an imaginary DC link. This splits the input and output frequencies into 2 distinct space vectors. These space vectors are the representation of the combined 3 phase currents, with the input space vector rotating at 60Hz, and the output space vector rotating at the provided frequency.

Figure 10: Space Vector Representation



With the space vectors rotating into different sections, this represents which virtual switches need to be set to the provided frequency, which is done utilizing imaginary matrix selection for the input and output, with the current largest voltage on the input being the virtual R phase, and the largest voltage output on the output being the virtual U Phase.

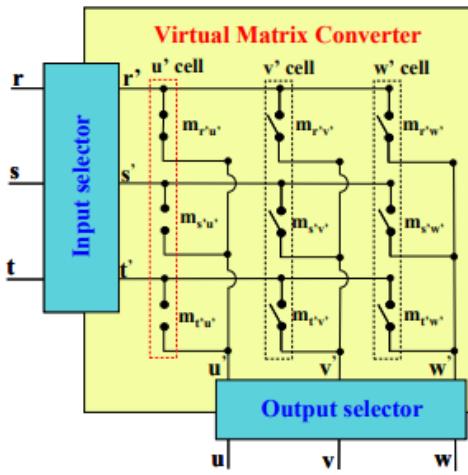


Figure 11: Virtual Matrix Selection

This allows for a simple matrix operation, where when

$$D = u_{r's'}^2 + u_{r't'}^2 + u_{s't'}^2$$

$$M_{virt} = \begin{bmatrix} m_{r'u'} = 1 & m_{r'v'} = 1 - m_{s'v'} - m_{t'v'} & m_{r'w'} = 1 - m_{s'w'} - m_{t'w'} \\ m_{s'u'} = 0 & m_{s'v'} = \frac{u_{u'v'} * (u_{r's'} - u_{s't'})}{D} & m_{s'w'} = \frac{u_{u'w'} * (u_{r's'} - u_{s't'})}{D} \\ m_{t'u'} = 0 & m_{t'v'} = \frac{u_{u'v'} * (u_{s't'} - u_{t'r'})}{D} & m_{t'w'} = \frac{u_{u'w'} * (u_{s't'} - u_{t'r'})}{D} \end{bmatrix}$$

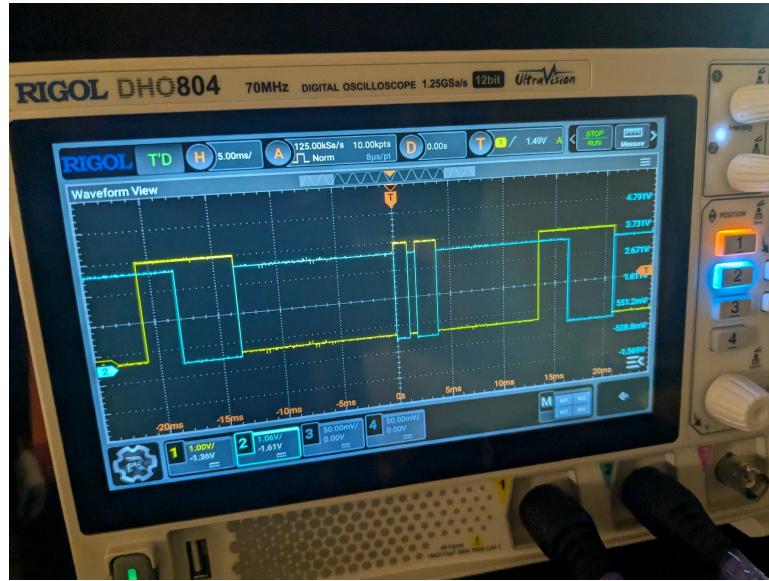
This creates a continuous signal for how the switches should be used, which is then converted into a discrete signal for the switches utilizing a 2.5kHz triangle carrier wave, where when the 1st and 2nd virtual input was greater than the triangle wave output, it would result in that switch being changed to, the 7th and 8th virtual output would be selected based off of being greater than the complemented carrier wave, and the 4th and 5th output

would be selected based off of if the respective associated output to the 1st and 7th, or the 2nd and 8th were on. This was then converted to a real output based off of the highest voltage on the output.

3.4.1.2. Validation

This was able to be validated in physical space, with the microcontroller able to output based off of the parameters set at the time for the appropriate input

Figure 12: Microcontroller Space Vector Modulation output for input A Phase



3.4.2. Computer Communication

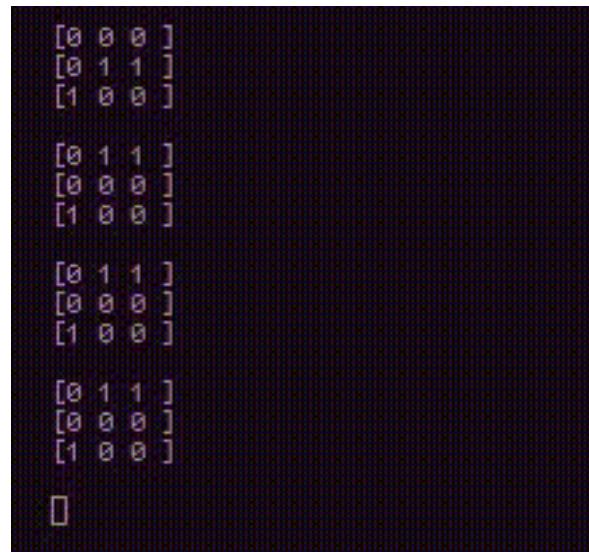
3.4.2.1. Operation

Communication of the STM32 to Computer is very simple, but important, with the computer control sending key inputs to the microcontroller, and the microcontroller sending back information of what the current frequency is set to, along with additional debug information as necessary. This enables a simple interface to interact with the matrix converter as a whole.

3.4.2.2. Validation

Utilizing picocom at a baud rate of 115200, tests with inputting frequency to the microcontroller, with the controller returning when prompted to. This was functional for asynchronous communication, which allowed for proper communication to happen for both setting frequency, providing for additional functionality, such as providing the current matrix output as visualized in a terminal output.

Figure 13: Terminal Uart Communication Functioning



A terminal window displaying a sequence of binary data. The data consists of four groups of three lines each, followed by a blank line. Each group contains the binary representation of three bits: [0 0 0], [0 1 1], [1 0 0]. The groups are separated by blank lines.

```
[0 0 0]
[0 1 1]
[1 0 0]

[0 1 1]
[0 0 0]
[1 0 0]

[0 1 1]
[0 0 0]
[1 0 0]

[0 1 1]
[0 0 0]
[1 0 0]

[]
```

3.4.3. Sensors

3.4.3.1. Voltage Crossing Sensor Operation

The Microcontroller utilizes the voltage sign sensors for the Space Vector Modulation, to create the $\theta_{A,B}$ and C for the virtual rectification stage. This is done utilizing rising edge interrupts for each of the pins, which then reset the theta V value, and then utilize the 50k timer to increment the $\theta_{A,B}$ and C timing.

3.4.3.2. Voltage Crossing Sensor Validation

To verify that operation of the interrupt was happening appropriately, validation was done by adding a debug command to send a message to the computer with the UART communication, with the microcontroller correctly receiving the message on the 60Hz frequency during the 3 phase operation. This unfortunately does not have an appropriate associated picture with it.

3.5. Subsystem Conclusion

Both commutation, and full current sensor functionality is working for the FPGA. The Microcontroller also has full functionality with both the zero crossing sensor, MC to Computer communication, Space Vector Modulation functionality, and communication from microcontroller to the FPGA. Full functionality and validation was done for the subsystem.

4. Pulse Generator Subsystem Report

4.1. Subsystem Introduction

This iteration of the Pulse Generator subsystem and board houses a linear voltage regulator which regulates 5 volts down to 3.3 volts, 3 current sign sensors, 3 voltage zero-crossing sensors, the FPGA, and the microcontroller (MCU) as the main components of the board, along with its passive components. The subsystem's intended purpose is to supply the Matrix Converter input, as the Pulse generator will produce output signals to allow for the matrix of switches to change at appropriate times.

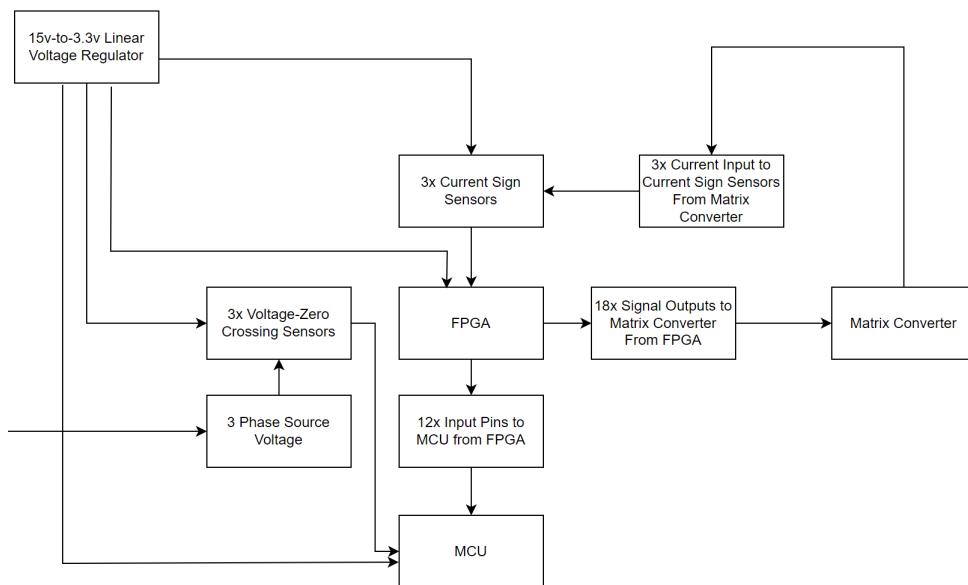


Figure 1: Block Diagram of Pulse Generator Circuit

4.2. Subsystem Faults

The pulse generator PCB was complete and validated on November 14, 2024. Before it was fully validated, the only portion of the subsystem left to validate was the zero crossing sensors. They weren't performing as expected. After looking at the datasheet of the sensors, it turns out that they weren't getting a high enough voltage. We were giving it 3.3 volts, while the sensors typically needed 15 volts to work properly. We had spare DC-DC converters, and installed one onto the PCB. After testing and validation, the sensors had then worked as we had expected.

Additionally, the diodes stopped working unexpectedly nearing the end of the semester during the night before the demo. We believe that the diodes on the board were not rated for 120 volts RMS, and as such during testing and validation, they had burnt out.

4.3. Subsystem Details

4.3.1. FPGA

The chosen FPGA is Intel's 10M04SAE144C8G. This FPGA was chosen mainly in part due to the requirements that the programmer had set for the commutation and sensor software. The FPGA is given 3.3 Volts for operation, with a max of 4.12 Volts needed, and it

has minimal current draw. The FPGA also had many decoupling capacitors required for operation, which were added under the board.

4.3.2. MCU

The chosen MCU is STMicroelectronics' STM32G491CET6. This MCU was chosen mainly in part due to the needs that the programmer had set for the space vector, communication, and sensor software. The MCU is given 3.3 Volts for operation, with a max of 4.0 Volts needed, and it has minimal current draw.

4.3.3. Linear Voltage Regulator

The chosen linear voltage regulator is STMicroelectronics' LD1117S33TR. The purpose of the voltage regulator is to power all the main electronics in the circuit. The voltage regulator needs 15 Volts to operate, and it has an output voltage of 3.3 Volts and an output current of 950 mA.

4.3.3.1. Linear Voltage Regulator - Validation

In order for the voltage regulator to be validated, it needed to output 3.3 Volts when connected to a 5 volt source. This test was conducted in the FEDC using a DC power supply and a digital multimeter. Once the PCB was connected to the power supply with a 5 volt input, the output of the voltage regulator measured across ground and the output to the voltage regulator. The multimeter read 3.3 volts which confirmed expected operation of the voltage regulator.



Figure 4: Multimeter showing the output of the Voltage Regulator with a 5 Volt input.

4.3.4. Current Sign Sensor

The chosen current sign sensor is Allegro Microsystems ACS71240LLCBTR-010B3. The sensor operates at 3.3 Volts, with the optimal sensing accuracy range being ± 10 Amps. This was chosen because the current that will be running through the matrix converter is nominally 10 Amps. The current sign sensor also has a short sensing capability, which will send a signal to the FPGA in case there is a short. The output of the sensors are connected to the FPGA, which holds the inputs to the matrix converter and drives the switching mechanism.

4.3.4.1. Current Sign Sensor - Validation

The current sign sensors were validated and worked as expected.

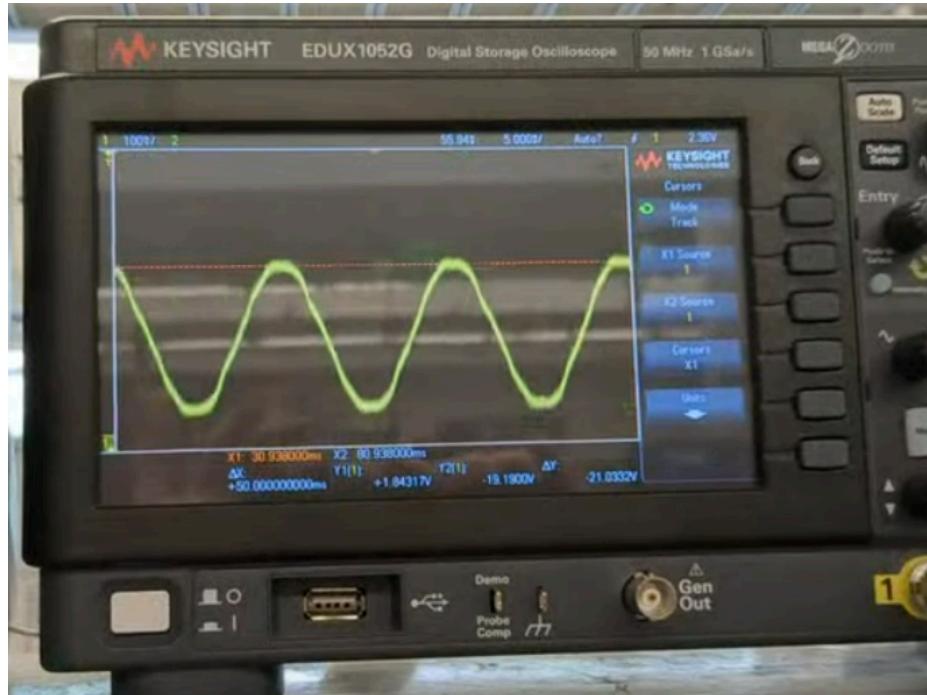


Figure ??: Output of the Current Sensor. 100W, 3Ω Power Resistor used.

4.3.5. Voltage Zero-Crossing Sensor

The chosen voltage-zero crossing sensor is Rohm Semiconductor's BM1Z002FJ-E2. The sensor operates at 3.3 Volts, and during active operation it has a current draw 160 μ A. Its intended purpose is to check when the input voltage crosses zero, which will then send a pulse signal to the MCU. The MCU will then control which switch is on or off during different time periods. This will help avoid a major shortage within the circuit as a whole.

4.3.5.1. Zero Crossing Sensors - Validation

The zero crossing sensors were validated and worked as expected.

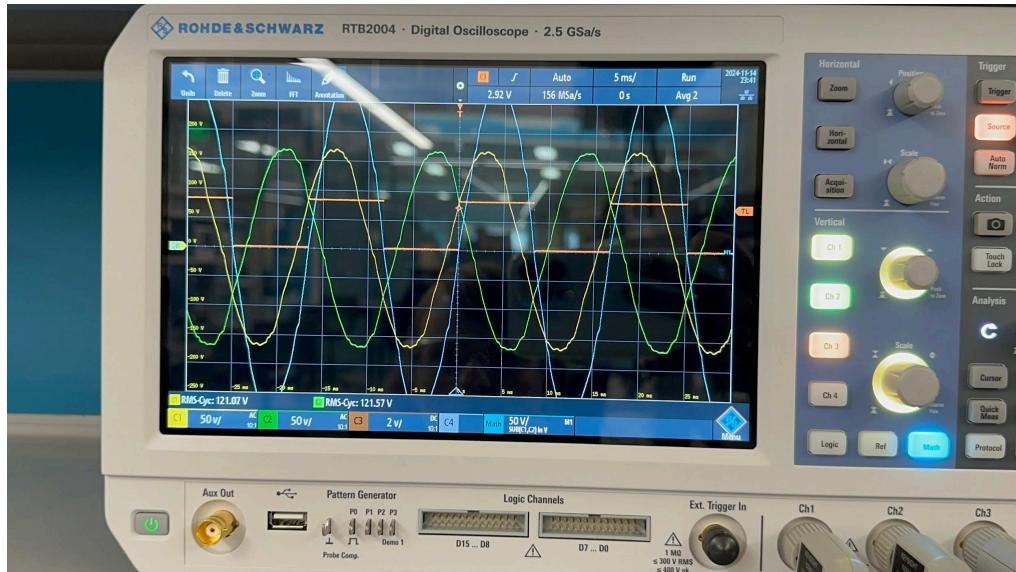


Figure ???: This image shows the zero crossing sensors working as expected.
Yellow sinusoid is phase A, Green sinusoid is phase B, Blue sinusoid is Phases A-B, square wave is the output of Sensor.

4.4. Subsystem Conclusion

Overall, the subsystem performed as expected after necessary adjustments were made throughout the year. Unfortunately, many unexpected issues arose right before the demo, and as such rendered some of the components on the pulse generator PCB unusable.

3 Phase Matrix Converter

Chase Barnes

Daniel Loeza

Shanelle Algama

SYSTEM DESCRIPTION AND DEVELOPMENT

REVISION – 1

SUBSYSTEMS REPORT FOR 3 Phase Matrix Converter

PREPARED BY:

Author Date

APPROVED BY:

Project Leader _____ **Date** _____

John Lusher II PE Date

T/A Date

Change Record

Rev	Date	Originator	Approvals	Description
1	11/30/2024	Chase Barnes		Original Release

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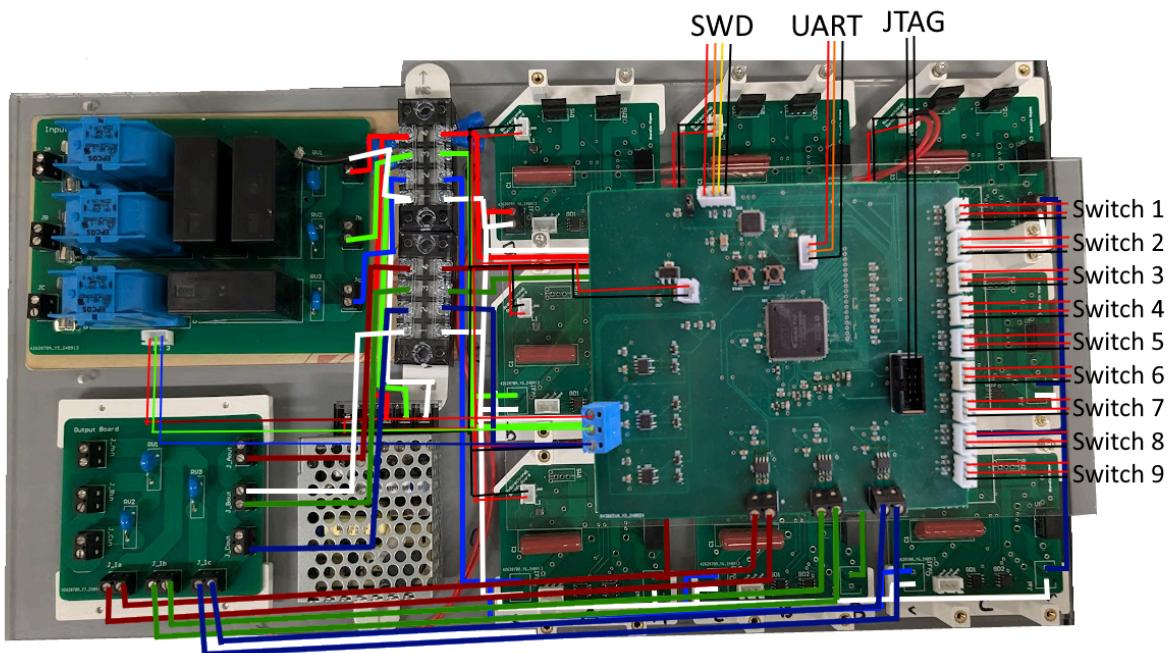
Figure 1: Matrix Converter

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1. Overview

The 3 Phase Matrix converter converts 208V 60Hz 3 Phase power into a variable frequency from 0-60 and will be able to power a ¼ horsepower motor. The system is broken down into 3 subsystems, the matrix of bidirectional switches, the hardware integration of processing devices and sensors for the conversion process, and the software integration of the digital devices and sensors. Due to errors in the subsystems, we were unfortunately unable to get complete integration. However, had further time been available, we had a clear direction into completing the integration. There are clear integration connections for the final product as described below.

Figure 1: The Matrix Converter



2. Development Plan and Execution

2.1. Design Plan

As previously mentioned, there were 3 individual subsystems which together formed the full Matrix Converter. The first semester of senior design focused on the initial subsystem design and project idea. The second semester focused on finishing up the individual subsystems and ideally validate full integration of all three systems. The objective is to be able to vary the frequency of a motor 0-60Hz using direct AC-AC conversion from 3 phase 208V. Unfortunately due to recurring issues from each subsystem, most of the second semester was spent diagnosing and attempting to solve these issues before integration. Fortunately, almost all of these issues (outlined in section 3.1) were eventually resolved, however full-system integration was not demonstrably completed. The goal by the end of the semester was to validate at least one phase.

2.2. Execution

Overall, the execution of the project did not go as planned due to many unforeseen circumstances. While we managed to nearly recover in the second half of ECEN 404, there were still plenty of issues we encountered, which will be discussed later in the report. Mainly, the first semester was focused on the development of each subsystem, and was focused on getting them ready for integration in the second semester of senior design. The second semester was unfortunately mainly focused on fixing all of the unresolved issues left over from the previous semester. The firmware and pulse generator subsystems were both fully integrated around late in the semester. The matrix converter subsystem was worked on until the end of the semester, and it had begun to work right before the demo. Unfortunately during testing and end-to-end validation of the system, we believe a short occurred somewhere and had blown out the power supply and many of the other components. All of the execution plans are previously shown in the report.

2.3. Analysis

The system, for the most part, had begun to work for a single phase. Like previously mentioned, the entire system seemed to work as expected up until we began testing. During testing, when we grounded an oscilloscope probe on the pulse generator board, we had a DC-DC converter on a bidirectional switch blow out, resulting in the power supply we were using, the DC DC converter on both, one of the bidirectional switches and on the pulse generator board, the linear regulator, microcontroller, and several of the zero crossing input diodes all started malfunctioning and became nonfunctional. We believe had we had more time, we could have gotten more of the switches to work, along with getting a replacement for any of the components that had been rendered nonfunctional.

3. Conclusion

3.1. Issues

As mentioned in the subsystem reports, there were several prevalent issues to be fixed throughout the course of the semester. For the matrix converter subsystem, one of the first major issues was the current draw into the DC-DC converter. This problem became apparent after testing with the new PCBs and new DC-DC converter. It was later discovered that pinouts on the DC-DC converter were flipped, and was thus corrected. There were further issues regarding the switches conducting when the gate drivers were off, and it was discovered that switching the IGBT configuration to common-emitter from common-collector was the solution, however this did not leave us with much time to convert the rest of the switches for a full matrix. During isolated testing to diagnose and solve these issues on the bidirectional switch, I repeatedly ran into more issues with accidentally shorting or frying components with the device under test, such as the IGBTs, gate drivers, and DC-DC converters. I later discovered that the input filter should be connected to the input of the bidirectional switch at all times to mitigate costly risks. Unfortunately, the damage was already done for some of the switches and further repair and additional testing was not possible at the time. Full-system integration was not yet completed.

3.2. Limitations and Disadvantages

There are several limitations and disadvantages for the three-phase matrix converter. One limitation includes requiring the use of a computer to control the system, since the system does not have a built-in user-friendly interface such as a GUI. The maximum voltage gain is also limited to 86.6% of the input voltage due to the space-vector modulation strategy. Implementing space vector modulation is also a highly complex commutation algorithm that requires precise timing to avoid leaving the output open or shorting the inputs, which can be a disadvantage. High component count (18 IGBTs utilized for the bidirectional switch versus 12 for traditional VFDs) is also required, which can restrict the three-phase matrix converter to specialized situations.

3.3. Future Work

Several improvements have been thought of to better improve the matrix converter. This includes but is not limited to:

changing from IGBT based bidirectional switch to either a Silicon Carbide (SiC) or a Gallium Nitride (GaN) based bidirectional switch, which would allow for both switching speed to be increased, and switching losses to be reduced.

changing from a space vector modulation algorithm to a neural network to further improve switching efficiency and speed. This would require a much faster and more accurate sensing setup however.

Adding an improved user interface that doesn't require an external computer would also help with marketability and make the device more accessible.

Improved